The Development of Students' Mental Models of Chemical Substances and Processes at the Molecular Level

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BSc. (Hons), Grad. Dip. Ed.

A thesis submitted in fulfilment of the requirements for the award of the degree

DOCTOR OF PHILOSOPHY

From

University of Western Sydney

2003
I hereby declare that this submission is my own work, and that, to the best of my knowledge and belief, it contains no material previously published by another person except where due acknowledgement is made in the text.

This thesis contains no material that has been submitted or accepted for the award of any other degree or diploma of a university or other institute of higher learning,

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No education is ever complete without a boogie-woogie-woogie beat!

(from ABC Boogie)
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Abstract

The development of students’ mental models of chemical substances and processes at the molecular level was studied in a three-phase project. Animations produced in the VisChem project were used as an integral part of the chemistry instruction to help students develop their mental models.

Phase one of the project involved examining the effectiveness of using animations to help first-year university chemistry students develop useful mental models of chemical phenomena. Progress from a pre-test to post-test, and evidence from one-to-one interviews, revealed that VisChem animations assisted in the learning of specific key features of molecular and ionic substances, and improved students’ confidence and imagery vividness. A transfer test and supporting interviews demonstrated that some students applied their mental models to new situations. Surveying and interviewing third-year university students revealed that those who had seen animations in their first year of university chemistry: had more detailed mental models than those who had not; recalled animations two or more years after instruction; and felt that animations had been useful to their learning of chemistry.

Phase two of the project explored factors affecting the development of students’ mental models, analysing results in terms of a proposed model of the perceptual processes involved in interpreting an animation. Based on the results of multiple regression analysis, it is proposed that prior knowledge, disembedding ability and study style have the most significant effect on the development and sophistication of students’ mental models of substances shown in animations and ability to apply these mental models to new situations. A follow-up study, replicating aspects of the original study, confirmed the role of prior knowledge, and to a lesser extent disembedding ability, in students’ mental model development. The small sample sizes used in these analyses mean that these conclusions can only be considered tentative.

Phase three involved four case studies that served to confirm and elaborate on the effects of prior knowledge and disembedding ability on students’ mental model development, and support the influence of study style on learning outcomes.

Recommendations for the use of VisChem animations, based on the above findings, include: considering the prior knowledge of students; focusing attention on relevant features; encouraging a deep approach to learning; using animation to teach visual concepts; presenting ideas visually, verbally and conceptually; establishing “animation literacy”; minimising cognitive load; using animation as feedback; using student drawings; repeating animations; and discussing “scientific modelling”.

Chapter 1

Literature Review

1.1. Introduction

Multimedia resources designed to teach chemistry often include computer-generated depictions of the molecular level. These depictions seem an ideal resource with which to teach concepts that are otherwise invisible. However, as is the case with all educational material, it cannot be assumed that learning will occur simply through exposure to such resources. There is an urgent need to determine whether students learn from these resources and under what conditions this learning occurs.

Much of this report will focus on the use of selected molecular-level animations portraying chemical substances and processes, in a face-to-face lecture setting. Some of the immediate and long-term benefits and pitfalls associated with the use of these computer animations in the teaching of chemistry, at a university level, are identified in two studies. The use and effectiveness of such visualisation tools are explored further through the examination of factors affecting students’ ability to learn from complex visual media; and from an in-depth look at the development of students’ mental images of chemical substances and processes through a first-year university chemistry course.

This chapter will begin with a concise outline of the relevant literature, highlighting the main research that has prompted the development of multimedia products in chemistry, and stimulated a belief that molecular-level animations may be able to target many of the misconceptions that students develop in chemistry. The starting point is a model of chemistry learning proposed by Alex Johnstone in 1982, which suggests that chemistry thinking occurs on a number of different levels: the “macro”, “sub-micro” and “representational” levels. The second section describes common student misconceptions regarding the confusion between the molecular and symbolic levels. The third section is an outline of research in the use of visualisation tools to assist in learning about the molecular level. These tools include
diagrams, animations and interactive multimedia programs. The chapter concludes with the aims of the research presented in this thesis and an outline of the structure of the thesis.

1.2. Macro, Sub-micro and Representational Levels of Thinking

A seminal work by Johnstone (1982) introduced science education researchers to the concept of multilevel thought. Johnstone proposed that thinking in chemistry exists on three levels which can be represented at the points of a triangle (see Figure 1.1). These levels are labelled macro (also referred to as “laboratory” or “macroscopic”), sub-micro (also referred to as “molecular” or “particulate”), and representational (also referred to as “symbolic”). The first level, macro, includes chemistry that is visible and tangible, incorporating what we observe in the chemistry laboratory. The second level of understanding, sub-micro, consists of descriptions that chemists use to explain what is happening at the macroscopic level, in terms of atoms, ions and molecules. We can then represent observed phenomena and molecular-level processes in terms of mathematics, symbols and chemical equations. Johnstone designates this the representational level.
Johnstone (1991) suggests that much of the difficulty associated with science learning occurs because “so much of teaching takes place within the triangle where the three levels interact in varying proportions and the teacher may be unaware of the demands being made on the pupils”. Many students find it difficult to see the relationships between the three levels (Kozma & Russell, 1997) and therefore, find it practically impossible to switch their thinking spontaneously between them. Understanding the relationships between the three levels does, however, vary from student to student, regardless of academic success (Hinton & Nakhleh, 1999). When students fail to see these relationships their knowledge is ultimately fragmented (Gabel, 1999) and many concepts may have only been learnt at a superficial level. Lack of meaningful learning is demonstrated by the fact that many students can solve traditional-style chemistry problems without understanding the underlying molecular processes (Nurrenbern & Pickering, 1987; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Niaz, 1995). Various researchers recommend teaching about the different levels of thinking in an explicit way, and helping students to draw links between the levels (Tasker, Chia, Bucat & Sleet, 1996; Russell, Kozma, Jones, Wykoff, Marx & Davis, 1997; Hinton & Nakhleh, 1999). Various multimedia programs have been produced for this purpose and are discussed below in Section 1.4.4.

Gabel (1999) suggests that problems arise because chemistry instruction has traditionally concentrated on the abstract, symbolic level and that teachers often haven't considered the three levels in their own thinking. It is likely that teachers do not realise that they are routinely moving from one level to another during their teaching. Conversely, presenting the three levels simultaneously to a novice is likely to overload his or her working memory (Johnstone,
1991; Gabel, 1999). If the levels are introduced together, numerous opportunities should be given to relate them, so that linkages are formed in the long-term memory.

Research into student misconceptions in chemistry reveals that students seem to have difficulty developing scientific ideas and images regarding the sub-micro level and relating these to chemical symbolism and laboratory work. An outline of some of the relevant research is described in Section 1.3.

1.3. Misconceptions

Nakhleh (1992) defined the term "misconception" as "any concept that differs from the commonly-accepted scientific understanding of the term". Tables 1.1 to 1.6 summarise common misconceptions identified among students, from various age groups, regarding the nature of matter, molecular substances, aqueous substances, chemical reactions and chemical formulae.

In the current study, a teaching strategy to address common misconceptions using molecular-level animations is evaluated. These animations were developed to target specific misconceptions. They are integrated with symbolic and macroscopic depictions in order to facilitate links between the three levels. This research is described in Chapter 2.

This research also supports and extends the research on misconceptions in the literature, in detailed studies of students’ conceptions in a variety of chemistry topics including those described in Tables 1.1 to 1.6. These studies involved the analysis of students’ responses to questionnaires designed to probe aspects of their mental models (Chapter 2), and in-depth interviews examining the changes in four students’ mental models over time (Chapter 4).
### The Nature of Matter

<table>
<thead>
<tr>
<th>Misconception/Difficulty</th>
<th>References</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students conceive matter as continuous and have difficulty conceiving of empty space between particles</td>
<td>Novick &amp; Nussbaum (1981)</td>
<td>Year 5 to first-year university</td>
</tr>
<tr>
<td></td>
<td>Andersson (1990a)</td>
<td>Ages 12 to 16</td>
</tr>
<tr>
<td></td>
<td>Renstrom, Andersson &amp; Marton (1990)</td>
<td>Years 7 to 9</td>
</tr>
<tr>
<td></td>
<td>Nakhleh (1994)</td>
<td>Year 11</td>
</tr>
<tr>
<td></td>
<td>Novick &amp; Nussbaum (1981)</td>
<td>Year 5 to first-year university</td>
</tr>
<tr>
<td></td>
<td>Griffiths &amp; Preston (1992)</td>
<td>Year 12</td>
</tr>
<tr>
<td>Students believe that atoms and molecules have macroscopic qualities</td>
<td>Ben-Zvi, Silberstein &amp; Mamluk (1990)</td>
<td>Year 10, 15 year olds</td>
</tr>
<tr>
<td></td>
<td>Haidar &amp; Abraham (1991)</td>
<td>Years 11 and 12, average age of 17</td>
</tr>
<tr>
<td></td>
<td>Griffiths &amp; Preston (1992)</td>
<td>Year 12</td>
</tr>
<tr>
<td></td>
<td>Lee et al. (1993)</td>
<td>Year 6</td>
</tr>
<tr>
<td></td>
<td>Harrison &amp; Treagust (1996)</td>
<td>Years 8 to 10</td>
</tr>
<tr>
<td>Students have difficulty in conceiving of matter as multi-particulate</td>
<td>Ben Zvi, Silberstein &amp; Mamluk (1990)</td>
<td>Year 10</td>
</tr>
<tr>
<td>Students may not spontaneously use particulate models</td>
<td>Haidar &amp; Abraham (1991)</td>
<td>Years 11 and 12, average age of 17</td>
</tr>
<tr>
<td></td>
<td>Lee et al. (1993)</td>
<td>Year 6</td>
</tr>
<tr>
<td></td>
<td>Ebenezer &amp; Gaskell (1995)</td>
<td>Year 11</td>
</tr>
<tr>
<td></td>
<td>Ginns &amp; Watters (1995)</td>
<td>Pre-service elementary teachers, aged 17 to 44 (median of 18)</td>
</tr>
<tr>
<td>Matter is conceived as static</td>
<td>Novick &amp; Nussbaum (1981)</td>
<td>Year 5 to first-year university</td>
</tr>
<tr>
<td></td>
<td>Andersson (1990a)</td>
<td>12 to 16 year olds</td>
</tr>
<tr>
<td></td>
<td>Pereira &amp; Pestana (1991)</td>
<td>Years 8 to 12</td>
</tr>
<tr>
<td></td>
<td>Lee et al. (1993)</td>
<td>Year 6</td>
</tr>
</tbody>
</table>

*Table 1.1 Summary of misconceptions related to the nature of matter*
<table>
<thead>
<tr>
<th>Misconception/Difficulty</th>
<th>References</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students conceive of molecules in a liquid as being reasonably spaced such that it could be compressible</td>
<td>Hill (1988)</td>
<td>First-year university science</td>
</tr>
<tr>
<td></td>
<td>Pereira &amp; Pestana (1991)</td>
<td>Years 8 to 12, ages 13 to 18</td>
</tr>
<tr>
<td>Students believe that there is a significant reduction in density when a solid melts</td>
<td>Hill (1988)</td>
<td>First-year science</td>
</tr>
<tr>
<td></td>
<td>Pereira &amp; Pestana (1991)</td>
<td>Years 8 to 12, ages 13 to 18</td>
</tr>
<tr>
<td>Students believe that there is little reduction in density when a liquid changes to a gas</td>
<td>Hill (1988)</td>
<td>First-year university science</td>
</tr>
<tr>
<td></td>
<td>Pereira &amp; Pestana (1991)</td>
<td>Years 8 to 12, ages 13 to 18</td>
</tr>
<tr>
<td>There is a tendency to suggest that ice is more densely packed than liquid water and that the molecules in ice touch each other continuously leaving no space</td>
<td>Griffiths &amp; Preston (1992)</td>
<td>Year 12</td>
</tr>
<tr>
<td></td>
<td>Ginns &amp; Watters (1995)</td>
<td>Pre-service elementary teachers, aged 17 to 44 (median of 18)</td>
</tr>
<tr>
<td>Students ignore the orderly structure of solids</td>
<td>Gabel &amp; Samuel (1987)</td>
<td>Pre-service elementary teachers</td>
</tr>
<tr>
<td></td>
<td>Griffiths &amp; Preston (1992)</td>
<td>Year 12</td>
</tr>
<tr>
<td></td>
<td>Lee et al. (1999)</td>
<td>Pre-service chemistry teachers</td>
</tr>
<tr>
<td>Students believe that molecules increase in size when moving from solid to liquid to gas</td>
<td>Gabel &amp; Samuel (1987)</td>
<td>Pre-service elementary teachers</td>
</tr>
<tr>
<td></td>
<td>Pereira &amp; Pestana (1991)</td>
<td>Years 8 to 12, ages 13 to 18</td>
</tr>
<tr>
<td></td>
<td>Griffiths &amp; Preston (1992)</td>
<td>Year 12</td>
</tr>
<tr>
<td>Students believe that molecules decrease in size when moving from solid to liquid to gas</td>
<td>Griffiths &amp; Preston (1992)</td>
<td>Year 12</td>
</tr>
<tr>
<td>Students believe that intramolecular forces are broken in phase changes</td>
<td>Ben-Zvi, Silberstein &amp; Mamlok (1990)</td>
<td>Year 10, 15 year olds</td>
</tr>
</tbody>
</table>

Table 1.2  Summary of misconceptions related to molecular substances
### Ionic Solids

<table>
<thead>
<tr>
<th>Misconception/Difficulty</th>
<th>References</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>There is a tendency to believe that there are molecules or discrete ion pairs in ionic solids</td>
<td>Butts &amp; Smith (1987)</td>
<td>Year 12</td>
</tr>
<tr>
<td></td>
<td>Taber (1994)</td>
<td>Ages 16 to 19</td>
</tr>
<tr>
<td></td>
<td>Boo (1998)</td>
<td>Year 12, ages 17 to 19</td>
</tr>
<tr>
<td></td>
<td>Lee et al. (1999)</td>
<td>Pre-service chemistry teachers</td>
</tr>
<tr>
<td>Some students think that a covalent bond holds sodium and chloride atoms together into a molecule whereas the ionic bonds hold these molecules together to form a crystal lattice</td>
<td>Butts &amp; Smith (1987)</td>
<td>Year 12</td>
</tr>
<tr>
<td>Some students believe that the molecules in an ionic solid are held together by covalent bonds</td>
<td>Butts &amp; Smith (1987)</td>
<td>Year 12</td>
</tr>
<tr>
<td>Students may think that an ionic bond, formed through the attraction of oppositely charged particles, results in a neutral molecule</td>
<td>Boo (1998)</td>
<td>Year 12, ages 17 to 19</td>
</tr>
<tr>
<td>There may be the misconception that a sodium atom can donate one electron and hence can only form one ionic bond</td>
<td>Taber (1994, 1997, 1998, 1999)</td>
<td>Ages 14 to 19</td>
</tr>
<tr>
<td>Students may think that bonds are only formed between atoms that donate/accept electrons and ions interact with the counterions around them, but for those not ionically bonded, these interactions are just forces or another form of bond</td>
<td>Taber (1994, 1997, 1998, 1999)</td>
<td>Ages 14 to 19</td>
</tr>
<tr>
<td>Students believe it is not possible to point to where the ionic bonds are unless you know which chloride ions have accepted electrons from which sodium ions</td>
<td>Taber (1997)</td>
<td>Ages 14 to 19</td>
</tr>
</tbody>
</table>

Table 1.3 Summary of misconceptions related to ionic solids
### Dissolution and Aqueous Solutions

<table>
<thead>
<tr>
<th>Misconception/Difficulty</th>
<th>References</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>There is a common inability to discriminate between dissolving and melting</td>
<td>Haidar &amp; Abraham (1991)</td>
<td>Years 11 and 12, average age of 17</td>
</tr>
<tr>
<td></td>
<td>Lee et al. (1993)</td>
<td>Year 6</td>
</tr>
<tr>
<td></td>
<td>Ebenezer &amp; Gaskell (1995)</td>
<td>Year 11</td>
</tr>
<tr>
<td>Students may over-represent the number of solute particles compared with solvent particles</td>
<td>Hill (1988)</td>
<td>First-year science</td>
</tr>
<tr>
<td>Particles in aqueous solutions are not generally drawn touching</td>
<td>Butts &amp; Smith (1987)</td>
<td>Year 12</td>
</tr>
<tr>
<td>Students may not conceive of movement</td>
<td>Lee et al. (1993)</td>
<td>Year 6</td>
</tr>
<tr>
<td>Some students believe that sugar goes into the empty &quot;air&quot; spaces in water when dissolved</td>
<td>Ebenezer &amp; Gaskell (1995)</td>
<td>Year 11</td>
</tr>
<tr>
<td>Some students think that dissolved particles go into empty spaces inside water molecules</td>
<td>Sequeira &amp; Leite (1990)</td>
<td>Years 8 and 9</td>
</tr>
<tr>
<td>Students generally do not see dissolving as an interactive process but rather the automatic separation, then dispersal of solute molecules throughout the solvent</td>
<td>Haidar &amp; Abraham (1991)</td>
<td>Years 11 and 12, average age of 17</td>
</tr>
<tr>
<td>Students rarely acknowledge the role of the polar nature of the water molecule in the process of dissolution</td>
<td>Butts &amp; Smith (1987)</td>
<td>Year 12</td>
</tr>
<tr>
<td>Some students suggest that a chemical reaction occurs on dissolution</td>
<td>Butts &amp; Smith (1987)</td>
<td>Year 12</td>
</tr>
<tr>
<td></td>
<td>Haidar &amp; Abraham (1991)</td>
<td>Years 11 and 12, average age of 17</td>
</tr>
<tr>
<td></td>
<td>Ebenezer &amp; Gaskell (1995)</td>
<td>Year 11</td>
</tr>
<tr>
<td>Some students do not dissociate any ionic species in their representations of aqueous solutions</td>
<td>Butts &amp; Smith (1987)</td>
<td>Year 12</td>
</tr>
<tr>
<td></td>
<td>Smith &amp; Metz (1996)</td>
<td>University chemistry undergraduates to faculty members</td>
</tr>
<tr>
<td></td>
<td>Boo (1998)</td>
<td>Year 12, ages 17 to 19</td>
</tr>
<tr>
<td></td>
<td>Taber (1999)</td>
<td>Ages 14 to 19</td>
</tr>
<tr>
<td>Students may believe that &quot;intramolecular&quot; forces between ionic molecules are broken to release ions in solution</td>
<td>Butts &amp; Smith (1987)</td>
<td>Year 12</td>
</tr>
<tr>
<td>Some students think that there might be some residual NaCl structure when NaCl dissolves in water because Na(^+) and Cl(^-) still attract each other</td>
<td>Butts &amp; Smith (1987)</td>
<td>Year 12</td>
</tr>
<tr>
<td>Some students rationalise the separation of NaCl into ions by suggesting that electrons are returned to the original atoms before solvation can occur</td>
<td>Boo (1998)</td>
<td>Year 12, ages 17 to 19</td>
</tr>
<tr>
<td></td>
<td>Taber (1999)</td>
<td>Ages 14 to 19</td>
</tr>
</tbody>
</table>

**Table 1.4** Summary of misconceptions related to dissolution and aqueous solutions
### Chemical Reactions

<table>
<thead>
<tr>
<th>Misconception/Difficulty</th>
<th>References</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students have a &quot;reluctance&quot; to perceive or represent chemical reactions as multi-particulate</td>
<td>Ben-Zvi, Eylon &amp; Silberstein (1987)</td>
<td>Aged 15+</td>
</tr>
<tr>
<td></td>
<td>Ben-Zvi, Silberstein &amp; Mamlok (1990)</td>
<td>Year 10, age 15</td>
</tr>
<tr>
<td></td>
<td>Smith &amp; Metz (1996)</td>
<td>Undergraduate university chemistry</td>
</tr>
<tr>
<td>The symbols (s), (l) and (g) are commonly ignored or have no meaning for students in multi-particulate terms <em>i.e.</em>, formulae followed by these symbols are often represented in the same way</td>
<td>Ben-Zvi, Silberstein &amp; Mamlok (1990)</td>
<td>Year 10, age 15</td>
</tr>
<tr>
<td></td>
<td>Smith &amp; Metz (1996)</td>
<td>Undergraduate university chemistry</td>
</tr>
<tr>
<td>The (aq) symbol is also ignored or misunderstood, as shown by the fact that students often fail to indicate that water is present in a reaction</td>
<td>Smith &amp; Metz (1996)</td>
<td>Undergraduate university chemistry</td>
</tr>
<tr>
<td>It is common for students not to dissociate ionic species when representing precipitation reactions</td>
<td>Smith &amp; Metz (1996)</td>
<td>University chemistry undergraduates to faculty members</td>
</tr>
<tr>
<td>Students &quot;cannot grasp the interactive nature of a chemical reaction&quot;</td>
<td>Ben-Zvi, Eylon &amp; Silberstein (1987)</td>
<td>Aged 15+</td>
</tr>
</tbody>
</table>

**Table 1.5  Summary of misconceptions related to chemical reactions**
<table>
<thead>
<tr>
<th>Misconception/Difficulty</th>
<th>References</th>
<th>Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>The coefficient indicates the number of the first element in the formula only <em>e.g.</em>, 2NaCl</td>
<td>Smith &amp; Metz (1996)</td>
<td>Undergraduate university chemistry</td>
</tr>
<tr>
<td>contains 2 sodium ions and 1 chloride ion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Students have an additive view of chemical species <em>e.g.</em>, the substance &quot;NiCl₂&quot; contains Ni</td>
<td>Ben-Zvi, Eylon &amp; Silberstein (1987)</td>
<td>Aged 15+</td>
</tr>
<tr>
<td>atoms and Cl₂ molecules</td>
<td>Ben-Zvi, Silberstein &amp; Mamlok (1990)</td>
<td>Year 10, age 15</td>
</tr>
<tr>
<td></td>
<td>Smith &amp; Metz (1996)</td>
<td>Undergraduate university chemistry</td>
</tr>
<tr>
<td></td>
<td>Garnett &amp; Hackling (2000)</td>
<td>Year 10, age 15</td>
</tr>
<tr>
<td>Students have difficulty converting between formulae and molecular representations for</td>
<td>Keig &amp; Rubba (1993)</td>
<td>Years 10 to 12</td>
</tr>
<tr>
<td>symmetrical molecules</td>
<td>Garnett &amp; Hackling, (2000)</td>
<td>Year 10, age 15</td>
</tr>
<tr>
<td>Students consider the total number of atoms present when drawing a molecular representation,</td>
<td>Yarroch (1985)</td>
<td>Secondary high school</td>
</tr>
<tr>
<td>without regard to the different meanings of coefficients and subscripts at a molecular level</td>
<td>Garnett &amp; Hackling, (2000)</td>
<td>Year 10, age 15</td>
</tr>
<tr>
<td>Students may use their prior knowledge (familiarity) to assess whether or not a proposed</td>
<td>Keig &amp; Rubba (1993)</td>
<td>Years 10 to 12</td>
</tr>
<tr>
<td>formula or representation is plausible, or to come up with a particular translation <em>e.g.</em>,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>a familiar sounding name, knowledge that a particular element exists as a diatomic molecule</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Students have difficulty in distinguishing between O₂ and 2O and O₂(g)</td>
<td>Ben-Zvi, Silberstein &amp; Mamlok (1990)</td>
<td>Year 10, age 15</td>
</tr>
<tr>
<td>Coefficients are for balancing purposes only</td>
<td>Yarroch (1985)</td>
<td>Secondary high school</td>
</tr>
<tr>
<td></td>
<td>Ben-Zvi, Eylon &amp; Silberstein (1987)</td>
<td>Year 10</td>
</tr>
</tbody>
</table>

**Table 1.6 Summary of misconceptions related to chemical formulae**
1.4. Visual Representations and Learning

For students to hold scientifically acceptable, useful mental models, they need visual images of their concepts. Many of the misconceptions outlined above are associated with a general inability to imagine structures and processes at the molecular level.

Visual mental images in chemistry can be constructed either from interpretation of text and verbal explanations or through exposure to visual representations such as diagrams, animations or three-dimensional models. The importance of visualisation in chemistry is described in Section 1.4.1.

1.4.1. The Importance of Visualisation

In the following discussion, the term “visualisation” will be used to describe the act of creating a visual mental image.

Jones, Jordon and Stillings (2001) advocate the use of visual representations for "helping students understand the dynamics involved in chemistry", to "provide a means of helping students improve their conceptions" and to portray simply and directly "the effect of subtle interactions between molecules, which are complex and difficult to describe simply". Visual representations are also useful in showing the three-dimensional spatial arrangements that are particularly important in organic chemistry (for example, see Treagust, Chittleborough & Mamiala, 2000). Research also suggests that visualisation tools in teaching may help students develop mental images of chemical phenomena (for example see Williamson & Abraham, 1995) and to think in three dimensions (Talley, 1973). The construction of suitable visual mental images in chemistry seems to act as a mediator for deep learning (Kleinman, Griffin & Kerner, 1987; Sleet, 1993), high-level thinking (Talley, 1973; Treagust et al., 2000) and problem-solving (Baker and Talley, 1972; 1974).

Sleet (1993) states that in order to develop a deep understanding of chemical processes at the macroscopic level, students need to be able to visualise the structures and behaviours of atoms, ions and molecules (i.e., molecular-level processes). This belief is supported by a study conducted by Kleinman et al. (1987) in which chemistry terms, such as "bond energy", "mole" and "solubility" prompted spontaneous images in people ranging from undergraduates
to post-doctoral students. The number of mental images experienced, as well as the level of abstraction, increased with educational level. This suggests that images become more sophisticated with increasing depth and expertise in chemistry. The authors concluded that:

"...students may be unable to learn chemistry, and that classroom communication might fail, because they cannot relate to or form the image appropriate to a concept...classroom instructional methods should consider that the ability of a student to understand chemistry may be related to the student's ability to develop specific images appropriate to the chemical concepts. The frustrated student may be unable to shift from the associative image (such as rote chemical or mathematical formulas) to the more abstract and specific images that professional chemists use." (Kleinman et al., 1987, p. 769)

1.4.2. Visual Imagery From Verbal Content

Although visual images seem to be associated with higher-order thinking in chemistry, the constructed visual images must be scientifically sound for them to be useful. To help students construct suitable images, an instructor may exploit visual models such as diagrams and modelling kits. If visual models are neglected in the teaching of chemistry, problems can arise. For students who are left to generate their own ideas from verbal statements, "a wrong model may result from erroneous visualisation" (Greca & Moreira, 1997, p. 713). Certain statements made by lecturers or written in textbooks have the power to mislead (McCubbin & Embeywa, 1987; Andersson, 1990a; Sleet 1993; Sanger & Greenbowe, 1999), as they may be unintentionally ambiguous. Ambiguous statements can lead to the development of inappropriate concepts and images. For example, the statement, "the ions carry the charge" may unintentionally create the misconception of an ion carrying an electron - through a solution, as described by Garnett, Garnett & Treagus (1990).

Where a student develops a particular image from a verbal statement, what is the likelihood that it is the image we expect? If we consider that the interpretation of the verbal content and the construction of visual imagery is also affected by prior knowledge (Johnstone, 1991; Sleet, 1998; Matthewson, 1999), then we would expect the range of interpretations and constructed images to be extensive (Kleinman et al., 1987).
A study by McCubbin and Embeywa (1987) illustrated the variability in students’ interpretations and representations of physics statements. More able students paid more attention to the specifics in the written language and tested their constructed images for consistency with the text. Interpretation of one item specifically suggested that “the more able student may be penalised through realising alternative interpretations but being unable to find sufficient textual clues to choose between them” (p. 236). Less experienced students showed a greater variety of errors in their responses. This study illustrates the need for pedantic use of language and to "employ language expressing direct causal relations rather than indirect ones" (McCubbin & Embeywa, 1987, p. 243).

There is a need to develop strategies for assisting students to construct visual images. Section 1.4.3 describes research into the use of visual models, i.e., two-dimensional representations and animations in chemistry education, for this purpose.

1.4.3. Use of Diagrams to Teach Chemistry

In science, diagrams are prolific in instructional material and they are invaluable for the communication of certain ideas. Some of these diagrams are complex, however, and are constructed using a number of scientific and artistic conventions. Unfortunately, students can find scientific diagrams difficult to interpret (Lowe, 1986 1987, 1988; Wheeler & Hill, 1990; Matthewson, 1999; Pinto & Ametller, 2002). Despite this, relatively few studies have been undertaken on the design, use and interpretation of diagrams in chemistry. Studies on the effectiveness, use and interpretation of diagrams have, however, been conducted in other areas of science (Mayer, 1989; Mayer & Gallini, 1990; Mayer, Bove, Bryman, Mars & Tapangco, 1996) and in mathematics (Mousavi, Low & Sweller, 1995). This research suggests that under certain conditions diagrams can be a very effective learning tool. Mayer (1989) showed that labelled diagrams with accompanying text may help students develop mental models that enable them to solve transfer problems. Concise, annotated, pictorial summaries, without accompanying text, were also found to be useful (Mayer et al., 1996). Mousavi et al. (1995) suggest that verbal narratives accompanying pictures, rather than text, might enhance student learning.

Some work has been done on the use of diagrams when teaching chemistry for representing problems (Sleet, Trigwell & Wilson, unpublished), improving laboratory manuals (Johnstone,
Sleet & Vianna, 1994; Dechsri, Jones & Heikkinen, 1997) and representing the molecular level (Gabel, 1993; Noh & Scharmann, 1997). The following discussion (Section 1.4.3.1) will focus on the use of diagrams for teaching about the molecular level of matter.

1.4.3.1. **Teaching about the Molecular Level of Matter Using Diagrams**

Research into the effectiveness of using molecular-level diagrams in the teaching of chemistry is limited. Two notable examples follow.

Gabel (1993) worked with high-school students to determine whether their understanding of chemistry could be enhanced by emphasising the particulate nature of matter in relation to the macroscopic and symbolic levels of representation. Molecular-level representations were a major feature in the instruction, in the form of overhead transparencies, work-sheets and circle cut-outs. Results showed that treatment classes performed better on all three levels of representation – sub-microscopic, macroscopic and symbolic, compared with the control group. This transfer of knowledge indicates the importance of directly teaching molecular-level occurrences and suggests that emphasis on the molecular level improves students’ conceptual understanding of equations and laboratory work. The small sample size used in this study, however, limits the extent to which these results can be generalised.

Noh and Scharmann (1997) presented a more thorough examination of the effectiveness of using molecular-level representations for teaching high-school (year 11, age 16–17) students chemistry. The study focused on students' conceptions regarding matter and physical changes and their problem-solving ability. Pictures of matter at the molecular level were used in instruction prior to the introduction of the quantitative aspects, and the molecular level was emphasised during problem solving. The authors focused on the topics: states of matter, phase changes, diffusion and dissolution. Data obtained suggested that instruction using molecular-level depictions was only slightly effective in improving students’ conceptions of chemistry concepts. The treatment group outperformed the control group in the topics of diffusion and dissolution. Scores for tests on the particulate nature of matter and states of matter, however, were not significantly higher for the treatment groups, perhaps due to significant prior knowledge in these areas. The authors suggested that the molecular-level approach was most
effective for students learning new or difficult concepts because it emphasised conceptual understanding more adequately than traditional instruction.

These studies suggest a potential benefit from the use of molecular-level pictorial instruction. Section 1.4.3.2 outlines the problems associated with the use of poor diagrams in teaching.

1.4.3.2. **Textbook Diagrams as a Source of Misconceptions**

The misleading nature of some diagrams in textbooks used to teach about the molecular level is commonly identified as a source of misconceptions (Hill, 1988; Andersson, 1990a; Wheeler & Hill, 1990; Sleet, 1993; Sanger & Greenbowe, 1999).

Diagrams are not always easy to interpret, particularly in the domain of chemistry where depictions often represent abstract concepts that cannot be experienced first-hand. Conventions, such as the scale modifications or the use of circles to represent molecules, are therefore open to misinterpretation when they are not discussed explicitly.

Hill suggested in 1988 that textbooks commonly in use contained drawings and diagrams that could mislead novices. He identified a number of "errors" common in textbook diagrams. These included: solute particles being over-represented, and misrepresentations of the densities of solids, liquids and gases. He demonstrated that some misconceptions students hold about the molecular level of matter are consistent with these textbook "errors". He concluded:

"The responses and reasons given for those responses suggest that many of these first-year students were not able to read and interpret diagrams in a critical manner and recognise their limitations. Rather, they depend on a qualitative global appreciation of the relationships involved and do not distinguish between the diagram and model it represents." (Hill, 1988, p. 296)

Wheeler and Hill (1990) suggested that seemingly simple diagrams may contribute to students' difficulties, confusion and even misconceptions in science. They suggest that typical diagrams of the dissolution process, for example, give false impressions of the numbers, sizes and relative shapes of the particles present, as well as the ratio of solvent to solute; that
covalent bonds and bonding in ionic lattices are often presented in the same way; and that particles in liquids are rarely shown to be touching, to mention but a few examples. Wheeler and Hill suggested that effective diagrams would narrow the gap between the intended learning outcome and the actual outcome.

Andersson (1990a) proposed that the belief that particles are embedded in continuous matter may be caused by or exacerbated by textbook diagrams. For example, it is common to see water molecules or ions floating in macroscopically depicted water. Students who perceive matter as continuous and have difficulty imagining empty space may interpret such diagrams to mean that both water and particles are present. He also points out that textbook diagrams often present erroneous depictions of the distances between particles in solids, liquids and gases.

1.4.3.3. Summary

Diagrams have the potential to either enhance or inhibit learning. Whether or not diagrams enhance learning is likely to depend on a number of factors including prior knowledge, the nature of the diagrams used, and the way the diagrams are presented.

This thesis will extend the current literature on the use of diagrams in chemistry by presenting student interpretations and critical analyses of two-dimensional representations of the molecular level. This research is presented in Chapter 4.

1.4.4. Use of Animations to Teach Chemistry

Section 1.4.3 suggested that diagrams of the molecular level incorporated into instructional sequences might enhance learning in chemistry under certain conditions. One limitation of diagrams is that they cannot portray movement directly (Lowe, 2001). Instead, they rely on symbols to convey dynamic aspects indirectly. Decoding of this symbolism can lead to working memory overload or misinterpretation (Lowe, 2001). An animated display could be less cluttered because it does not need to use such symbolism (Lowe, 2001). With recent developments in computer technology, an abundance of animations have been produced to accompany textbooks and websites. Animations, after all, are able to provide more detailed and accurate representations by showing movement (Lowe, 2001). As a result, however, they are inherently more visually complex than diagrams. The potential for this complexity to
reduce their effectiveness is a concern. The following section describes research into the design and use of animations to ensure maximum effectiveness in the teaching of chemistry.

The potential for the use of animations in chemistry instruction was pointed out by Jones et al. (2001) in a report prepared for the "2001 Gordon Research Conference on Science Education and Visualisation":

"Animation can add considerable learning potential to computer-generated visualization. We might distinguish roughly between two uses of animation. First, animation can be used to clarify information that is essentially static. For example, by rotating a computer-generated molecular model, one can get a better appreciation of its 3D structure; by systematically assembling and taking apart the visualization of a crystal, one can clarify structural relationships. Second, animation can be used to visualize the dynamics of individual molecules or molecular interactions. There is much educational potential in both these uses, but the second seems clearly the most important, since it extends molecular visualization to the processes that are at the heart of chemistry." emphasis mine (Jones et al., 2001, p. 11)

The following papers deal exclusively with the second use of animations described in the quotation above. Animations have been designed and used for a variety of topics including: states of matter, aqueous solutions, equilibrium, redox reactions, and chemical formulae. Different authors have studied the effectiveness of various animations and multimedia packages to help students build more scientific mental models, reduce student misconceptions and help students draw links between the macroscopic, molecular and symbolic levels in chemistry.

Williamson and Abraham (1995) aimed to determine whether two- and three-dimensional computer animations have any effect on college-level students’ visualisation of chemical concepts and whether they enhanced their understanding more than static drawings. Topics examined in the research included the particulate nature if matter, states of matter, dissolution, reactions in aqueous solutions and reaction types. They examined the effects of animations on conceptual understanding, course achievement and attitudes towards instruction. Although instruction using animations was found to have no effect on course achievement or attitudes, the animation group demonstrated greater conceptual understanding and reduced
misconceptions compared with the control. The animations seemed to encourage a particulate view of matter, as indicated by the conservation of particles between drawings and fewer “continuous matter” drawings. The authors concluded that animations helped students build dynamic mental models of chemical phenomena, whereas pictures either encouraged the formation of static mental models or failed to help students build any form of mental model.

Various chemistry educators adopt Johnstone’s concept of multilevel thought as a framework for designing multimedia interfaces or instructional sequences that incorporate animations of the molecular level. In this approach, animations portraying the molecular level are linked explicitly to representations of the symbolic and macroscopic levels.

A preliminary study by Greenbowe (1994) suggested that when animations are used during lectures to teach electrochemistry, they are most effective when “coupled with live demonstrations of electrochemical cells” (p. 556). A follow-up study conducted by Sanger and Greenbowe (1997) examined the effects of animations, coupled with live demonstrations and a balanced equation, on students’ conceptual understanding of electrochemistry. In this way, they hoped to facilitate a linking of the macroscopic, symbolic and molecular-level processes. Sanger and Greenbowe looked specifically at the common misconception that electrons move individually through the solution and the salt bridge in an electrochemical cell. Students were required to answer questions relating to current flow in electrochemical cells. Responses were compared to those obtained in another study, in which students responded to similar questions. Results tentatively suggested that viewing the animation helped students to visualise the process and significantly decreased the number of students consistently demonstrating this misconception, as compared with students in the comparison study.

In 1998, Burke, Greenbowe and Windschitl published a paper outlining the effective use of their animations of electrochemical processes. They advised that animation sequences should be short (20–60 s) and focused. Among other things, they must have "accurate" chemistry content, address misconceptions in the literature and ideally would allow for some student interactivity with appropriate feedback. As mentioned by Sanger and Greenbowe (1997), animations should be used in conjunction with lecture demonstrations to help students draw connections between the macroscopic, symbolic and molecular levels of representation. Also, when animations are used in a classroom instructional sequence, the teacher or lecturer should
provide a verbal narrative. Access to animations outside the lectures was also considered important. The authors concluded that when care is taken to design and use animations appropriately, students' understanding should improve as a result.

Sanger, Phelps and Fienhold (2000) reported the use of an animation to help students develop an understanding of the molecular-level processes involved in a can-crushing experiment. Their results suggested that students who viewed animations of the molecular-level process were more able to discuss the relevant details relating to water condensation and pressure in their explanations of the phenomena, and were less likely to blindly apply gas laws. Therefore, it was concluded that the animations assisted in conceptual understanding.

Russell et al. (1997) developed an interactive chemistry multimedia program on the topic of equilibrium (4M:Chem - Multimedia and Mental Models) which draws explicit links between the different levels of chemistry thinking. The program was designed to directly address some of the main misconceptions students hold on the topic of equilibrium, including the idea that equilibrium systems are static and that they contain equal amounts of reactants and products. The program utilised four different levels of representation (laboratory, symbolic, molecular animation, graphs and diagrams), which can be shown individually or in combination. When played synchronously, the manipulations carried out on one area (e.g., laboratory) induce changes in all areas. The multiple-representation approach was designed to help students build mental links between various aspects of different representations and thus strengthen their mental models. An initial evaluation of a general university chemistry course showed significant improvement in answers to a post-test following two one-hour presentations of 4M:Chem, when compared with a pre-test. A decrease in "misconceptual" statements was also noted. Students demonstrated an increased understanding of the nature of equilibria and the effects of temperature on these systems. 4M:Chem was not successful, however, in improving students’ understanding of the effects of pressure on equilibria (Kozma, Russell, Jones, Marx & Davis, 1996). Furthermore, the percentage of students that still did not demonstrate an understanding of equilibrium reactions after instruction was quite large.

Garnett and Hackling (2000) explored the use of a multimedia tool entitled "Balancing and Interpreting Chemical Equations", in improving year 10 students' understanding of the molecular level of chemical reactions. A pre-test and post-test examined the students' ability to translate (or transform) from symbolic to particulate representations and vice versa. Results
indicated an improvement in the students' understanding of the symbolic notation of chemical equations and representations of chemical reactions at the molecular level.

The previous research demonstrates the effectiveness of animations in helping students build more scientific mental models, reduce student misconceptions and help students draw links between the macroscopic, molecular and symbolic levels in chemistry. These papers, however, utilise animations in a two-dimensional environment. These have the potential to create false or incomplete mental models. To fully utilise the computer's potential and move closer to scientific “reality”, Tasker and co-workers (1996) developed a number of three-dimensional animations portraying structures and processes in the molecular world. The project was entitled “VisChem© – Visualising the Molecular World”. In accordance with the three levels of chemical thinking, animations are presented separately, then simultaneously, with equations and laboratory-level simulations. The use of these animations in the teaching of chemistry is a major focus of this thesis. A description of these animations and previous research into their effectiveness is given in Section 1.4.5.

1.4.5. VisChem Animations

VisChem animations were specifically designed to confront common misconceptions found in the literature concerning the nature of matter at the molecular level (Tasker, Chia, Sleet & Bucat, 1996). Care was taken to represent molecular structures with scientific accuracy because as discussed by Tasker (1998), poorly constructed animations may promote the generation of misconceptions. Nevertheless, the designers conceded that no representation can be an exact replica of reality and that the animations can only ever be “models”:

“The speed of atomic and molecular movements, and the uncertain (non-Newtonian) nature of electrons in atoms, requires substantial ‘artistic license’ to enable the structure and collisions at this level to be represented. For this reason the presentation of these animations as only a ‘model’ of reality must be reinforced often in the program modules.” (Tasker et al., 1996, p. 395)

During instruction, emphasis needs to be placed on the importance of animations for helping students construct useful mental models of the molecular level.
The animations were produced using the three-dimensional drawing package Infini D (Specular International), and assembled in Director (Macromedia). Compressed as Quicktime movies they range from 200 to 300 frames running at 10 frames per second, and use from three to 15 Mb of memory (Tasker et al., 1996). The VisChem animations are available in analogue format on videotape and digitally as compressed animations on CD or on the Web, and have been incorporated into a range of multimedia programs (see Table 1.7).
<table>
<thead>
<tr>
<th>Descriptions of Multimedia Programs</th>
<th>Sample Frames from Multimedia Programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>• This interactive CD supplement covers five major topic areas and includes VisChem animations, interactive questioning and molecular-level constructions.</td>
<td></td>
</tr>
<tr>
<td><strong>Snapshots</strong></td>
<td></td>
</tr>
<tr>
<td>• Molecular-level constructions encourage students to consider their mental models of particular substances before seeing a corresponding animation. Frame (a) shows misconceptions specifically targeted in the animation, with voiceover, shown in frame (b).</td>
<td>(a) (b)</td>
</tr>
<tr>
<td>• These web-deliverable modules, on selected topics in each chapter, use interactive animations and simulations to develop thinking at the molecular level. There is a major emphasis on molecular-level visualisation.</td>
<td></td>
</tr>
<tr>
<td><strong>Snapshots</strong></td>
<td></td>
</tr>
<tr>
<td>• After clicking on the top-right animation frame (frame (c)), the VisChem animation appears embedded in an interactive interface. (frame (d)) Students are encouraged to engage with the animation by answering questions and clicking on hotspots.</td>
<td>(c) (d)</td>
</tr>
<tr>
<td>Descriptions of Multimedia Programs</td>
<td>Sample Frames from Multimedia Programs</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>---------------------------------------</td>
</tr>
<tr>
<td>• This program features pre- or post-lab modules for selected laboratory experiments in university-level general chemistry, containing VisChem animations, with student tracking.</td>
<td>(e)</td>
</tr>
<tr>
<td>• This site contains web-deliverable versions of VisChem animations to complement and supplement Figures in the textbook. These can be downloaded directly from the website.</td>
<td>(f)</td>
</tr>
</tbody>
</table>
Table 1.7  Descriptions and snapshots of multimedia programs incorporating VisChem animations

<table>
<thead>
<tr>
<th>Descriptions of Multimedia Programs</th>
<th>Sample Frames from Multimedia Programs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tasker R (2001) CD and Web Site for <em>ChemCom — Chemistry in the Community</em>. An American Chemical</td>
<td></td>
</tr>
<tr>
<td>whfreeman.com/chemcom and go to “Interactive ChemCom Media”)</td>
<td></td>
</tr>
<tr>
<td>• These web-deliverable modules use VisChem animations and interactive graphics to develop thinking</td>
<td></td>
</tr>
<tr>
<td>at the molecular level. There is a major emphasis on applications to everyday contexts.</td>
<td></td>
</tr>
</tbody>
</table>
A preliminary investigation was carried out (Tasker, Chia, Bucat & Sleet, unpublished) to evaluate the effectiveness of VisChem animations of the molecular world of water (states and state changes) and teacher and student attitudes towards them. Students and teachers from around Australia (at both secondary and tertiary levels) answered surveys about a video featuring the animations. Students completed a test before and after a single viewing of the video. Teachers and students made favourable comments concerning the animations. Results of the post-test indicated that some students corrected their misconceptions (see Table 1.8).

<table>
<thead>
<tr>
<th>Question</th>
<th>% Incorrect in Pre-test</th>
<th>% Incorrect in Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>State two differences at the molecular level between the liquid and gaseous states of water.</td>
<td>39</td>
</tr>
<tr>
<td>2</td>
<td>Describe briefly what happens to ice at the molecular level when it melts</td>
<td>38</td>
</tr>
<tr>
<td>3</td>
<td>What is in between the molecules in a glass of water</td>
<td>62</td>
</tr>
<tr>
<td>4</td>
<td>What is inside the bubbles in boiling water?</td>
<td>61</td>
</tr>
<tr>
<td>5</td>
<td>From the following three sets of diagrams, select the set (tick 1, 2 or 3) that best represents the relative size of the molecules in the three states (solid, liquid and gas) of a molecular compound. Note that a circle represents a molecule. Give a brief explanation for your choice.</td>
<td>35</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>solid</th>
<th>liquid</th>
<th>gas</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6. Draw a labelled diagram of a water molecule | 26 | 14 |

Table 1.8  Student data (N = 160) from the pre-test and post-test in study by Tasker et al.

This thesis will extend the current research on the use of animations in chemistry by examining the effectiveness of using VisChem animations in first year university chemistry; and studying some of the long-term effects of their use. There is little or no research published on long-term (in this case, two years) retention of images derived from animations. This research will be discussed in Chapter 2.
Research on student attributes that influence ability to learn from VisChem animations will be presented. There is little research on factors affecting students’ interpretation of animations, and ability to construct suitable mental models of the phenomena. This work provides a significant contribution in this area, including a proposed model of the perceptual processes involved in perceiving an animation. This research is described in Chapter 3.

1.5. Aims of the Research

The main aims of the research presented in this thesis are:

- To examine the effectiveness of using VisChem computer animations to help students develop useful and acceptable mental models of chemical phenomena.

- To explore whether or not certain student attributes influence their ability to construct such mental models.

- To examine, using detailed case studies, the effects of instruction using the animations, and of the key attributes identified above, on the development of mental models by four students, during their first year of university chemistry.

1.6. Structure of the Research Project

The research began in 1999 with preliminary studies of student misconceptions in a variety of topics, and changes to student imagery following discussion of VisChem animations. Based on these studies, hypotheses and methodology for the main research conducted in 2000, were refined. As a result, the effectiveness of the VisChem animations and factors influencing their effectiveness were evaluated. The first set of data for a study on the longitudinal effects of exposure to VisChem animations was also obtained in 1999. The second set of data for this study was collected in 2000. Studies conducted in 2001 served to confirm and elaborate on some of the findings from 2000, and in-depth interviews were conducted with four students to examine the development of their mental models.
1.7. Outline of the Thesis

The research aims listed in Section 1.5 will be examined in three main chapters. Each chapter considers the relevant literature, lists the hypotheses and aims of each study, describes the methodology used, then presents the results and discussion. A decision was made not to present methodology, results and discussion as discrete chapters due to the fact that each component of the overall research represents distinctly different aims, as outlined above. Conclusions drawn across the three chapters will be summarised in Chapter 5 of the thesis.
Chapter 2 deals almost exclusively with data obtained on the effectiveness of VisChem animations. Two studies are presented; the first considering the effects of animations on the mental models of first year university chemistry students; the second considering the longitudinal effects by examining the attitudes and images of third year chemistry students. In the first study, various aspects of effectiveness were investigated including: the vividness of students’ mental images and their confidence in these images. The methodology employed a pre-test/post-test design with follow-up, semi-structured interviews. Tuition involved the animations presented in the teaching context of a face-to-face lecture as part of the normal curriculum. The second study involved two questionnaires completed by third year chemistry students. One questionnaire examined students’ images, the other examined their recall of animations and their perceived benefits. Follow-up interviews were also conducted.

Chapter 3 presents a statistical analysis of data obtained on particular student attributes, ranging from their attitudes towards chemistry, to their ability to visualise everyday scenes. The influence of these factors on responses in two post-questionnaires, was examined using multiple regression analysis.
The final results chapter, Chapter 4, presents comprehensive case studies of four first year university chemistry students, selected on the basis of their scores on two questionnaires. The data largely consist of a series of semi-structured interviews used to probe students’ understanding of a variety of chemical topics.

Finally Chapter 5 summarises findings from the results chapters, drawing conclusions about how students learn from visual media in chemistry, and how best to present VisChem animations to maximise meaningful learning. The chapter concludes with an outline of avenues for further research.
Chapter 2

Effectiveness of VisChem Animations

2.1. Introduction

This chapter presents the results of studies that evaluate the effectiveness of VisChem animations in assisting students to build useful mental models of the molecular world.

Section 2.2 describes the use of VisChem animations in teaching first-year university chemistry. This study was conducted over two years, with most data collected in the first year, and further data collected in the second year with a new set of first-year university students. Section 2.3 presents further insights into data collected in the first year.

Section 2.4 presents evidence for the long-term effects of exposure to the animations. This study involved two consecutive groups of third-year university chemistry students.

2.1.1. Preliminary Study

In 1999, prior to conducting the studies outlined in Sections 2.2 to 2.4, a small preliminary study was undertaken with first-year university students. The preliminary study had two main aims:

- To identify student misconceptions relating to molecular and ionic substances;
- To examine whether VisChem animations helped students develop scientifically-acceptable mental models of chemical phenomena.

A questionnaire was distributed to 19 first-year chemistry students during their first laboratory session, to identify misconceptions held by students at the outset of their studies at a metropolitan university in NSW, Australia. The questionnaire looked at students’ images and ideas of the molecular substance water (solid and liquid states), and the ionic substance sodium chloride (solid, liquid and aqueous). The misconceptions that emerged both confirmed and extended the data reported in the literature and served as a starting point for the
development of the diagnostic questionnaire used in the main research study. The more common misconceptions identified are outlined in Table 2.1.

Approximately one week after completing the questionnaire, six of the 19 students described above, participated in discussion sessions. During these discussions, they were shown animations of some of the above substances. Approximately two weeks after the discussion, these students completed a further questionnaire that measured the retention of ideas developed during the discussion sessions. The most significant finding was that each student seemed to develop his/her images to a different extent, even though they had participated in equivalent discussion of and exposure to the animations. For example, one had developed the correct ion-hydration model, three had adopted some aspects of this model, and one showed little development. Figure 2.1 shows a sample of changes in student responses, relating to ion hydration. This finding encouraged me to explore the factors affecting the development of students’ images. This research is presented in Chapter 3.
<table>
<thead>
<tr>
<th>Misconception</th>
<th>Percentage (number of responses) (N = 19)</th>
<th>Sample Quotes</th>
</tr>
</thead>
<tbody>
<tr>
<td>There is no (mention of) movement in solid NaCl</td>
<td>79% (15)</td>
<td>“molecules are not free to move”</td>
</tr>
<tr>
<td>Molecules in liquid water are further apart than in ice</td>
<td>68% (13)</td>
<td>“As we heat the water more, molecules move faster and faster and are move apart from each other and therefore water becomes less dense”</td>
</tr>
<tr>
<td>In aqueous NaCl, there is no interaction of ions/molecules with water molecules</td>
<td>53% (10)</td>
<td>“Cl ions &amp; Na ions moving amongst the H₂O molecules”</td>
</tr>
<tr>
<td>Ionic solids contain molecules</td>
<td>47% (9)</td>
<td>“the NaCl molecules are held together by intermolecular forces”</td>
</tr>
<tr>
<td>Water molecules in ice do not move</td>
<td>42% (8)</td>
<td>“molecules not free to move”</td>
</tr>
<tr>
<td>When ionic solids melt, the intermolecular bonds between NaCl molecules break/molecules separate</td>
<td>42% (8)</td>
<td>“The sodium chloride molecules move around. The bonds between them have been broken”</td>
</tr>
<tr>
<td>Molecules in ice are closely packed¹</td>
<td>21% (4)</td>
<td></td>
</tr>
<tr>
<td>In dissolving, each NaCl unit (ions or molecule) sticks to a water molecule</td>
<td>16% (3)</td>
<td>“The salt and water molecules are attached to one another in some way”</td>
</tr>
<tr>
<td>In dissolving, the intramolecular bond in the NaCl molecule is broken</td>
<td>16% (3)</td>
<td>“The salt (NaCl) molecules are mixed with H₂O and then break apart and form their respective ions”</td>
</tr>
</tbody>
</table>

Table 2.1 Summary of the most common misconceptions revealed by first-year chemistry students in the preliminary study

¹ Misconception demonstrated in student drawings
### Pre-test Image

<table>
<thead>
<tr>
<th>Adoption of correct model of ion hydration</th>
</tr>
</thead>
<tbody>
<tr>
<td>NaCl(aq)</td>
</tr>
</tbody>
</table>

### Post-test Image

<table>
<thead>
<tr>
<th>Adoption of correct model of ion hydration</th>
</tr>
</thead>
<tbody>
<tr>
<td>NiBr$_3$(aq)</td>
</tr>
</tbody>
</table>

### Partial adoption of correct model of ion hydration

| NaCl(aq) |

### No change in concept of ion hydration

| NaCl(aq) |

---

*Figure 2.1*  Sample student responses before and after exposure to animations
2.2. The Use of VisChem Animations in First-Year University Chemistry

2.2.1. Research Hypotheses

This section describes research into the effectiveness VisChem molecular-level animations in teaching chemistry at university level. The aim was to determine if these animations helped students build useful and acceptable mental models of chemical phenomena.

For the purpose of this study, VisChem animations are deemed “effective” if they:

- Improved students’ images of certain substances in the molecular world, *i.e.*, students’ images became more detailed and scientifically acceptable;
- Improved students’ confidence in responding to questions regarding the molecular level;
- Improved the vividness of students’ visual mental images of certain substances; and
- Improved their ability to visualise chemical substances and systems not depicted by the VisChem animations.

These aspects of effectiveness are explored in this study.

2.2.2. Methodology

2.2.2.1. Sampling

The study was both quantitative and qualitative in nature, using a common pre-test/post-test design and follow-up interviews, similar to the design used by Tao and Gunstone (1999). A "transfer" test was also administered after the post-test and prior to interviews.

First-year chemistry students at a metropolitan university in NSW, Australia, participated in the study in 2000. Students (N = 48; 20 female, 28 male) completed a pre-test in the first lecture of semester 1, and a post-test in the final lecture of semester 1. Of the 48 students, 32
had previously completed chemistry at HSC\(^\ast\) level (two-unit Chemistry, three-unit Science or equivalent), 11 had not studied beyond junior (year 9/10) chemistry, two had studied year 11 chemistry only, one had not studied chemistry for many years, and one had an unknown background. Ages of the students ranged from 17 to 47 years, with a median of 18 years, at the time of completing the pre-test.

Of the students who completed both the pre-test and post-test, 39 completed the transfer test. The transfer test was administered in week one of semester 2, 2000.

One-to-one interviews were carried out with 14 volunteers from the students who had completed all three questionnaires: the pre-test, post-test and transfer test. These students demonstrated a range of academic abilities according to their semester 1 results. Interviews lasted approximately one hour and followed a semi-structured protocol. Interviews were fully recorded on audio-tape and transcribed verbatim. Full transcripts were compiled and processed using NUD*IST 4.

Participants were not advised that the effectiveness of the animations was being tested.

In the following year (2001), a slightly revised version of the questionnaire was administered to first-year chemistry students at the same university, to provide confirmatory data for some of the hypotheses developed after completion of the first part of the study. Questionnaires were administered during the first and penultimate weeks of semester 1. In total, 36 students completed both the pre-test and the post-test. Of these students, 18 were female, 18 male; 28 had completed HSC chemistry (two-unit Chemistry, three-unit Science or equivalent), three had no chemistry background beyond junior science, two had completed general science courses at HSC level, one completed year 11 chemistry only and two had unknown backgrounds. Ages of these students ranged from 17–32 years, with a median of 18 years.

Ethics approval was acquired through the university in which the studies were carried out. Students were provided with an information statement detailing the nature of the study and what was required of them. Completion of the pre-test or post-test was taken as an indication

\(^\ast\)HSC stands for Higher School Certificate. It refers to the completion of the final year of high school, in NSW schools, Australia.
of willingness to participate in the study. Interviewed students signed an information statement before participating in the research, to indicate the voluntary nature of their participation. The ethics approval letters can be found in Appendix F.

2.2.2.2. Design of the Pre-test/Post-test

The pre-test was designed to determine the students’ level of prior knowledge of substances in chemistry, in particular their images and ideas at the molecular level of a molecular substance (water) in the solid, liquid and gaseous states; an ionic solid (sodium chloride) and an ionic solution (an aqueous solution of sodium chloride).

An identical questionnaire was administered in the final lecture of the semester as the post-test, to evaluate any changes that had occurred in student images, confidence and imagery vividness.

2.2.2.2.1. Questions

The questionnaire was designed to identify common misconceptions, revealed in student representations from pilot studies in the previous year. The questions used to assess student images required the students to draw and/or explain their images (molecular substances), or to critically evaluate a variety of 2D representations at the molecular level of pure substances and solutions (ionic substances) (see Figure 2.2).

The use of student drawings to assess conceptual understanding is common (see for example: Novick & Nussbaum, 1981; Butts & Smith, 1987; Gabel & Samuel, 1987; Haidar & Abraham, 1991; Williamson & Abraham, 1995; Smith & Metz, 1996; Lee, 1999). Haidar and Abraham (1991) used an approach similar to that adopted in this study to assess students’ images of solid, liquid and gaseous water using student-generated drawings and descriptions. Student-generated drawings are described by White and Gunstone (1992) as revealing “hidden, unsuspected parts” (p. 104) of a student’s understanding.

Three questions in the questionnaire were multiple-choice and required students to justify their choice. These particular questions were adapted from a questionnaire developed and used by Tasker, Chia, Bucat and Sleet (unpublished). The use of multiple-choice questions to evaluate students’ conceptions is common (Nurrenbeim & Pickering, 1987; Nakhleh, 1993; Nakhleh & Mitchell, 1993; Sanger & Greenbowe, 1997). However, students have often been
Critical evaluation of 2D diagrams is essentially a slightly modified version of multiple-choice questions, requiring an explanation that more fully examines a student’s knowledge and understanding. Students were asked to select a diagram that most closely resembled a particular substance at the molecular level and then to comment on the correct and incorrect features in all the representations. This exercise requires students to recall all relevant features from their long-term memory and compare this information with the 2D representations presented. The analysis and evaluation required to respond effectively to these questions suggest that they examine student understanding at high cognitive levels, according to Bloom’s taxonomy. It should be noted that students had considerable practice in drawing their own 2D diagrams, and were also exposed to this style of diagram in textbooks and on the board during lectures and laboratory classes. Therefore, they were experienced in interpreting such representations.

The questionnaire was delivered in two parts, the first dealing with molecular substances and the second with ionic substances. In this way, representations provided in the ionic section did not bias responses involving student-generated images in the molecular section. A copy of the questionnaire is available in Appendix A.

2.2.2.2. Confidence and Imagery Scales

In addition to responding to questions, students were asked to fill in a "confidence level" scale at the end of each question, and a "vividness of visual imagery" scale at the end of each question where drawing was required (see Figure 2.2). Students were asked to rate their confidence in their response between "uninformed guess" and "total confidence" along a graduated bipolar interval scale. Students also rated the vividness of some of their visual mental images along a bipolar interval scale between "no visual image" and "extremely vivid visual image (like reality)".

The idea of measuring students’ confidence in responses to questions is not new, but has perhaps been under-utilised in chemistry education research. Frazer and Sleet (1984) had students rate their confidence in their answers to chemistry problems on a Likert-type scale.
from one to five, a rating of five being "very sure I am correct". MacGuire and Johnstone (1987) also recommended a similar rating scale for measuring students’ confidence in their answers, suggesting the use of a one-to-five scale from "just guessing" to "I know I’m right". Similarly, mental imagery has been measured using Likert-style scales, such as that used by Marks (1973) in his "Vividness of Visual Imagery Questionnaire", where participants were required to rate the vividness of their visual imagery on a five-point scale from "perfectly clear and as vivid as normal vision" to "no image at all, you only 'know' that you are thinking of the object". Bipolar analogue scales have also been used in health research to measure mental imagery (Gift, 1989; Quilter, Band & Miller, 1999), and are considered "reliable, valid and sensitive" (Gift, 1989). The scales used are typically horizontal or vertical 100-mm lines in which the two ends represent the extremes of the construct being studied.
<table>
<thead>
<tr>
<th>Multiple-choice</th>
<th>Open-ended</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Critical evaluation of 2D diagrams**

Figure 2.2  Sample question types from pre-test/post-test, showing confidence and vividness scales
2.2.2.3. Development of the Pre-Test/Post-Test Marking Scheme

The questionnaire was divided into a molecular substances component and an ionic substances component. These were further subdivided into “substance” categories (Molecular: general features, specific features; Ionic: solid, solution).

A marking scheme was developed and refined by a panel of three experienced tertiary educators and one experienced secondary educator, to determine whether the students had developed certain key ideas about the substances. Each “substance” category was divided into “key features” (see Figure 2.3). Altogether, 35 key features were identified, based on:

- Ideas that students were expected to develop from animations;
- Misconceptions reported in the literature and/or identified in the preliminary studies discussed in section 2.1.1;
- What could be expected from students based on what they were taught;
- What could be expected from students based on the structure of the question;
- How the students interpreted the questions.

Completed questionnaires were inspected to assess the answers students were providing; then for each key feature, a list of acceptable responses was designed. In some cases, evidence of a key feature came from more than one question. It was assumed that a student giving one of these responses (without contradiction in other questions) demonstrated adequate knowledge of a particular key feature. An excerpt from the marking scheme is given in Table 2.2. Questionnaires were marked according to this marking scheme. Each student was allocated a mark out of 35 for the number of key features for which they demonstrated an understanding in the questionnaire.

The complete marking scheme and associated rationale are given in Appendix A. A copy of the marking sheet used for marking questionnaires can also be found in Appendix A.
2.2.2.3.1. **Confidence and Imagery Scales**

Confidence and imagery scales were marked as follows. For the confidence scale, a mark of zero was given for the response “uninformed guess” and a mark of six for “complete confidence”. Each graduation on the scale represented a discrete number between 0 and 6. However, some students chose to mark between graduations. In these cases, a qualitative judgement was made either to give the score closest to the marked point (if the mark was skewed towards a particular graduation), or to allocate half marks (if the mark fell immediately between two graduations).

A similar approach was adopted for the imagery scale, with a score of zero allocated for “no visual image” and a score of 6 for “extremely vivid visual image”.

![Diagram of Pre-Test/Post-Test structure](image-url)
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image [numbers in brackets refer to the relevant question in the post-test]</th>
</tr>
</thead>
<tbody>
<tr>
<td>IONIC SOLUTIONS</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>There is an electrostatic</td>
<td>The hydrating water molecules are orientated according to polarity, towards the ions (oxygen points towards cations, hydrogen points towards anions)</td>
<td>In aqueous NaCl there is no interaction of solute particles with water</td>
<td>Pilot study, 1999; Haidar and Abraham, 1991</td>
<td>Criticism of incorrect representations</td>
<td>(11) representations of aqueous sodium chloride&lt;br&gt;Feedback for representation 1 states that the water molecules are correctly oriented towards the ions&lt;br&gt;OR&lt;br&gt;Feedback for representation 4 or 5 states that water molecules should orient themselves towards the ions according to polarity&lt;br&gt;OR&lt;br&gt;Comment on representation 3 states that water molecules are correctly oriented towards the ions</td>
</tr>
<tr>
<td>attraction between water</td>
<td>molecules and ions</td>
<td>molecules</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>molecules and ions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>When salt dissolves in water,</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>salt penetrates into the empty</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>spaces in water</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2  Excerpt from the marking scheme for the pre-test/post-test
2.2.2.4. Design of the Transfer Test

The transfer test was designed to examine students’ mental models of substances and chemical systems not represented by VisChem animations. Little or no emphasis was given to the molecular levels of these substances and systems during lectures or laboratory work. More specifically, the transfer test examined students’ mental models of

1. New examples of the substance types (molecular, ionic substance, ionic solution) assessed by the pre-test/post-test (DIRECT TRANSFER);
2. New chemical systems requiring application of substance types assessed by the pre-test/post-test (APPLIED TRANSFER);
3. Substances and processes in topics requiring an understanding of molecular-level processes in solution chemistry (TOPIC TRANSFER).

As in the pre/post-test, the transfer test utilised student drawings and/or descriptions and criticisms of incorrect molecular-level diagrams to identify students’ conceptions. A copy of the transfer test can be found in Appendix A.

2.2.2.5. Development of the Transfer Test Marking Scheme

A marking scheme was constructed for the direct and applied sections of the transfer test in a manner similar to that described for the pre/post-test. The marking scheme was evaluated and refined by a panel of three experienced tertiary educators.

The “direct transfer” component was subdivided into molecular and ionic (solid and solution) sections, which were further sub-divided into key features (see Figure 2.4). Because the key features were partly based on the structure of the question and students’ interpretations of the question, they were not necessarily identical to those assessing similar concepts in the pre/post test. Thirty key features were identified, 14 for molecular substances, seven for ionic substances and nine for ionic solutions. Therefore, students received a mark out of 30 for this component of the test.
Figure 2.4  Structure of the marking scheme for the “Direct Transfer” component of the Transfer Test

The “applied transfer” section of the test did not contain a molecular substances component, but consisted solely of an ionic solid component and an ionic solution component. These were broken down into key features (see Figure 2.5). Three questions in the questionnaire assessed students’ transfer of ideas about ionic solutions to different contexts. Therefore, students could be awarded more than one mark for some key features. The greater number of key features identified indicated a greater ability to transfer concepts to different situations. Students could score up to 22 marks for the applied section of the transfer test.

Figure 2.5  Structure of the marking scheme for the “Applied Transfer” component of the Transfer Test
The “topic transfer” section of the test was marked slightly differently. Marks were given for correct ideas provided in response to each question, to a certain maximum value, as shown in Figure 2.6. Students received a mark out of 17 for this component of the test.

In total, students received a mark out of 69 for the transfer test. A detailed outline of the marking scheme and associated rationale can be found in Appendix A, together with a copy of the marking sheet used for marking the transfer test.

![Figure 2.6](image)

**Figure 2.6** Structure of the marking scheme for the “Topic Transfer” component of the Transfer Test

### 2.2.2.6. Presentation of Animations Using Best Practice

VisChem animations were integrated into the lecturer’s teaching strategy. A document describing how to present the animations using "best practice " was produced by Tasker, based on practical experience in using the animations at a first-year level, and with reference to a review by Milheim (1993). A copy of the “best practice” protocol is available in Appendix F. The first-year chemistry lecturer was not involved directly in this research but adhered as much as possible to the "best practice" method. In general, this resulted in the lecturer showing animations at least twice: once with no explanation, to allow students to gain a global perspective of the animation, and once with the lecturer pointing out important features in the animation. The necessity of using a verbal narrative with animations has been emphasised in previous research (Mayer & Anderson, 1991, 1992; Davis, 1997; Burke, Greenbowe & Windschitl, 1998; Mayer & Moreno, 1998). Macroscopic depictions of the phenomena (e.g., solid dissolving in a test tube) were also shown, and efforts were made to relate the molecular representations to the symbolic and laboratory representations. The lecturer correlated the animation content to the context of the lesson, so the features pointed
out varied slightly from one viewing of an animation to the next viewing of that animation in a later lecture. Effort was made to emphasise features about which students were known to hold misconceptions, based on previous research and the results of the pre-test.

Table 2.3 lists the relevant animations used during lectures (other animations were also shown), with the weeks during which they were presented and the associated lecture topics. Figure 2.7 shows key frames from some of these animations. Animations can be viewed on the attached CD (see Appendix G). Code-names for each animation are given in Figure 2.7 and Table 2.3. All images assessed using the pre- and post-tests were represented at least once using animations.

Students were also exposed to 3D models (including modelling kits), 2D drawings made by the lecturer, and diagrams from textbooks and lecture notes. They were given extensive practice at drawing substances at the molecular level, and were also expected to draw representations of certain substances in their mid-semester exam.

<table>
<thead>
<tr>
<th>Week Shown</th>
<th>Animation</th>
<th>Lecture Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Video: &quot;Water: A Molecular Substance&quot;, showing animations of solid, liquid and gaseous water, evaporation, melting and inside a bubble of boiling water.</td>
<td>The Building Blocks of Substances</td>
</tr>
<tr>
<td>3</td>
<td>Solid Sodium Chloride [D2No01]</td>
<td>The Building Blocks of Substances</td>
</tr>
<tr>
<td></td>
<td>Sodium Chloride Melting [F1No01]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Video replay: &quot;Water: A Molecular Substance&quot;</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Video: Aqueous Solution of Sodium Chloride</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sodium Chloride Dissolving [E1No01]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrated Sodium Ion [C3No11]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrated Chloride Ion [C3No02]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aqueous Solution of Sodium Chloride [D4No06]</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Formation of a Hydronium Ion [E4No05]</td>
<td>Acids and Bases</td>
</tr>
<tr>
<td>10</td>
<td>Solid Sodium Chloride [D2No01]</td>
<td>Structure and Bonding</td>
</tr>
<tr>
<td>11</td>
<td>Solid Sodium Chloride [D2No01]</td>
<td>Structure and Bonding</td>
</tr>
<tr>
<td></td>
<td>Sodium Chloride Melting [F1No01]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sodium Chloride Dissolving [E1No01]</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Aqueous Solution of Sodium Chloride [D4No06]</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3 Relevant animations, their timing of presentation and lecture topic
Chapter 2  Effectiveness of VisChem Animations

Solid water (Ice) [D3No05]  Liquid water [D3No06]

Gaseous Water [D3No03]

Solid Sodium Chloride [D2No01]  Hydrated Chloride Ion [C3No02]

Sodium Chloride Dissolving [E1No01]  Aqueous Solution of Sodium Chloride [D4No06]

Figure 2.7  Snapshots from some relevant VisChem animations
2.2.2.7. **Interview Protocol**

A semi-structured protocol was adopted for interviews. This method of interviewing was also used by Harrison and Treagust (1996) to probe students’ ideas about atoms and molecules.

An interview schedule was constructed to form the basis of the interview. The questions in this schedule were not necessarily used verbatim during interviews, but rather acted as a guide to structure the interview. The interviewer diverged from the schedule to further probe students’ responses, but always returned to it after doing so. This method allowed the interviewer to follow up interesting comments made by students. Through extra probing, students often recalled ideas that didn't occur to them immediately, and usually elaborated on their initial responses. A copy of the interview schedule is provided in Appendix C.

In this study, interviews were used to:

1. Determine whether students, unprompted, attributed any development of their mental images or improvement in confidence to viewing the VisChem animations;
2. Determine students’ ability to identify key features in animations they may not have recalled in earlier questioning;
3. Determine if students found their recall of VisChem animations useful for, or relevant to, transfer questions;
4. Determine students’ ability to relate animations shown to them in interviews to the content of the transfer test;
5. Examine students’ conceptions of the extent of their use of imagery in chemistry and relate this to the results of the post-test and transfer test.

The interview questions were worded to minimise the expectation that "the animations" was a desired response during questioning about the pre- and post-tests. Students were provided with their responses to all three questionnaires (pre-test, post-test and transfer test). They were then encouraged to discuss all the factors they believed contributed to the development of their mental images from pre-test to post-test, and to evaluate the factors that contributed to their ability to respond to problems in the transfer test. Animations were never referred to by
the interviewer before they were mentioned by the student. Finally, students were shown one or more animations and asked to provide a verbal narrative, pointing out all relevant features contained in the display. The interviews were carried out approximately three months after completion of the post-test, and approximately one month after completion of the transfer test.

Interview transcripts were scanned for references to animations. These quotes were then categorised according to key features, to serve as evidence of the effects of animations on students’ mental models.

2.2.3. Results and Discussion: Pre-test and Post-test 2000

Progress from pre-test to post-test is shown in Figure 2.8. The average number of key features identified by students increased substantially (p ≤ 0.0001, one-tailed paired t-test). Table 2.4 shows the pre-test and post-test averages for each section and the overall test. There was a significant improvement (p ≤ 0.0001, one-tailed paired t-test) in all sections of the test. This suggests that after instruction that included VisChem animations, students had significantly more detailed images of the substances being tested, on average. Evidence that this improvement is in part due to exposure to VisChem animations comes from interview data. All fourteen students interviewed spontaneously mentioned animations in relation to the development or confirmation of their mental images or improvement in confidence. Table 2.5 shows the animations referred to by interviewed students in relation to their responses to questions on the post-test.

![Figure 2.8](image-url)  
Comparison of pre-test and post-test overall scores in 2000

<table>
<thead>
<tr>
<th>Section</th>
<th>Pre-test Average</th>
<th>Post-Test Average</th>
<th>Change from</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 to 5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 to 10</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>11 to 15</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>16 to 20</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21 to 25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>26 to 30</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Chapter 2  Effectiveness of VisChem Animations

<table>
<thead>
<tr>
<th></th>
<th>(standard deviation) (N = 48)</th>
<th>(standard deviation) (N = 48)</th>
<th>Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Substances: General Features (out of 14)</td>
<td>6.2 (2.4)</td>
<td>8.0 (1.8)</td>
<td>+ 1.8</td>
</tr>
<tr>
<td>Specific Features Regarding Water (out of 6)</td>
<td>1.7 (0.9)</td>
<td>2.2 (0.8)</td>
<td>+ 0.5</td>
</tr>
<tr>
<td>Molecular Substances Total</td>
<td>7.9 (3.0)</td>
<td>10.3 (2.2)</td>
<td>+ 2.4</td>
</tr>
<tr>
<td>Ionic Solid (out of 6)</td>
<td>2.5 (1.5)</td>
<td>3.8 (1.6)</td>
<td>+ 1.3</td>
</tr>
<tr>
<td>Ionic Solution (out of 9)</td>
<td>2.0 (1.9)</td>
<td>5.7 (1.5)</td>
<td>+ 3.7</td>
</tr>
<tr>
<td>Ionic Substances Total</td>
<td>4.5 (3.0)</td>
<td>9.5 (2.4)</td>
<td>+ 5.0</td>
</tr>
<tr>
<td>Test Total</td>
<td><strong>12.4 (5.1)</strong></td>
<td><strong>19.8 (4.0)</strong></td>
<td><strong>+ 7.4</strong></td>
</tr>
</tbody>
</table>

Table 2.4  Averages for sections on pre-test and post-test in 2000
<table>
<thead>
<tr>
<th>CONTENT</th>
<th>Spacing of molecules in a liquid</th>
<th>Spacing of molecules in a gas</th>
<th>Size of molecules in the three states</th>
<th>Model of water molecule</th>
<th>Liquid water</th>
<th>Gaseous water</th>
<th>Solid water</th>
<th>Space between the molecules</th>
<th>Solid sodium chloride</th>
<th>Vibrations in solid sodium chloride</th>
<th>Aqueous solution of sodium chloride</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student 1</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>evap</td>
<td>water</td>
<td>water</td>
<td>anim</td>
<td>icemelt</td>
<td>NaCl(aq)</td>
</tr>
<tr>
<td>Student 2</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>anim</td>
<td>NaCl(s)</td>
<td>NaClmelt</td>
<td>NaCl(aq)</td>
<td></td>
</tr>
<tr>
<td>Student 3</td>
<td>water</td>
<td>anim</td>
<td>anim</td>
<td>anim</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaCl(diss)</td>
<td>NaCl(diss)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 4</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaCl(s)</td>
<td>NaClmelt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 5</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaClmelt</td>
<td>NaClmelt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 6</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaCl(s)</td>
<td>NaClmelt</td>
<td>NaClmelt hydions</td>
<td></td>
</tr>
<tr>
<td>Student 7</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaCl(s)</td>
<td>NaClmelt</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 8</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaClmelt</td>
<td>anim</td>
<td>NaCl(diss)</td>
<td></td>
</tr>
<tr>
<td>Student 9</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaCl(s)</td>
<td>NaClmelt</td>
<td>NaCl(aq)</td>
<td></td>
</tr>
<tr>
<td>Student 10</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>icemelt</td>
<td>hydions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 11</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaClmelt</td>
<td>NaCl(aq)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 12</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaClmelt</td>
<td>NaCl(aq)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 13</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>NaClmelt</td>
<td>NaCl(aq)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Student 14</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>water</td>
<td>evap</td>
<td>water</td>
<td>water</td>
<td>anim</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Key:**
- **water**  Solid, liquid or gaseous water
- **evap**  Evaporation of liquid water
- **icemelt**  Ice melting
- **NaCl(s)**  Solid sodium chloride
- **NaCl(diss)**  Sodium chloride dissolving
- **NaCl(aq)**  Aqueous solution of sodium chloride
- **NaClmelt**  Sodium chloride melting
- **anim**  General reference to animations
- **hydions**  Hydrated ions

**Table 2.5**  Animations mentioned by students in relation to particular questions on the post-test
2.2.3.1. **Key Features Analysis**

Sections 2.2.3.3 to 2.2.3.4 examine more closely the effects of instruction on the development of students’ images, by looking at the progress made for each key feature. Each section of the pre-test/post-test is examined separately under the headings “Molecular substances”, “Ionic Substances: Solid Sodium Chloride” and “Ionic Substances: Aqueous Solution of Sodium Chloride”. This section further probes improvements in students’ images of the molecular world for certain substances and looks at improvements in student confidence and the vividness of their visual images following instruction. The section also presents interview data aimed at

- Determining whether students, unprompted, attributed any development in their mental images or improvement in confidence to viewing the VisChem animations and
- Determining students’ ability to identify key features in animations that they may not have recalled in earlier questioning.

2.2.3.2. **Molecular Substances**

2.2.3.2.1. **Key Features**

Tables 2.6 and 2.7 and Figures 2.9 and 2.10 show the percentages of students demonstrating knowledge of each key feature in the pre-test compared with the post-test, for the molecular substances section.
### Table 2.6 Changes in percentages of students demonstrating knowledge of molecular substance key features from pre-test to post-test in 2000

<table>
<thead>
<tr>
<th>KEY FEATURE</th>
<th>Percentage in Pre-Test (N = 48)</th>
<th>Percentage in Post-Test (N = 48)</th>
<th>Percentage Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Features Of Molecular Substances</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Molecules in a liquid are closely crowded</td>
<td>15</td>
<td>13</td>
<td>- 2</td>
</tr>
<tr>
<td>2. Molecules in a gas are widely spaced</td>
<td>94</td>
<td>100</td>
<td>+ 6</td>
</tr>
<tr>
<td>3. Molecules do not change size from solid to liquid to gas</td>
<td>52</td>
<td>81</td>
<td>+ 29</td>
</tr>
<tr>
<td>4. The molecular level is multi-particulate</td>
<td>96</td>
<td>98</td>
<td>+ 2</td>
</tr>
<tr>
<td>5. Molecular substances contain identically structured particles in the solid, liquid and gas states</td>
<td>63</td>
<td>83</td>
<td>+ 20</td>
</tr>
<tr>
<td>6. There is empty space between the molecules</td>
<td>71</td>
<td>81</td>
<td>+ 10</td>
</tr>
<tr>
<td>SOLID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Structured lattice</td>
<td>25</td>
<td>31</td>
<td>+ 6</td>
</tr>
<tr>
<td>8. Vibrate in fixed positions</td>
<td>19</td>
<td>60</td>
<td>+ 41</td>
</tr>
<tr>
<td>9. Significant intermolecular attractions</td>
<td>21</td>
<td>23</td>
<td>+ 2</td>
</tr>
<tr>
<td>LIQUID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Movement</td>
<td>71</td>
<td>90</td>
<td>+ 19</td>
</tr>
<tr>
<td>11. Collisions</td>
<td>6</td>
<td>19</td>
<td>+ 13</td>
</tr>
<tr>
<td>12. Significant intermolecular attractions</td>
<td>21</td>
<td>19</td>
<td>- 2</td>
</tr>
<tr>
<td>GAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. Movement (translational, vibrational and rotational)</td>
<td>69</td>
<td>81</td>
<td>+ 12</td>
</tr>
<tr>
<td>14. Collisions</td>
<td>2</td>
<td>21</td>
<td>+ 19</td>
</tr>
</tbody>
</table>
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### KEY FEATURE

<table>
<thead>
<tr>
<th>Percentage in Pre-Test (N = 48)</th>
<th>Percentage in Post-Test (N = 48)</th>
<th>Percentage Change from Pre-test to Post-test</th>
</tr>
</thead>
</table>

#### Specific Features Regarding Water

**WATER**

15. Greater spacing in solid than liquid due to H-bonding

16. Water molecules can react with each other to form hydronium ions and hydroxide ions

**WATER MOLECULE**

17. Correct model

18. Bent

19. Overlapping electron clouds

20. Different sized atoms

<table>
<thead>
<tr>
<th>15</th>
<th>2</th>
<th>10</th>
<th>+ 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>16</td>
<td>2</td>
<td>4</td>
<td>+ 2</td>
</tr>
<tr>
<td>17</td>
<td>94</td>
<td>100</td>
<td>+ 6</td>
</tr>
<tr>
<td>18</td>
<td>40</td>
<td>60</td>
<td>+ 20</td>
</tr>
<tr>
<td>19</td>
<td>15</td>
<td>29</td>
<td>+ 14</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>25</td>
<td>+ 10</td>
</tr>
</tbody>
</table>

| Table 2.7 Changes in percentages of students demonstrating knowledge of specific features of water key features from pre-test to post-test in 2000 |

| Figure 2.9 Percentage of students demonstrating knowledge of molecular substances key features in the pre-test and post-test in 2000 |
2.2.3.2.2. **Confidence and Imagery**

Although some key features were not developed by many students, students seemed to be more confident in their knowledge of molecular substances. The Anderson–Darling normality test (using Minitab 10 Xtra) was carried out on the data collected from confidence and imagery scales. Results suggest a lack of normality for most sets of data. The Wilcoxon matched-pairs signed-ranks test (Siegel, 1956) was therefore used to examine changes in confidence and imagery vividness.

Table 2.8 shows the average score for each rating scale in the pre-test compared with the post-test. The average of all ratings improved. Confidence in responses improved significantly ($p < 0.001$) for all questions. Self-perceptions of image vividness for the three states of water (solid, liquid, gas) also increased significantly ($p < 0.001$), suggesting that this method of instruction helped to improve students’ ability to clearly visualise certain substances at a molecular level.

It is important to note that students showed improved confidence in their *incorrect* responses regarding the spacing of molecules in a liquid (see Table 2.8). This may suggest that the instruction generated or confirmed the misconception.
The lowest confidence in the post-test for this section was found for the idea that there is empty space between molecules (see Table 2.8). This relatively low confidence might result from the fact that "empty space" is not so much a feature as it is the absence of features. Students might not assume that there is empty space between the molecules, simply because nothing is depicted between the molecules in the animations. Students at this level are likely to be aware that features might be left out of a model to simplify the representation (Grosslight, Unger & Jay, 1991). These findings are consistent with a preliminary examination of the effectiveness VisChem animations to help high-school students correct their misconceptions regarding water at the molecular level (Tasker et al., unpublished). The study found that students’ misconceptions about what exists between molecules were particularly stubborn. Teachers also suggested that the idea of empty space was not clear in the animations.

It may be necessary, therefore, to emphasise more strongly the idea of empty space when showing the VisChem animations, and it should not be assumed that this concept will be obvious to students. Sleet (1993) suggests that asking students to calculate the amount of empty space in a sample of pure gas may be useful in promoting the development of a correct image. Relating the calculated value to the visual image may help to emphasise the feature of empty space. Sleet has effectively used this thinking task in his instruction of first-year university students.
<table>
<thead>
<tr>
<th>Content</th>
<th>Scale (0–6)</th>
<th>Pre-test average (standard deviation)</th>
<th>Post-test average (standard deviation)</th>
<th>Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacing of Molecules in a Liquid</td>
<td>Confidence in choice</td>
<td>4.4 (1.7)</td>
<td>5.2 (0.9)</td>
<td>+ 0.8</td>
</tr>
<tr>
<td></td>
<td>Confidence in explanation</td>
<td>3.6 (1.5)</td>
<td>4.7 (0.9)</td>
<td>+ 1.1</td>
</tr>
<tr>
<td>Spacing of Molecules in a Gas</td>
<td>Confidence in choice</td>
<td>4.5 (1.6)</td>
<td>5.4 (0.8)</td>
<td>+ 0.9</td>
</tr>
<tr>
<td></td>
<td>Confidence in explanation</td>
<td>3.6 (1.6)</td>
<td>4.7 (0.9)</td>
<td>+ 1.1</td>
</tr>
<tr>
<td>Sizes of Molecules in the Three States</td>
<td>Confidence in choice</td>
<td>3.4 (1.8)</td>
<td>4.5 (1.4)</td>
<td>+ 1.1</td>
</tr>
<tr>
<td></td>
<td>Confidence in explanation</td>
<td>3.0 (1.8)</td>
<td>4.3 (1.3)</td>
<td>+ 1.3</td>
</tr>
<tr>
<td>Model of Water Molecule</td>
<td>Confidence</td>
<td>3.5 (1.5)</td>
<td>4.9 (0.9)</td>
<td>+ 1.4</td>
</tr>
<tr>
<td>Liquid Water</td>
<td>Confidence</td>
<td>3.6 (1.6)</td>
<td>4.9 (0.9)</td>
<td>+ 1.3</td>
</tr>
<tr>
<td></td>
<td>Imagery Vividness</td>
<td>3.4 (1.5)</td>
<td>4.8 (0.9)</td>
<td>+ 1.4</td>
</tr>
<tr>
<td>Gaseous Water</td>
<td>Confidence</td>
<td>3.6 (1.6)</td>
<td>4.9 (1.1)</td>
<td>+ 1.3</td>
</tr>
<tr>
<td></td>
<td>Imagery Vividness</td>
<td>3.3 (1.6)</td>
<td>4.8 (1.0)</td>
<td>+ 1.5</td>
</tr>
<tr>
<td>Solid Water</td>
<td>Confidence</td>
<td>3.5 (1.7)</td>
<td>4.8 (1.2)</td>
<td>+ 1.3</td>
</tr>
<tr>
<td></td>
<td>Imagery Vividness</td>
<td>3.4 (1.6)</td>
<td>4.8 (1.1)</td>
<td>+ 1.4</td>
</tr>
<tr>
<td>What is Between the Molecules?</td>
<td>Confidence</td>
<td>2.8 (1.8)</td>
<td>4.1 (1.4)</td>
<td>+ 1.3</td>
</tr>
</tbody>
</table>

Table 2.8  Averages of confidence and vividness of imagery ratings for questions relating to molecular substances (key features 1 to 20)

### 2.2.3.2.3. Interview Analysis

Fourteen students participated in follow-up interviews. The following analysis reveals that these students found benefit from VisChem animations in developing ideas about molecular substances. Tables 2.9 and 2.10 (pages 59–61) summarise evidence that VisChem animations have:

- Helped students add certain key features to their images (learnt); or
- Served to reinforce ideas (reinforced).

The “learnt” category incorporates those students who did not express knowledge of a key feature in the pre-test but mentioned it in the interview when discussing an animation, regardless of whether or not they mentioned it in the post-test.
The “reinforcement” category incorporates:

- Explanations of improved imagery vividness and confidence; and
- Mention of key features during description of an animation, where the student provided evidence in the pre-test of having been aware of this feature.

The tables indicate the number of students who mentioned these ideas during interviews in relation to animations, and provides sample quotes. Key features (9, 12, 15) that were not mentioned in interviews in relation to the animations are omitted from the table. Features of the water molecule (key features 18–20) are discussed in relation to modelling in Section 2.3.1.2. A complete list of quotes is given in Appendix D.

As the questionnaire data indicate, students on average developed seven key features. Therefore, it was not expected that all students would comment on all key features. The mention of an animation as helping even one student to develop a key feature is taken to mean that the animation can be effective in portraying that key feature.
## General Features Of Molecular Substances

<table>
<thead>
<tr>
<th>Number of Students</th>
<th>Sample Quotes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Molecules in a liquid are closely crowded</td>
<td>Reinforced 2</td>
</tr>
<tr>
<td>2. Molecules in a gas are widely spaced</td>
<td>Learnt 1</td>
</tr>
<tr>
<td>3. Molecules do not change size from solid to liquid to gas</td>
<td>Reinforced 1</td>
</tr>
<tr>
<td>4. The molecular level is multi-particulate</td>
<td>Learnt 2</td>
</tr>
<tr>
<td>5. Molecular substances contain discrete particles in the solid, liquid and gas states</td>
<td>Reinforced 1</td>
</tr>
<tr>
<td>6. There is empty space between the molecules</td>
<td>Learnt 2</td>
</tr>
</tbody>
</table>

**Interviewer:** Well your idea is obviously different now…you said no there’s nothing, everything remains the same except the ability to move around. How do you think you developed that sort of an idea? **Student 14:** Obviously from the animations, how they obviously they show that that was frozen and as the temperature rise they become more mobile and when it gets to the gaseous stage, it’s just wooshka everywhere. **Student 2:** The…images, these…visual images that are used, they describe not only the particles but because they can be seen vibrating they describe also the small amount of space which is between the particles.
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Table 2.9 Supporting quotes for general features of molecular substances

<table>
<thead>
<tr>
<th>SOLID</th>
<th>Learnt 2</th>
<th>Student 4: Yeah, that again would have come from those animations. Interviewer: Okay, so if you had to picture maybe the animation of ice in your head…could you describe that to me? Student 4: Yeah, I can see it. There are molecules stacked up in rows…</th>
</tr>
</thead>
<tbody>
<tr>
<td>8. Vibrate in fixed positions</td>
<td>Learnt 8</td>
<td>Student 5: what [the lecturer] did in the lectures with the computer animation things, that really helped I guess. I never well you know, specifically with the solid, I guess I never knew that they still moved a little bit.</td>
</tr>
<tr>
<td>LIQUID</td>
<td>Learnt 2</td>
<td>Student 10: Well that was definitely the video because in the video it shows the molecules are moving…</td>
</tr>
<tr>
<td>10. Movement</td>
<td>Reinforced 5</td>
<td>Student 1: …like the pictures are good and that but videos are better because it shows a moving description of it rather than just this then that. It shows the transitional period between it…</td>
</tr>
<tr>
<td>11. Collisions</td>
<td>Learnt 1</td>
<td>Student 14: Because they’re moving…cause that’s liquid so it’s…they’re colliding into each other. Interviewer: …is that an image that you developed yourself? Student 14: No. Interviewer: Well where did you steal it from? … Student 14: …From those animations again…</td>
</tr>
<tr>
<td>GAS</td>
<td>Reinforced 1</td>
<td>Student 2: The videos of the water molecules bumping around.</td>
</tr>
<tr>
<td>13. Movement (translational, vibrational and rotational)</td>
<td>Learnt 3</td>
<td>Interviewer: Okay, the videos, can you talk a little more about that? Student 3: …Solid they’re all packed together, sort of um rigidly, I think that’s the word, and then liquid they vibrate and they sort of they move but like not as much as gases. Gases then they start floating up.</td>
</tr>
<tr>
<td>14. Collisions</td>
<td>Reinforced 1</td>
<td>Student 1: …Exactly like in the video that’s how I…remember. It was like those molecules…in the water state some of them are going up but it’s not enough to make a real difference so if they’ve got more energy then they’re able to like…you just see one or two of them going off and the more moving to gas you know that the more have got energy to go and I just see them pretty much moving from there to there.</td>
</tr>
</tbody>
</table>

Table 2.9 Supporting quotes for general features of molecular substances
## Specific Features Regarding Water

<table>
<thead>
<tr>
<th>Number of Students</th>
<th>Sample Quotes</th>
</tr>
</thead>
<tbody>
<tr>
<td>WATER</td>
<td></td>
</tr>
</tbody>
</table>
| 16. Water molecules can react with each other to form hydronium ions and hydroxide ions | Reinforced 1  
Student 7: Like I keep on saying, the projector thing…  
Interviewer: …Can you describe to me sort of what you can see?  
Student 7: Well, I don't know like…great big spheres with little tiny spheres with the Mickey Mouse shape and its bent and it's bouncing around…. say liquid water, say and it's bouncing around and some are connected…or **some have more hydrogens or less um hydrogens than the others**, they're like really…they're crowded but some are connected and some aren’t, they don't have that much energy but they have some energy. |
| WATER MOLECULE² | Learnt 1  
Interviewer: Okay, do you remember particular things that were done in lectures or shown to you…that made you realise that **water doesn’t consist of these two separate particles**?  
Student 13: **The animations.**  
Reinforced 5  
Interviewer: Can you tell me why you selected that model over the others?  
Student 4: I think that would have probably been because **we watched those computerised animations...they looked like that.** |

Table 2.10  Supporting quotes for specific features regarding water

² Other reasons for selection of the space-filling model over other models (including key features 19 and 20) are discussed in Section 2.3.1.2.
In addition to the examples shown in Tables 2.9 and 2.10, some students commented on the effects of the VisChem animations on their mental models, without mentioning particular key features, as the following quotes demonstrate.

**Quote 1:**

Interviewer: ....So you don’t think that your images of water at the solid, liquid, gaseous states have changed at all?

Student 3: Nup, pretty much the same

Interviewer: Can you identify why you might have rated your visual image as being stronger?

Student 3: I think because of more reassurance

Interviewer: Okay

Student 3: It’s been sort of, we spoke about it more and it just memory, more sort of this is what water is, this is what water is. It gets the message across.

Interviewer: Okay so how was it reinforced? Was it just said to you?

Student 3: Said, written, the video images

Interviewer: So just a bit of everything

Student 3: a variety

Interviewer: Did anything in particular have a bigger affect on you than other things?

Student 3: The videos because you actually saw what was happening and you remember them more than someone just telling you that this just happened because then when you’re trying to remember it again you think oh, you know, this is what happened in the video…it’s just easier, memory-wise.

**Quote 2:**

Interviewer: Can you describe to me the particular learning strategies within chemistry where you saw this again, that reinforced the ideas that you originally had?

Student 6: Well, just the way he did it. He first put it up on the screen with the animations…and I actually found the animations a bit boring after a while because it was okay, we’ve seen that, I don’t have to see it again because it was so effective the first time, it didn’t need to be repeated, but if no-one had done chemistry before then it was probably good for them to see it again…and then he went to the board and did it on the board after we saw the actual animation of it…

Evidence shows that the VisChem animations have helped students develop certain key features of molecular substances. Some of the results, however, call for comment. The animations were not mentioned or hardly mentioned in relation to helping students develop some particular key features (1, 9, 12, 14, 15, 16); for some key features, progress from pre-test to post-test was poor (key features 1, 7, 9, 12, 15, 16); and large numbers of students apparently did not incorporate certain features into their mental images, as evidenced by low percentages in the post-test (key features 1, 7, 9, 11, 12, 14, 15, 16, 19, 20). These results may
indicate that the instruction was not effective in teaching these key features. The following section (pages 63–69) discusses possible reasons for this lack of effect for key features 1, 7, 9, 11, 12, 14, 15, 16, 19 and 20.

**Spacing in a Liquid (Key Feature 1)**

The questionnaire data suggest that the number of students mentioning key feature 1, crowding in a liquid, did not improve following instruction. Furthermore, no students commented during interviews that the animations helped them develop an image of a liquid as being closely crowded. This evidence suggests that the animations did not adequately show the close packing of molecules in liquid water.

*Prima facie*, the interview data seem to support the idea derived from confidence ratings, that the animations confirmed or introduced the misconception that there is a reasonable amount of space between the molecules in a liquid, because two students identified the animations as influencing their choice of representation. The first student had originally chosen the third representation in which the molecules were most widely spaced, but changed to the second representation in which the molecules were closer together but not touching. The second changed from the correct representation to one in which the molecules were more widely spaced. A quote from the second student is given below.

Interviewer: So this is the spacing in the liquid… Your confidence has gone through the roof and your answer has changed. Can you think of anything that may have influenced this sort of a change?

Student 10: …I probably did this when we first started…so my memory wasn’t that good and it was just basically revising through the meanings of liquid state, solid state, gas state and that’s why I chose a different answer later in the year.

Interviewer: Okay, can you remember any…specific teaching strategies that taught you about solid state, liquid state and gaseous state that may have helped?

Student 10: Yeah, those videos that [the lecturer] always shows. You know those 3D videos? He showed lots of those at the beginning of the year and he showed particles at their solid state like that, it was like that and then he showed when the molecules moved around and then they went into their gas state…

In contradiction to this, Student 10 also mentioned that the animations reinforced her idea of the molecules in liquid water being closely crowded, as did another student (see Table 2.9, page 59). The confusion, therefore, may lie in *how* closely they are crowded. Students may use the animations as evidence of relative rather than absolute distances. This interpretation is supported by the fact that students often said they chose representation 2 (loosely packed
molecules; see Appendix A) because they believed representation 1 to be a closely packed solid (molecules touching) and 3 to be the representation of a gas (most widely spaced molecules). Students therefore do not seem to have developed an absolute idea of the spacing in a liquid but only conceive of distances in a relative sense: gas > liquid > solid. The animations confirm that liquids are more closely crowded than gases.

It is possible that students could not envisage the molecules in representation 1 moving because the circles were crowded so closely together. As a result, students may have chosen representation 2, which happened to show the molecules quite widely spaced. This need not indicate that students actually consider the molecules to be this widely spaced. It is reasonable to assume at this point, however, that the animations do not encourage students to envisage liquids as containing closely packed, touching molecules.

As a test of these hypotheses, this question was altered slightly in the questionnaire administered the following year, to include a representation in which some of the molecules were touching but which allowed conceptually for the idea of movement. The most widely spaced representation was removed to discourage reference to all three states of matter. The effect of this change is discussed in Section 2.2.4.1 (page 99).

Similarly with spacing in the gaseous state (key feature 2), students tended to assume that the three diagrams represented a solid, liquid and gas, and hence labelled the one with the widest spacing as the gas. As a criticism of the question itself, the representation of the gas given did not adequately represent the extent of the spacing between the molecules. Therefore, this questionnaire only tested whether students knew that the molecules in a gas are widely spaced, and not whether they had an idea of the magnitude of this spacing. To reduce the number of students selecting a response based on relative distances, and to encourage selection based on absolute differences, this question was also modified slightly for distribution in 2001. In the modified version, the three representations in the gas question were different from those given in the liquid question. The closely-packed representation was replaced with a representation that more closely resembled the actual spacing of molecules in a gas at standard temperature and pressure. The results of this modification are outlined in the Section 2.2.4.1 (page 100).
Structured Lattice (Key Feature 7)
The fact that two students mentioned in interviews that animations helped them to develop the idea of a structured lattice may suggest that the small increase in the number of students mentioning this key feature in the whole group is an actual effect brought on by the animations. To maintain objectivity in marking the questionnaire, students were only given a mark if they wrote that the lattice was structured and not when they only represented it in the diagram (unless it was obvious from the diagram that a structure was intentional). This may have resulted in an underestimation of the number of students aware of this idea. This cannot be regarded as a limitation of the marking scheme, but rather an example of some students’ inability to clearly demonstrate their understanding.

Significant Intermolecular Attractions in the Solid (Key Feature 9)
The fact that no students mentioned significant intermolecular attractions in the molecular solid (key feature 9) in relation to the animations is consistent with the group data showing that the number of students mentioning this feature increased by only 2% in the post-test. This may be because this key feature was not made explicit when the animations were shown. This feature is also rather obscure in the animations, and if it is not deliberately pointed out, it is unlikely that the students will notice it. Furthermore, the feature itself is not “visual”; you cannot “see” intermolecular forces in the animations. You can only infer that they are there from the orientation of different molecules with respect to each other. Therefore, students may have difficulty in visualising the idea. Instructors should make special note of the orientation of one water molecule with respect to the next. Different models may be used to teach the idea of hydrogen bonding, which use symbolism (such as dashed lines) to help students visualise the concept. However, for students to incorporate these ideas into their already existing images, explicit instruction may be required.

It is also true that, at the time the animation was shown, many students would not have had the understanding of polarity needed to interpret this feature. This lack of prior knowledge would inevitably hamper their ability to process this idea. The relevant animation should be shown again when students are studying intermolecular bonding, to encourage them to relate the new information to the animation with which they are already familiar. They would then have the relevant knowledge to extract the information from the animation.
Collisions in the Liquid (Key Feature 11)

The number of students mentioning collisions in liquid water increased by a reasonable percentage, but 81% of students still did not mention it in the post-test. Most students don’t seem to have incorporated this concept into their mental images.

It may be that students don’t perceive the gentle portrayal of “bumping around” of the water molecules in the liquid state (as shown in the VisChem animations) to be collisions. It is not possible to show accurately in an animation the speed at which molecules are moving relative to each other. Therefore, this is certainly a key feature that needs to be pointed out to students and discussed. It may be more pertinent to discuss the idea of these collisions in relation to reactions in solution, and then to extrapolate back to the idea that these collisions occur in all liquids, all the time, often without consequence. Collisions are most important in the context of chemical reactions, and students may need to appreciate the importance of ideas to incorporate them into their mental models.

Significant Intermolecular Attractions in the Liquid (Key Feature 12)

Similar to the perceptions of ice, and consistent with the group data, no student mentioned that animations helped them develop the idea of intermolecular attractions in molecular liquids. One student did allude to the "clustering" effect when discussing her recall of an animation of liquid water (see Table 2.9, page 59).

Once again, this may be due to the fact that this feature is not easily visualised without added symbolism. Intermolecular forces are represented in VisChem animations by the interactions of molecules as a result of attractive forces. Diagrams representing hydrogen bonding as dashed lines between molecules may be more effective in transmitting the idea to students, but may introduce the misconception that hydrogen bonding occurs at a distance or that hydrogen bonds are physical entities. Animations would then be useful to demonstrate the idea that these forces are not physical entities (lines connecting molecules), but can be “observed” by noting how the molecules interact with one another, and how hydrogen bonding holds the molecules in close proximity.

Students’ attention may not have been drawn to this feature when viewing the animations. This feature was referred to in the video of liquid water in terms of “clustering”, but it was not
explained further. Although students with an understanding of intermolecular forces may be able to interpret the idea of “clustering” and identify the feature in the animations, it is unlikely that novices could do so. Because this video was shown towards the beginning of the semester, it is likely that many students did not have the relevant prior knowledge to understand or interpret the idea. Therefore, it is little wonder that students did not retain it as part of their mental model of liquid water.

Although these animations can be used as a basic introduction to the nature of matter, it is advisable that they be shown again after students have studied some relevant chemistry. Students could be shown the animation of water evaporating after studying polarity, and then asked to comment on why they think some water molecules were not quite able to break away from the liquid surface. Once the idea of intermolecular forces is established, the animation of liquid water could be shown again. Questions like “Do you notice similar interactions occurring throughout the liquid?” could be used to encourage students to search for evidence of intermolecular forces in the display.

**Collisions in a Gas (Key Feature 14)**

The number of students mentioning collisions in gaseous water rose by a reasonable percentage, but only reached 21% in the post-test. Most students don’t seem to have incorporated this into their mental images.

None of the interviewed students mentioned "collisions" prior to instruction. Four mentioned "collisions" in the post-test. Only one of these students explicitly identified the animations as helping to develop the idea of collisions but mentioned collisions with the glass, not with other molecules (see Table 2.9, page 59). Two other students mentioned the animations in relation to the development of their mental images of water in the three states, but were not directly questioned about the gaseous state. Therefore, it is difficult to say with certainty whether or not the animations helped specifically with this key feature.

Students may not have regarded the concept as important when viewing the animation of gaseous water, and so did not recall it. The importance of gaseous collisions could be highlighted for students by relating the idea to gas-phase chemical reactions, or by drawing their attention to the fact directly when showing the animation and asking students why such events might be important at the molecular level.
Greater Spacing in Solid Water than in Liquid Water Due to H-bonding (Key Feature 15)

The greater spacing in solid ice compared with liquid water is counter-intuitive for many students, and was barely elaborated in lectures. This may explain the relatively small improvement in the numbers of students mentioning this feature in the questionnaires.

It was obvious from some students’ comments in interviews that the animations did not help with this particular idea, consistent with the small effect in the total sample. For example, two students spoke of the water molecules being tightly packed together (Student 13; Student 10), and one student expressed confusion over why ice is less dense than water when she believed that the water molecules should be closer together in ice (Student 11). It is obvious that if this information is to be conveyed using animations, it must be done quite explicitly. Animations of solid and liquid water should be shown simultaneously and students should be questioned about the densities of the two substances, perhaps with reference to a commonly known phenomenon, such as freezing. The collapse of the water molecules into the more disorderly and closely packed liquid state on melting should be demonstrated using the melting ice animation, to help students understand the increase in density on melting. Students should be assured that the situation for water is unique and that their initial idea that solids are more tightly packed than liquids is correct for most molecules.

Water Molecules Can React with Each Other to Form Hydronium Ions and Hydroxide Ions (Key Feature 16)

An extremely small change was seen, from pre-test to post-test, in the number students who mentioned the autoprotolysis of water molecules. Consistent with this result, no students mentioned in interviews that the animations helped them develop this idea.

This idea was taught separately from the concepts of solids, liquids and gases. An animation was shown of this reaction, but once again separately from images of all three states. Mentally linking these separate images of liquid water would require deep learning strategies, i.e., consciously relating the new image to an existing mental image. The fact students did not recall autoprotolysis as a feature of liquid water suggests that students did not adopt this deep approach and that their knowledge may be somewhat compartmentalised. This emphasises the importance of helping students draw links between different knowledge and different
animations. This may be achieved by encouraging students to mentally visualise their existing models before viewing the new animation.

One student demonstrated her knowledge of this key feature in the pre-test and post-test, and in the interview she incorporated the idea into her description of the liquid water animation. Her prior knowledge may have enabled her to successfully draw links between different animations, incorporating ideas from these animations into a single mental model.

**Choice of a model of water and reasons for selection (Key Features 17–20)**

All students were able to select a correct model of a water molecule. In lectures, the bent shape of water (key feature 18) was dealt with in relation to VSEPR theory and Lewis structures, accounting for the reasonable number of students commenting on this feature. The features of different models were not discussed directly with students, however, which may account for the low numbers of students mentioning key features 19 and 20 in the post-test. These are features that only occur in the space-filling model, and the low numbers could be attributable to the fact that students chose different correct representations. This was not the case, however. The vast majority of students chose the space-filling representation in the post-test (see Table 2.33, page 123). Some students chose this model on the basis of its three-dimensional appearance, and not because it showed size differences or overlapping electron clouds. Furthermore, some students may have chosen the model because:

1. It was used so extensively in lectures, producing a skewed view of its importance, or suggesting to students that it was the desired answer; or

2. It was used in VisChem animations, which convey a sense of realism, prompting students to adopt it as the most realistic model.

These possibilities suggest that some students may not have convincing reasons for choosing the space-filling model over the other correct representations. They also suggest that overuse of one particular model might induce a perception of the “reality” of that representation, especially when the model is incorporated into a realistic computer animation. It is suggested that special attention be given to discussing scientific modelling and the “reality” of models with students, specifying the uses, benefits and limitations of each model. Similar recommendations have been made by a number of science education researchers (Renstrom,
Andersson & Marton, 1990; Davies, 1991; Harrison & Treagust, 1996, 2000; Oversby, 1999; Jones et al., 2001). Further comment on students’ choice of models is given in Section 2.3.1.

2.2.3.2.4. Summary

From the evidence presented in Section 2.2.3.2.1 and Tables 2.9 and 2.10, it can be seen that the animations were considered useful in helping students develop mental models of many of the key features of molecular substances. The animations seemed to be particularly successful at conveying the idea of vibrations in the solid, and in reinforcing the idea of movement in a liquid. This is consistent with Milheim’s (1993) discussion of the effectiveness of animations to represent dynamic processes.

Lack of development or mention of certain key features, discussed in Section 2.2.3.2.3, may have been due to the design of specific questions in the questionnaire, a lack of instructional emphasis on key features, the lack of relevant prior knowledge, or a failure to draw links between various materials.

During instruction, students were shown a video animation of water molecules. This video featured a voice-over that mentioned the relevant features in the animations. The students were exposed to six animations in close temporal proximity. The number of features that students were required to learn in this time was quite high. This bombardment of information may have reduced the effectiveness of the animations, especially for novices. It is recommended, therefore, that if a video is to be used to introduce new concepts, that it be stopped and started between animations to allow time for reflection and discussion. Alternatively, after showing the video, individual animations could be shown using Quicktime, so that important features can be pointed out and emphasised by the instructor, and any problems regarding students’ understanding can be clarified through discussion. Using Quicktime allows the instructor to stop and start the animation to direct the students’ attention to the relevant features in the display.

2.2.3.3. Ionic Substances: Solid Sodium Chloride

2.2.3.3.1. Key Features

Table 2.11 and Figure 2.11 show the percentages of students demonstrating knowledge of each key feature of solid sodium chloride in the pre-test compared with the post-test.
### Table 2.11 Changes in percentages of students demonstrating knowledge of ionic solid key features from pre-test to post-test in 2000

<table>
<thead>
<tr>
<th>KEY FEATURE</th>
<th>Percentage in Pre-Test (N = 48)</th>
<th>Percentage in Post-Test (N = 48)</th>
<th>Percentage Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionic Solids</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21. Correct model</td>
<td>75</td>
<td>85</td>
<td>+ 10</td>
</tr>
<tr>
<td>22. Ions not molecules</td>
<td>10</td>
<td>38</td>
<td>+ 28</td>
</tr>
<tr>
<td>23. Ions not atoms</td>
<td>43</td>
<td>56</td>
<td>+ 13</td>
</tr>
<tr>
<td>24. Structured</td>
<td>46</td>
<td>81</td>
<td>+ 35</td>
</tr>
<tr>
<td>25. Closely packed</td>
<td>50</td>
<td>56</td>
<td>+ 6</td>
</tr>
<tr>
<td>26. Vibrations in fixed positions</td>
<td>23</td>
<td>60</td>
<td>+ 37</td>
</tr>
</tbody>
</table>

#### 2.2.3.2. Confidence

Student confidence in responses to the two questions focusing on solid sodium chloride (Table 2.12) increased significantly ($p < 0.001$, Wilcoxon matched-pairs signed-ranks test). This is consistent with the overall improvement in students’ responses to these questions.
Table 2.12  Averages of confidence ratings for questions relating to ionic solids (key features 21 to 26)

<table>
<thead>
<tr>
<th>Content</th>
<th>Scale (0–6)</th>
<th>Pre-test Average (standard deviation)</th>
<th>Post-test Average (standard deviation)</th>
<th>Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid Sodium Chloride</td>
<td>Confidence</td>
<td>3.1 (1.9)</td>
<td>4.8 (0.9)</td>
<td>+ 1.7</td>
</tr>
<tr>
<td>Vibrations in Solid Sodium Chloride</td>
<td>Confidence</td>
<td>2.7 (1.7)</td>
<td>4.5 (0.9)</td>
<td>+ 1.8</td>
</tr>
</tbody>
</table>

2.2.3.3.  Interview Analysis

This section presents quotes from interviews to support that idea that VisChem animations helped students develop their mental image of solid sodium chloride. The quotes have been organised according to key features, as in the molecular substances analysis (Section 2.2.3.2.3). A complete list of quotes is given in Appendix D.

During the final section of the interview, six of the fourteen students were also asked to give an interpretation of the animation of solid sodium chloride. Some quotes from this interpretation are included in the following analysis to support the idea that the animations can convey at least some of these key features, even if students did not necessarily comment on them during the preceding section of the interview. These quotes are given under the heading “animation interpretation”.

One key feature (22) was not mentioned in interviews in relation to the animations, and hence is not included in Table 2.13.
Some comment is required on trends emerging from the questionnaires and interviews, as was done with earlier data on molecular substances. Once again, key features will be discussed for which progress from pre-test to post-test was poor (25), in relation to which the animations were not mentioned or were hardly mentioned (22, 23, 24, 25), or where percentages in the post-test were low (22, 23, 25). It is also disappointing that only 85% of students were able to select the most scientifically acceptable representation of solid sodium chloride (key feature 21). Therefore, this key feature will also be discussed.
Correct model (Key Feature 21)

Although a large majority of students were able to select the most scientifically acceptable representation of solid sodium chloride (85%) after instruction, a substantial number were still unable to do so. There was no consistency in the alternative responses, so it is difficult to assess what prevented the remaining students from developing the correct model. During interviews, students commonly identified the ball-and-stick model as helping develop their image of an ionic solid. It may be that some students were unable to move from a 3D ball-and-stick representation to a 2D space-filling model. It has been documented that students have difficulty translating between different representations in chemistry (Keig & Rubba, 1993).

Ions, not molecules (Key Feature 22)

The idea that molecules do not exist in solid sodium chloride (key feature 22) was made clear by only 38% of students in the post-test. Although this was a 28% increase over the pre-test, suggesting that the instruction had some effect, it still reflects that students have a poor understanding of ionic bonding. To examine ionic solids, students were given various representations of solid sodium chloride to criticise. One representation portrayed NaCl molecules separated by a small amount of space. It was common for students to mention that the molecules needed to be closer together, without mentioning that NaCl does not contain molecules. This may indicate that students believe there are molecules in solid sodium chloride despite their ability to recognise a more scientifically acceptable diagram. This is consistent with much of the work done by Taber (1994, 1997, 1998, 1999) regarding students’ alternative models of ionic bonding.

In an attempt to discourage students from mentioning the spacing (and mentioning the molecules instead), the revised version of the questionnaire, administered the following year, showed the molecules closer together than in the original version. The one concern here was that this would further reduce the numbers of students mentioning the close packing of the ionic solid. Results from the revised questionnaire are discussed in Section 2.2.4.1 (page 101).

Interview data indicate that exposure to animations was irrelevant to the increase in the numbers of students stating that ionic solids are constructed from discrete ions, not molecules or ion pairs. No students attributed the development of this idea to the animations. It may be
that students’ ideas about this concept relate more to their concept of ionic bonding than to their image of an ionic solid.

Three interviewed students, who failed to score a mark in the post-test for this key feature, provided an interesting revelation regarding students’ conceptions of ionic solids. They seemed to conceptualise (and even visualise) the ions as being in pairs as a "reminder" that they are in a particular ratio, rather than literally present as a molecule in the lattice. This concept seemed to act as a bridge between the ionic representation and the formula. An example is given below.

Student 6: …I naturally think of them as pairs of ions … it’s only paired as a concept because that just reminds me the charges there are the same…

These students all criticised the "molecular" representation of solid sodium chloride by suggesting that it was not closely packed or that the particles weren't joined, rather than criticising the existence of "molecules". Therefore, this research provides an alternative conception of ionic solids, not mentioned in Taber’s work. It also suggests that the number of students who understand this idea has been underestimated in marking the pre and post-tests.

These results highlight the fact that it is difficult to unravel students’ conceptions of ionic bonding, even when carefully designed written questions are used. The extent to which one must go, to reveal students’ conceptions of bonding in ionic solids, is demonstrated in previous research by Taber (1994, 1997), who used interviewing techniques and an extensive true/false style questionnaire.

**Ions, not atoms (Key Feature 23)**

There was only a small increase, from pre-test to post-test, in the number of students mentioning that there are "ions, not atoms" in ionic solids. This suggests that the instruction had only a slight impact. From the interview data, it does not appear that the animations helped students learn this idea. Students did not directly attribute the development of this idea to the animations, but none was questioned directly about the origin of the idea.

If we consider the various models used to teach the structure of sodium chloride, it is little wonder that some students do not discriminate between atoms and ions. Students were exposed to the VisChem animation, and frequently shown a ball-and-stick model of sodium
chloride. In both these representations, ions are represented as solid balls. There is little to suggest that these balls should be interpreted as ions, other than a key provided beside the animation. It is unlikely that the key will be recalled as part of the animation. Perhaps charges should be temporarily labelled on the animation to eliminate this split-attention effect.

Furthermore, there is no distinction between atoms and ions in ball-and-stick models. They are both represented as solid balls. A distinction is made in the VisChem animations of which students may be unaware. The visual differences between atoms and ions in VisChem animations may require very explicit emphasis for students, so that they can fully interpret the animations.

It appears that students may require a greater understanding of ionic bonding before they interpret animations or ball-and-stick models, to prevent their interpretations leading to self-reinforcement or the development of misconceptions.

In the revised version of the questionnaire, a number of questions were added to assess students’ knowledge and understanding of atoms, ions and molecules, and their ability to distinguish between ionic and molecular substances. The effect of this basic knowledge on the development of mental models is examined in Chapter 3 (Section 3.7).

It is possible that the number of students who understood that ions rather than atoms make up an ionic solid has been underestimated. The understanding of some students may have been masked by their inability to express their ideas. Students commonly confuse the terms ions, atoms and molecules, and use them interchangeably, even though they may be able to provide correct definitions of each when asked (Hinton & Nakhleh, 1999). In the current study, Students 4 and 9 seemed confused over the differences between atoms, ions and molecules, but eventually settled on the term “ions” to describe the particles that make up sodium chloride.

If students do not have these simple terms clearly distinguished in their minds, then it is to be expected that they will have difficulty interpreting explanations of bonding in ionic solids. In terms of this study, the number of students incorrectly using the terms “atoms” and “ions” in their responses to the questionnaire is assumed to be small, considering that chemical symbols and charges were provided in a key given to students, followed by either the term "atom" or "ion". This provides the relevant information necessary to distinguish the two types of
particles. It is therefore likely that if students did not make clear that they understood this idea, then they probably did not. To ensure that students did not just ignore the given key, the terms "atom" and "ion" were highlighted in bold in the revised version of the questionnaire (results are discussed in Section 2.4.1.1, page 101). Some students noticed correctly that the sizes of the sodium and chlorine atoms were different to those of the sodium and chloride ions. Many, however, remarked that the sizes were incorrect, not realising that the particles were representations of atoms rather than ions. It was hoped that highlighting the terms in bold might help focus students’ attention on the more relevant criticism: that the lattice should have been constructed from ions, not atoms.

The increase in the number of students mentioning this idea in the post-test may have been influenced by alternative instructions, such as diagrams drawn on the board. Drawings made by the lecturer were labelled with positive and negative ions, as described in the following excerpt.

Interviewer: What do you picture in your head now if I tell you to picture sodium chloride?

Student 3: The sodium ion and the chloride ion in a lattice...

Interviewer: …Do you picture in your head some kind of diagram you saw? Do you picture a model you’ve been shown? How do you think you developed that particular image that you bring up?

Student 3: From drawings, [the lecturer’s] drawings on the board.

Interviewer: Okay…and how did he draw them?

Student 3: Ball and stick, sort of in a rigid sort of one here one there… Positive, negative, positive, negative in like a cubical, sort of.

Two students mentioned that these drawings helped them develop their images of solid sodium chloride.

Attractive forces are perhaps best shown using animations when interactions between positive and negative particles are demonstrated. In this case, the idea that solid sodium chloride is constructed from charged particles can be discussed with reference to the animation of sodium chloride dissolving. Questioning techniques could be used to direct students’ attention to the relevant ideas. For example, students could be asked why the water molecules are attracted to the lattice and why it is difficult for the water to remove the ions. This should then lead to a discussion of competing lattice and ion-dipole forces. Obviously ideas of ions,
polarity and electrostatic attraction should be introduced before attempting this style of discussion. It is proposed that this situation would work most effectively with maximum student participation. This is difficult in a lecture. Collaborative learning at a computer in small groups with tutor interaction may be a more appropriate learning environment.

**Structured (Key Feature 24)**

Student understanding of the concept that ionic solids are structured improved substantially following instruction. However, none of the interviewed students stated that the animation of solid sodium chloride helped them to understand this idea, although one student seemed to have been unclear about the idea before viewing the animations.

A 3D ball-and-stick model that was regularly brought into lectures and/or the ball-and-stick representation presented on the board may also have contributed to conveying the idea of a structured lattice. This is supported by the fact that five interviewed students (Students 5, 8, 11, 14 and 10) mentioned the ball-and-stick model as contributing to the development of their mental images of solid sodium chloride.

**Closely packed (Key Feature 25)**

The close packing of ionic solids was only mentioned by a further 6% of students in the post-test, compared with the pre-test. This can hardly be considered a significant gain. Mention of this idea, in relation to the animations, was also lacking in the interviews. In fact, in this group, there was a decrease in the number of students identifying this feature in the post-test. This evidence suggests that the animations had little effect on students’ ideas regarding close packing in ionic solids.

The lack of any effect contributed by the animation may suggest that students have been strongly influenced by the ball-and-stick model of sodium chloride, and hence either did not think to mention it or were not aware that the ions should be closely packed.

**Vibrations (Key Feature 26)**

The most significant gain from pre-test to post-test was found for the "vibrations" in the solid (key feature 26), as was found for molecular substances. This suggests the successful involvement of animations, which is supported by the interview data (see Table 2.13, page 73). Despite the number of students mentioning this in interviews, some students seemed to
believe that vibrations in the solid only occurred if the solid was heated (Students 3, 8 and 10). This idea was often derived from the animations that showed either ice or sodium chloride melting. Although the idea of vibrations in the solid at room temperature may not have been conveyed to some students, most were able to discuss the effect of raising the temperature on the extent of vibration.

Student 10: ...On the video he showed us that when you heat it up, water, it'll start to vibrate and then it'll start to rotate then it'll start to move around and then it'll become a gas so like it might be different for salt, but that's probably where I got it from. I know that if you heat up...molecules they will start to vibrate.

2.2.3.3.4. Summary

It is clear that animations were useful in helping students develop the idea of vibrations in the solid, but it is still unclear whether the animations developed an understanding of the other key features of ionic solids. The fact that students did not mention ions rather than atoms or molecules in relation to the animations is not surprising considering the perceived difficulty in “seeing” these features without specific prior knowledge. Recall of a 3D ball-and-stick model seems to have influenced students’ models of solid sodium chloride, helping to establish the idea of a structured lattice but perhaps hindering the development of the idea of close packing.

2.2.3.4. Ionic Substances: Aqueous Solution of Sodium Chloride

Table 2.14 and Figure 2.12 show the percentages of students demonstrating knowledge of each key feature of an aqueous solution of sodium chloride in the pre-test compared with the post-test.
2.2.3.4.1. **Key Features**

<table>
<thead>
<tr>
<th>KEY FEATURE</th>
<th>Percentage in Pre-test (N = 48)</th>
<th>Percentage Post-test (N = 48)</th>
<th>Percentage Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionic Solutions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27. Correct model</td>
<td>15</td>
<td>98</td>
<td>+ 83</td>
</tr>
<tr>
<td>28. High water-to-salt ratio</td>
<td>10</td>
<td>73</td>
<td>+ 63</td>
</tr>
<tr>
<td>29. Closely crowded</td>
<td>31</td>
<td>77</td>
<td>+ 46</td>
</tr>
<tr>
<td>30. Hydration of ions</td>
<td>4</td>
<td>73</td>
<td>+ 69</td>
</tr>
<tr>
<td>31. There is an electrostatic attraction between water molecules and ions</td>
<td>19</td>
<td>46</td>
<td>+ 27</td>
</tr>
<tr>
<td>32. The solution is electrically neutral</td>
<td>15</td>
<td>40</td>
<td>+ 25</td>
</tr>
<tr>
<td>33. Ions not molecules</td>
<td>54</td>
<td>88</td>
<td>+ 34</td>
</tr>
<tr>
<td>34. Ions not atoms</td>
<td>46</td>
<td>79</td>
<td>+ 33</td>
</tr>
<tr>
<td>35. Dynamic (movement, collisions, water exchange)</td>
<td>6</td>
<td>0</td>
<td>- 6</td>
</tr>
</tbody>
</table>

Table 2.14  Changes in percentages of students demonstrating knowledge of ionic solution key features from pre-test to post-test in 2000

![Graph of the percentage of students demonstrating knowledge of ionic solution key features in the pre-test and post-test in 2000](image-url)
2.2.3.4.2. **Confidence**

Once again, confidence in the question on an aqueous solution of sodium chloride increased significantly ($p < 0.001$, Wilcoxon matched-pairs signed-ranks test). This is also consistent with the overall improvement in students’ responses to these questions.

<table>
<thead>
<tr>
<th>Content</th>
<th>Scale (0–6)</th>
<th>Pre-test average (standard deviation)</th>
<th>Post-test average (standard deviation)</th>
<th>Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aqueous Solution of Sodium Chloride</td>
<td>Confidence</td>
<td>2.6 (1.8)</td>
<td>4.8 (0.9)</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Table 2.15 Average of confidence ratings for question relating to an ionic solution (key features 27 to 35)

2.2.3.4.3. **Interview Analysis**

This section presents interview data to support the effectiveness of animations in helping students develop scientifically acceptable mental models of an aqueous solution of sodium chloride. Once again, data from the “animation interpretation” section of the interviews is included in this section, as described in Section 2.2.3.3.3 (page 72). Eleven of the fourteen students were asked to give an interpretation of the animation of an aqueous solution of sodium chloride (or sodium chloride dissolving). A complete list of quotes is given in Appendix D.
### Ionic Solutions

<table>
<thead>
<tr>
<th>Number of Students</th>
<th>Sample Quotes</th>
</tr>
</thead>
<tbody>
<tr>
<td>28. High water-to-salt ratio</td>
<td></td>
</tr>
<tr>
<td>Learnt 2</td>
<td>Student 11: This is like more of the animations that we got from [the lecturer] that were fairly identical to these actually…I didn't realise in the beginning and then the number of water molecules would be much greater.</td>
</tr>
<tr>
<td>Animation Interpretation 3</td>
<td>Student 12: …the ratio of ions to water molecules is very low.</td>
</tr>
<tr>
<td>29. Closely crowded</td>
<td></td>
</tr>
<tr>
<td>Animation Interpretation 2</td>
<td>Student 11: …they’re like crowding around each other</td>
</tr>
<tr>
<td>30. Hydration of ions</td>
<td></td>
</tr>
<tr>
<td>Learnt 5</td>
<td>Student 8: They had sodium chloride in a big lattice and the water molecules moving in and as like the water molecules move in the sodium chloride they just start like separating and then like the chloride’s surrounded by water and the sodium’s surrounded by water so there’s no connection like they’re not together so that’s how I pictured it.</td>
</tr>
<tr>
<td>Reinforced 1</td>
<td>Student 2: The only ones I would bring up in memory would be the animation images, they’re the ones that you bring up mentally…</td>
</tr>
<tr>
<td>Animation Interpretation 9</td>
<td>Student 3: That’s hydrated, I know that, surrounded by six water molecules.</td>
</tr>
<tr>
<td>31. There is an electrostatic attraction between water molecules and ions</td>
<td></td>
</tr>
<tr>
<td>Learnt 5</td>
<td>Student 9: …computer animations again…the water molecules at the positive poles are attracted to the chlorine ions and the negative poles are attracted to the sodium ions.</td>
</tr>
<tr>
<td>Reinforced 1</td>
<td>Student 2: The only ones I would bring up in memory would be the animation images, they’re the ones that you bring up mentally…</td>
</tr>
<tr>
<td>Animation Interpretation 8</td>
<td>Student 3: Na’s positive so then it’s got to have the O next to it. The water molecules, how they attach to the ion itself…chloride is a Cl minus therefore the positive H ions are attached to it.</td>
</tr>
</tbody>
</table>
32. The solution is electrically neutral

<table>
<thead>
<tr>
<th>Learnt</th>
<th>Animation Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student 9: … computer animations again… the water molecules are at the positive poles are attracted to the chlorine ions and the negative poles are attracted to the sodium ions… and there's an even number of each.</td>
<td></td>
</tr>
</tbody>
</table>

33. Ions not molecules

<table>
<thead>
<tr>
<th>Learnt</th>
<th>Animation Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student 12: Okay, that’s just, there’s two ions, and one’ll come up later… That’s obviously a negative ion, the green one because… the hydrogens of the water molecules are facing towards it… That must make the other one positive.</td>
<td></td>
</tr>
</tbody>
</table>

34. Ions not atoms

<table>
<thead>
<tr>
<th>Learnt</th>
<th>Animation Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student 13: Sodium chloride in water… you see chloride is a negative ion but then it's surrounded by water molecules with the positive end of the water molecules… I learnt that during the year, first semester [by] going to lectures and the animations again</td>
<td></td>
</tr>
</tbody>
</table>

35. Dynamic (movement, collisions, water exchange)

<table>
<thead>
<tr>
<th>Learnt</th>
<th>Animation Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student 9: … computer animations again… they're all moving everywhere</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Animation Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student 10: There's heaps of water molecules and they're everywhere, no specific like pattern and they're rotating and they're moving</td>
</tr>
</tbody>
</table>

Table 2.16 Quotes for ionic solution

Nine of the fourteen students mentioned various animations as helping them to develop ideas about the molecular/ionic level of an aqueous solution of sodium chloride. This varied from a vague mention of "animations" (one student), to descriptions of animations of hydrated ions (two students), sodium chloride dissolving (two students) and an aqueous solution of sodium chloride (four students). Two of the students who did not mention the animations as helpful chose the correct representation in the pre-test. Of these, one stated that his image hadn’t changed, and the other attributed changes to having been "told" in lectures. The three
remaining students identified the practical lessons and drawings on the board or being "told" certain features as helpful in developing certain ideas.

Once again, it is interesting to examine some of the results that emerge from the questionnaire and interview data. Post-test percentages for key features 31, 32 and 35 were low, and the percentage change from pre-test to post-test for key feature 35 was dismal. No student mentioned during interviews that the animations helped them develop the idea of closely crowded molecules in solution (key feature 29). Issues relating to these key features will be discussed. Although the percentages of students mentioning key features 28 and 34 rose to high levels in the post-test, these features are also discussed with reference to the interview data.

**High Water-to-Salt Ratio (Key Feature 28)**

With reference to Table 2.16, only two students revealed during interviews that they had learnt this key feature. Such limited mention of this feature was surprising, considering that a further six students from the fourteen interviewed had also developed the idea, according to the questionnaires, and that this feature is seemingly so obvious in the animation of an aqueous solution of sodium chloride. This might be explained by the fact that only four students (including the two students who mentioned learning this key feature) stated that the animation of an aqueous solution of sodium chloride helped them develop their images (see Table 2.5). This suggests that an alternative method of instruction, such as molecular-level drawings, also assisted with the development of this idea. One student suggested that just being told was enough.

Student 6: That’s something that changed… In high school we didn’t, we weren’t told, as far as I can remember, when drawing a representation of water that there are a lot more water molecules than there are ionic molecules that have been hydrated…but once we were told, I thought, well that’s reasonable, since there are lots and lots and lots and lots of water to start off with, and we only have a little bit of whatever we’re adding that dissolves into ionic form…. As soon as he said it there was just an intuitive understanding of why that would be so.

To emphasise this key feature in the animations, it may be useful if students calculate the number of water molecules present per mole of solute; and thence the ratio of water molecules to ions in an aqueous solution.
Closely Crowded (Key Feature 29)

No student mentioned learning from viewing the animations that the particles in the solution are closely crowded, but the number of students scoring a mark for this key feature improved dramatically following instruction. This is perhaps consistent with the suggestion discussed in Section 2.2.3.2.3 (page 63) that the animations may not effectively demonstrate the idea of close crowding of particles in liquids. Counter to this argument is the fact that two students mentioned the idea when viewing the animation during interviews. It is, therefore, difficult to say conclusively what contributed to students’ understanding of this idea, but it is likely that a number of factors are involved.

Electrostatic Attraction Between Water Molecules and Ions (Key Feature 31)

Even though there was a significant increase in the number of students commenting on the idea of electrostatic attractions between ions and water molecules, it only reached 46% in the post-test. It is common for students to enter university with a well-established concept of an ionic solution as containing separate ions floating among water molecules, without an understanding of all the ion-dipole forces present. If this concept is established firmly enough in the learners’ minds, then they may resist the idea of electrostatic interactions between particles.

The interview data suggest, however, that the animations helped many students to visualise this concept. This may indicate that more students were aware of the idea than the questionnaire data suggest. The questionnaire may not have been sufficiently sensitive to assess this idea. To test this second hypothesis, a modified question (administered as part of the pre/post-test in 2001) featured a representation showing water molecules incorrectly oriented, to replace one of the original representations given in this question. This was done to cue students to discuss the idea of electrostatic attractions. The effect of this modification is described in Section 2.2.4.1 (page 101).

Solution is Electrically Neutral (Key Feature 32)

Similarly, although 25% percent of students appeared to develop the idea that there are equal numbers of sodium and chloride ions in solution, the total number amounted to only 40% of the sample. This may be just the result of some students failing to notice that one of the
representations in the questionnaire contained the wrong ratio of ions, \textit{i.e.}, there may be factors such as disembedding ability (see Chapter 3) affecting students’ responses.

The fact that few students commented in interviews on the concept of an equal ratio of sodium ions to chloride ions in the solution, suggests that it may not be a feature that students adopted from the animations. Students may be more likely to discuss such ratios when thinking about formulae and would probably learn the idea when constructing formulae and chemical equations.

Alternatively, students may not realise the importance of electrical neutrality, and hence did not think to mention it in the questionnaire or interview. It may be important to explain this idea to students beyond just showing them the ratio of elements in a formula. The idea is essential to understanding certain chemical systems, such as electrochemical cells.

\textbf{Ions, Not Atoms (Key Feature 34)}

An understanding of the idea that ions rather than atoms are present in an aqueous solution was often revealed through students’ discussions of electrostatic interactions between water molecules and ions, which students often mentioned in relation to the animations. This was not taken into account in the marking scheme for the questionnaire, and may suggest that the number of students that were aware of this idea was underestimated in the post-test.

Recognising that balls represent ions in the VisChem animations is the only way that the idea of ions can be directly extracted from the animation; otherwise one must rely on electrostatic effects in solution. It is a conundrum that in order to take this information from the animations, one must understand electrostatic effects in solution, but in order to understand electrostatic effects, one must already be aware that there are ions in solution. Although the animations probably helped transmit this idea to a certain extent by representing the interactions between water molecules and ions, it is likely that other methods of instruction, perhaps using the chemical symbolism of ions, also contributed to the increase in the number of students aware of this idea.
Movement (Key Feature 35)

It is possible to deduce that, because students did not mention movement in the questionnaires, they were not aware of the idea. Contrary to this statistical data, some students demonstrated an awareness of movement in an aqueous solution of sodium chloride and several students pointed out the movement when viewing the animation during the interview.

The lack of written statements regarding movement might suggest that the questionnaire design did not encourage this response. Students were required to comment on the incorrect features in a number of representations of an aqueous solution of sodium chloride. In retrospect, they were unlikely to comment on a lack of movement in a 2D "snapshot". In the pre-test, a few students did comment that the ions had to be "free to move", a term often used by high-school teachers to describe the dissociation of ions and the conductivity in an ionic solution. In the post-test, students focused on other details in the given representations, such as hydration and the orientation of water molecules.

Ideas about movement may need to be probed in a manner that encourages students to relate this information. This could be achieved by asking students to describe chemical processes in conjunction with substances, by asking students to describe an animation or “movie” of the substance, or by asking students to compare a 2D image to their mental simulation. An extra question was added to the post-test for the following year’s first-year chemistry students, in an attempt to improve the sensitivity of the test to this key feature. This question encouraged students to compare their mental image of an aqueous solution to a static 2D diagram. Results are discussed in Section 2.2.4.1 (page 101).

2.2.3.4.4. Summary

Students commonly mentioned animations in relation to the development of their mental images of an aqueous solution of sodium chloride. In particular, the VisChem animation seems to have been highly successful in teaching about the hydration of ions and electrostatic attractions between ions and molecules. However, the extent to which the animations were helpful in conveying some other key features is debatable. For example, the evidence that the animations helped students to understand the close crowding of particles (29), “ions, not atoms” (34), and solution electroneutrality (32), appears limited from the interview data.
2.2.3.5. General Overview

Overall, the VisChem animations, as used in the teaching in this research, appeared to be instrumental in helping students improve their mental models of the molecular levels of molecular and ionic substances.

For the great majority of key features, the number of students who identified particular key features in the post-test was greater than the number who identified these key features in the pre-test. Many of these improvements were substantial. There was also sufficient evidence, from interviews, to support the hypothesis that VisChem animations contributed to students’ development of many of these key concepts, and to improvements in confidence and imagery vividness.

Students’ development of certain key features, in turn suggests a reduction in the corresponding misconceptions outlined in the marking scheme. For example, instruction seems to have been successful at reducing the number of students who believed that:

- Molecular size changes with phase change; or
- Intramolecular forces break during phase changes.

Not all students, however, found the animations useful and the level of development varied from one student to the next. The extent of prior knowledge was proposed to explain why students might not have developed certain key images. Similarly, disembedding ability may be a factor that influences students’ ability to extract information from animations and/or diagrams in the questionnaire. There are probably additional factors involved in students’ development of mental images, including motivation and learning styles. Some of these factors are examined more closely in Chapter 3.

In this study, students were shown the animations during lectures. Some students, however, did not develop the ideas shown in animations. It is possible that students who did not develop these images sufficiently require further engagement and interaction with the animations. Milheim (1993) recommends giving students control over the viewing of animations, and creating environments where students can “test hypotheses and witness the consequences”. Many of the VisChem animations have been incorporated into interactive
Chapter 2  Effectiveness of VisChem Animations

multi-media programs. The effectiveness of these resources is certainly an area that warrants further investigation but is beyond the scope of this thesis.

There appears to have been resistance to the incorporation of certain key features into students’ mental models, as shown by small improvements from pre-test to post-test. Furthermore, in interviews, students did not identify the animations as having an effect on the development of certain key features. A summary of the key features that appear resistant to adoption by students in response to animations, and the proposed reasons for the lack of effect are given in Table 2.17. Where the percentage of students listing a key feature improved by less than 10%, or the total percentage of students listing a key feature in the post-test did not exceed 20%, the key feature is listed in column 2 of the table (minimal pre–post test improvement). Where the interview evidence supporting the hypothesis that animations contributed to learning is limited, the key features are listed in column 3 (minimal interview evidence). The latter include:

- Key features that no students mentioned in relation to animations, but some students had developed; and

- A few key features that were referred to by one student but for which a greater response was expected, e.g., where the number of interviewed students who had developed the idea was high.

If a particular key feature appears in both columns, it can be concluded that the instruction using animations to teach this key feature has not been very effective. If it appears in the first column only, i.e., there is evidence of an effect in interviews that is not represented in the questionnaires, slight modifications to the questionnaire may be required. If a key feature appears in the second column only, it is probable that something other than the animations was responsible for the observed improvement apparent in the questionnaire data.

Possible explanations for the lack of recall or mention of certain key features in the animations are:

- Insufficient emphasis given to particular key features or representations during lectures (“lack of instructional emphasis”);
• Students’ failure to draw mental links between different animations or between animations and other instructional content ("lack of cognitive links drawn");
• Difficulty in visualising certain ideas ("difficult to visualise");
• A lack of relevant prior knowledge necessary to understand certain features of the animations ("relevant prior knowledge missing");
• Lack of ability to interpret the symbolism in animations ("animation literacy lacking");
• Students’ inability to clearly demonstrate their understanding ("poor expression of ideas");
• Dominance of an alternative model used to teach a particular feature (for example, "influence of ball-and-stick model"); or
• The feature not being immediately obvious in the animation ("feature not obvious", "inadequately represented in animation").

As indicated in Table 2.17, some of the results may have been influenced by questionnaire design. Consistent with an action research protocol, some minor changes were made to the questionnaires to test the hypotheses made in this regard. Changes were designed to affect the responses for the following key features: spacing of molecules in a liquid (1); spacing of molecules in a gas (2); ions, not molecules in ionic solids (22); ions, not atoms in ionic solids (23); electrostatic attraction between water molecules and ions (31); and movement in an aqueous ionic solution (35). [See marking scheme, Appendix A, for the connection between questions and key features]. A summary of the changes made and the reasons for the changes are given in Table 2.18. The results of these changes are presented in Section 2.2.4. Further questions were also introduced to test an additional aspect of students’ prior knowledge: their understanding of the differences between atoms, ions and molecules. The results are presented in Chapter 3, Section 3.7. The modified questions are reproduced in Appendix A.
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Minimal Pre–Post Test Improvement</th>
<th>Minimal Interview Evidence</th>
<th>Possible Explanation</th>
</tr>
</thead>
</table>
| 1           | Molecules in a liquid are closely crowded | Molecules in a liquid are closely crowded | • Questionnaire design  
• Inadequately represented in animation |
| 7           | Structured molecular solid |  | • Poor expression of ideas |
| 9           | Significant intermolecular attractions in molecular solid | Significant intermolecular attractions in molecular solid | • Lack of instructional emphasis  
• Lack of cognitive links drawn  
• Relevant prior knowledge missing  
• Feature not obvious  
• Difficult to visualise |
| 11          | Collisions between molecules in a liquid |  | • Feature not obvious  
• Lack of instructional emphasis |
| 12          | Significant intermolecular attractions in molecular liquid | Significant intermolecular attractions in molecular liquid | • Lack of instructional emphasis  
• Lack of cognitive links drawn  
• Relevant prior knowledge missing  
• Feature not obvious  
• Difficult to visualise |
| 14          | Gaseous collisions |  | • Lack of instructional emphasis |
| 15          | Greater spacing in ice than liquid water due to H-bonding | Greater spacing in ice than liquid water due to H-bonding | • Feature not obvious  
• Lack of instructional emphasis |
| 16          | Autoprotolysis of water | Autoprotolysis of water | • Lack of cognitive links drawn |
| 22          | Ions, not molecules, in ionic solids |  | • Feature not obvious  
• Questionnaire design |
| 23          | Ions, not atoms, in ionic solids |  | • Animation literacy lacking  
• Split attention between key and animation  
• Feature not obvious  
• Difficult to visualise  
• Questionnaire design |
| 24          | Solid sodium chloride is a structure lattice |  | • Influence of ball and stick model |
| 25          | Particles in solid sodium chloride are closely packed | Particles in solid sodium chloride are closely packed | • Influence of ball and stick model  
• Questionnaire design |
| 29          | Close crowding of particles in aqueous sodium chloride |  | • Inadequately represented in animation |
| 32          | The solution is electrically neutral |  | • Influence of formula |
| 34          | Ions, not atoms, in aqueous sodium chloride |  | • Animation literacy lacking  
• Relevant prior knowledge missing  
• Feature not obvious  
• Difficult to visualise |
| 35          | Movement in aqueous sodium chloride |  | • Questionnaire design  
• Lack of instructional emphasis |

Table 2.17  Reasoning for lack of effect shown in questionnaires and/or interviews
### Table 2.18 Summary of modifications made to pre-test/post-test

<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Change Made to Questionnaire</th>
<th>Purpose of Change</th>
</tr>
</thead>
</table>
| 1. Molecules in a liquid are closely crowded      | The diagram showing the particles most widely spaced was replaced with a diagram showing some particles touching but enough space to conceptually allow for the idea of movement. | • To test the hypothesis that students conceive of spacing in a liquid as relative to solids and gases rather than as absolute.  
• To test whether animations confirm misconception that particles in a liquid are reasonably spaced. |
| 2. Molecules in a gas are widely spaced           | The diagram showing the particles most tightly packed was replaced with a diagram showing very widely spaced particles. | • To test the hypothesis that students conceive of spacing in a gas as relative to solids and liquids rather than as absolute. |
| 22. Ions, not molecules, in ionic solids          | The molecules in the second erroneous representation of sodium chloride were positioned closer together. | • To reduce the likelihood of the response “move closer together” and encourage a focus on the fact that there are molecules in the depiction. |
| 23. Ions, not atoms, in ionic solids              | Labels for ions and atoms were highlighted in bold.                                            | • To focus attention on particle type rather than particle size.  
• To reduce misuse of the terms atom and ion. |
| 31. There is an electrostatic attraction between water molecules and ions | One of the erroneous molecular-level diagrams that seemed not to prompt any additional information over the others was replaced with a diagram showing incorrect positioning of water molecules around ions. | • To test whether prompting for this feature would increase the number of responses. |
| 35. Movement in aqueous ionic solution           | A question was added following the original question on aqueous solution of sodium chloride, asking students to state any differences between their mental image and the 2D image on the page.* | • To test whether prompting for this feature would increase the number of responses. |

*change only made to post-test

In conclusion, the mental models of students appeared to improve following instruction. Animations, even when used in the transmission-mode of lectures, were identified by students as helping to develop, modify or confirm aspects of their mental models. Furthermore, the animations appeared to have improved both the students’ confidence in their images of the molecular world and the vividness of those images.

### 2.2.4. Results and Discussion: Pre-test and Post-test 2001

This section reports the results of the follow-up study conducted in 2001, with the slightly modified pre- and post-questionnaires. The modified questions are presented in Appendix A.
Progress from pre-test to post-test is shown in Figure 2.13. Table 2.19 gives the averages and standard deviations for each section before and after instruction. Like the results from the previous year, the overall progress is statistically significant (p ≤ 0.0001, one-tailed paired t-test). Changes for all sections of the test were statistically significant (p ≤ 0.0001, one-tailed paired t-test) except for one, the specific features of water, which showed no change (p ≥ 0.1, one-tailed paired t-test). This was largely due to a lack of improvement in students’ descriptions of models of the water molecule. Students from the 2001 group did not have adequate reasons for their choice of representation, perhaps for reasons similar to those discussed for the 2000 group in Section 2.2.3.2.3 (page 69). For example, they may have chosen a representation based on familiarity. This group may have failed to perform significantly better for this section because their prior knowledge was lower than that of the 2000 group. Prior knowledge is thought to influence a student’s ability to understand and critically evaluate models (Greca & Moreira, 2000). The effect of prior knowledge on modelling ability is further examined in Chapter 4.

Figure 2.13  Comparison of pre-test and post-test overall scores in 2001.
### Table 2.19  Averages for sections in pre-test and post-test in 2001

<table>
<thead>
<tr>
<th>Section</th>
<th>Pre-test Average (standard deviation) (N = 36)</th>
<th>Post-Test Average (standard deviation) (N = 36)</th>
<th>Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Substances: General Features</td>
<td>4.6 (2.7)</td>
<td>6.6 (2.3)</td>
<td>+ 2.0</td>
</tr>
<tr>
<td>Molecular Substances: Specific Features Regarding Water</td>
<td>1.5 (0.7)</td>
<td>1.6 (0.7)</td>
<td>+ 0.1</td>
</tr>
<tr>
<td>Molecular Substances Total</td>
<td>6.1 (3.0)</td>
<td>8.1 (2.6)</td>
<td>+ 2.0</td>
</tr>
<tr>
<td>Ionic Solid</td>
<td>1.3 (1.1)</td>
<td>2.9 (1.4)</td>
<td>+ 1.6</td>
</tr>
<tr>
<td>Ionic Solution</td>
<td>1.3 (1.3)</td>
<td>5.3 (2.3)</td>
<td>+ 4.0</td>
</tr>
<tr>
<td>Ionic Substance Total</td>
<td>2.6 (1.9)</td>
<td>8.2 (2.9)</td>
<td>+ 5.6</td>
</tr>
<tr>
<td>Test Total</td>
<td>8.8 (3.9)</td>
<td>16.3 (4.8)</td>
<td>+ 7.5</td>
</tr>
</tbody>
</table>

### Table 2.20  Comparison of 2000 and 2001 pre-test results.

<table>
<thead>
<tr>
<th>Section</th>
<th>Pre-test Averages 2000 (standard deviation) (N = 48)</th>
<th>Pre-test Averages 2001 (standard deviation) (N = 36)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Substances: General Features</td>
<td>6.2 (2.4)</td>
<td>4.6 (2.7)</td>
</tr>
<tr>
<td>Molecular Substances: Specific Features Regarding Water</td>
<td>1.7 (0.9)</td>
<td>1.5 (0.7)</td>
</tr>
<tr>
<td>Molecular Substances Total</td>
<td>7.9 (3.0)</td>
<td>6.1 (3.0)</td>
</tr>
<tr>
<td>Ionic Solid</td>
<td>2.5 (1.5)</td>
<td>1.3 (1.1)</td>
</tr>
<tr>
<td>Ionic Solution</td>
<td>2.0 (1.9)</td>
<td>1.3 (1.3)</td>
</tr>
<tr>
<td>Ionic Substance Total</td>
<td>4.5 (3.0)</td>
<td>2.6 (1.9)</td>
</tr>
<tr>
<td>Test Total</td>
<td>12.4 (5.1)</td>
<td>8.8 (3.9)</td>
</tr>
</tbody>
</table>

### Table 2.21  Comparison of 2000 and 2001 changes from pre-test to post-test.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Substances: General Features</td>
<td>+ 1.8</td>
<td>+ 2.0</td>
</tr>
<tr>
<td>Molecular Substances: Specific Features Regarding Water</td>
<td>+ 0.5</td>
<td>+ 0.1</td>
</tr>
<tr>
<td>Molecular Substances Total</td>
<td>+ 2.4</td>
<td>+ 2.0</td>
</tr>
<tr>
<td>Ionic Solid</td>
<td>+ 1.3</td>
<td>+ 1.6</td>
</tr>
<tr>
<td>Ionic Solution</td>
<td>+ 3.7</td>
<td>+ 4.0</td>
</tr>
<tr>
<td>Ionic Substance Total</td>
<td>+ 5</td>
<td>+ 5.6</td>
</tr>
<tr>
<td>Test Total</td>
<td>+ 7.4</td>
<td>+ 7.5</td>
</tr>
</tbody>
</table>
A survey of the averages for each section of the pre-test and post-test reveals some interesting trends. First, the 2001 group of students, as a whole, appears to have a lower level of prior knowledge than the 2000 group (see Table 2.20). However, it can be seen from Table 2.21 that the changes from pre-test to post-test are remarkably similar. As a consequence of their lower levels of prior knowledge, post-test results are also lower for the 2001 group. This finding suggests that prior knowledge is a significant factor in the development of students’ images and that students build on what they already know. As an analogy, it seems that each group is able to climb the same number of rungs on a ladder, even though they begin on different rungs. On average, students with less prior knowledge do not learn less, but are unable to make up the missing prior knowledge or learn the extra information that would enable them to finish at the same level as students with more prior knowledge.

### 2.2.4.1. Key Features

A qualitative perusal of the graphs for changes in the percentage of students identifying key features reveals similar patterns for the 2000 and 2001 data (2000 data, see Figures 2.9–2.12; 2001 data, see Figures 2.14–2.17), suggesting that the instruction had similar effects on student learning. Changes from pre-test to post-test are tabulated in Tables 2.22–2.25. Some of the prominent differences occur for key features that were assessed differently (marked with an asterisk in Tables 2.22–2.25). These are discussed individually from page 99.
### Key Feature

<table>
<thead>
<tr>
<th>KEY FEATURE</th>
<th>Percentage in Pre-Test (N = 36)</th>
<th>Percentage in Post-Test (N = 36)</th>
<th>Percentage Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Features Of Molecular Substances</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. Molecules in a liquid are closely crowded*</td>
<td>78</td>
<td>94</td>
<td>+16</td>
</tr>
<tr>
<td>2. Molecules in a gas are widely spaced*</td>
<td>39</td>
<td>39</td>
<td>0</td>
</tr>
<tr>
<td>3. Molecules do not change size from solid to liquid to gas</td>
<td>19</td>
<td>50</td>
<td>+31</td>
</tr>
<tr>
<td>4. The molecular level is multi-particulate</td>
<td>69</td>
<td>89</td>
<td>+20</td>
</tr>
<tr>
<td>5. Molecular substances contain discrete particles in the solid, liquid and gas states</td>
<td>42</td>
<td>78</td>
<td>+36</td>
</tr>
<tr>
<td>6. There is empty space between the molecules</td>
<td>42</td>
<td>53</td>
<td>+11</td>
</tr>
<tr>
<td>SOLID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7. Structured lattice</td>
<td>8</td>
<td>22</td>
<td>+14</td>
</tr>
<tr>
<td>8. Vibrate in fixed positions</td>
<td>3</td>
<td>33</td>
<td>+30</td>
</tr>
<tr>
<td>9. Significant intermolecular attractions</td>
<td>11</td>
<td>14</td>
<td>+3</td>
</tr>
<tr>
<td>LIQUID</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10. Movement</td>
<td>64</td>
<td>72</td>
<td>+8</td>
</tr>
<tr>
<td>11. Collisions</td>
<td>0</td>
<td>6</td>
<td>+6</td>
</tr>
<tr>
<td>12. Significant intermolecular attractions</td>
<td>19</td>
<td>14</td>
<td>−5</td>
</tr>
<tr>
<td>GAS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>13. Movement (translational, vibrational and rotational)</td>
<td>58</td>
<td>64</td>
<td>+6</td>
</tr>
<tr>
<td>14. Collisions</td>
<td>8</td>
<td>28</td>
<td>+20</td>
</tr>
</tbody>
</table>

*indicates questions altered from 2000 version

Table 2.22 Changes in percentages of students demonstrating knowledge of molecular substance key features from pre-test to post-test in 2001
Figure 2.14  Percentage of students demonstrating knowledge of molecular substances in the pre-test and post-test in 2001

<table>
<thead>
<tr>
<th>KEY FEATURE</th>
<th>Percentage in Pre-Test (N = 36)</th>
<th>Percentage in Post-Test (N = 36)</th>
<th>Percentage Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Specific Features Regarding Water</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>WATER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15. Greater spacing in solid than liquid due to H-bonding</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>16. Water molecules can react with each other to form hydronium ions and hydroxide ions</td>
<td>3</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td><strong>WATER MOLECULE</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>17. Correct model</td>
<td>97</td>
<td>100</td>
<td>+ 3</td>
</tr>
<tr>
<td>18. Bent</td>
<td>36</td>
<td>28</td>
<td>– 8</td>
</tr>
<tr>
<td>19. Overlapping electron clouds</td>
<td>8</td>
<td>17</td>
<td>+ 9</td>
</tr>
<tr>
<td>20. Different sized atoms</td>
<td>8</td>
<td>8</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.23  Changes in percentages of students demonstrating knowledge of specific features of water from pre-test to post-test in 2001
Figure 2.15  Percentage of students demonstrating knowledge of specific features of water in the pre-test and post-test in 2001

Table 2.24  Changes in percentages of students demonstrating knowledge of ionic solid key features from pre-test to post-test in 2001

<table>
<thead>
<tr>
<th>KEY FEATURE</th>
<th>Percentage in Pre-Test (N = 36)</th>
<th>Percentage in Post-Test (N = 36)</th>
<th>Percentage Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionic Solids</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>21. Correct model</td>
<td>44</td>
<td>89</td>
<td>+ 45</td>
</tr>
<tr>
<td>22. Ions, not molecules*</td>
<td>0</td>
<td>25</td>
<td>+ 25</td>
</tr>
<tr>
<td>23. Ions, not atoms*</td>
<td>28</td>
<td>44</td>
<td>+ 16</td>
</tr>
<tr>
<td>24. Structured</td>
<td>17</td>
<td>53</td>
<td>+ 36</td>
</tr>
<tr>
<td>25. Closely packed</td>
<td>36</td>
<td>58</td>
<td>+ 22</td>
</tr>
<tr>
<td>26. Vibrations in fixed positions</td>
<td>8</td>
<td>25</td>
<td>+ 17</td>
</tr>
</tbody>
</table>

*indicates questions altered from 2000 version

Table 2.24  Changes in percentages of students demonstrating knowledge of ionic solid key features from pre-test to post-test in 2001

Figure 2.16  Percentage of students demonstrating knowledge of ionic solids in the pre-test and post-test in 2001
<table>
<thead>
<tr>
<th>KEY FEATURE</th>
<th>Percentage in Pre-Test (N = 36)</th>
<th>Percentage in Post-Test (N = 36)</th>
<th>Percentage Change from Pre-test to Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionic Solutions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>27. Correct model</td>
<td>17</td>
<td>81</td>
<td>+ 64</td>
</tr>
<tr>
<td>28. High water-to-salt ratio</td>
<td>11</td>
<td>67</td>
<td>+ 56</td>
</tr>
<tr>
<td>29. Closely crowded</td>
<td>17</td>
<td>69</td>
<td>+ 52</td>
</tr>
<tr>
<td>30. Hydration of ions</td>
<td>0</td>
<td>56</td>
<td>+ 56</td>
</tr>
<tr>
<td>31. There is an electrostatic attraction between water molecules and ions*</td>
<td>17</td>
<td>86</td>
<td>+ 69</td>
</tr>
<tr>
<td>32. The solution is electrically neutral</td>
<td>3</td>
<td>25</td>
<td>+ 22</td>
</tr>
<tr>
<td>33. Ions, not molecules</td>
<td>44</td>
<td>78</td>
<td>+ 34</td>
</tr>
<tr>
<td>34. Ions, not atoms</td>
<td>19</td>
<td>64</td>
<td>+ 45</td>
</tr>
<tr>
<td>35. Dynamic (movement, collisions, water exchange etc)*</td>
<td>3</td>
<td>3 (22)**</td>
<td>0</td>
</tr>
</tbody>
</table>

*indicates questions altered from 2000 version

**number in brackets indicates percentage mentioning movement in additional question

Table 2.25 Changes in percentages of students demonstrating knowledge of ionic solution key features from pre-test to post-test in 2001

![Graph showing changes in percentages of students demonstrating knowledge of ionic solution key features](image)

* percentage mentioning movement in additional question

Figure 2.17 Percentage of students demonstrating knowledge of ionic solutions in the pre-test and post-test in 2001

Molecules in a Liquid are Closely Spaced (Key Feature 1)

In the original questionnaire, most students chose a representation, after instruction, of a liquid that showed the molecules to be quite widely spaced.
In the revised version, 94% of students chose a representation in the post-test that showed the molecules closely arranged, with some touching, but conceptually allowing for the idea of movement. Few students chose the representation equivalent to the most popular representation in the original questionnaire. This tentatively suggests that students do not think there is a lot of space between the molecules of a liquid, but instead conceive them to be quite closely packed, albeit not as closely packed as a solid. Once again, many students seemed to have chosen this representation based on the relative intermolecular distances in the three representations, as they did in the previous version of the questionnaire (See Section 2.2.3.2.3, page 63). This tends to confirm the hypothesis that students do not have an absolute idea of the distances between molecules in a liquid. If it is deemed desirable for students to have the correct ideas regarding density, then discussion of molecular-level animations should be accompanied by experiments on compressibility and density, together with appropriate calculations. Students should be given assistance in drawing links between the various materials.

**Molecules in a Gas are Widely Spaced (Key Feature 2)**

The results for this key feature are more conclusive: although the majority of students are aware that molecules in gases are more widely spaced than molecules in liquids, they underestimate the amount of space between the molecules. Only 39% of students chose the representation in which the molecules were furthest apart, in both the pre-test and post-test, indicating that the instruction had no effect. This suggests that students no longer judged the representations to be of a solid, liquid and gas. A large percentage of students chose the representation that was most popular with the earlier version of the questionnaire. This finding is in line with research by Hill (1988) and Pereira and Pestana (1991) showing that students over-estimate the density of gases.

It is obvious that the animations alone do not convince students of the distances between the molecules in a gas. To overcome this problem, students should be encouraged to relate the results of simple experiments and calculations to molecular-level representations, e.g., comparing the volumes taken up by solid and gaseous carbon dioxide. Sleet (1993) advocates the use of calculations to help students develop correct ideas:
“…some students have difficulty in imagining empty space in gases and in understanding the behaviour of gases. By asking students to estimate (calculate) the amount of empty space in a sample of pure gas we can force them to think more deeply about the gaseous state of matter.” (p. 60)

Ions, Not Molecules and Ions, Not Atoms, in Ionic Solids (Key Features 22 and 23)

The percentages of students that developed key features 22 and 23 were remarkably similar in the 2000 and 2001 data, suggesting that subtle changes to the question had no effect. It is likely, therefore, that significant numbers of the first-year students in 2000 and 2001 did not know that “ions, not atoms” were present in ionic solids.

Electrostatic Attraction Between Water Molecules and Ions (Key Feature 31)

Cueing for this key features had extraordinary effects. Similar percentages of students were aware of the idea in the pre-test in both years (19% in 2000 and 17% in 2001). In 2000, this percentage rose to 46% after instruction. In 2001, it rose to 86%. This suggests that many students can recall the idea when cued to do so, but may not think to mention it otherwise. This cueing effect suggests that although students can recall being taught the idea, many do not incorporate it into a model of an aqueous solution that is recalled automatically. This may be attributable to the reasons discussed earlier, such as a resistance to incorporating new ideas into a firmly held idea. If this is the case, it is likely that students would abandon the new idea after some time, because this new idea is compartmentalised from the firmly held idea. This proposed effect questions the instructional method of gradually building up students’ mental models. However, the fact that students do retain this information, as evidenced by cueing effects, may mean that it just takes time to merge the new information with the old. Constant reinforcement over time is perhaps necessary for some students. Some of these ideas are dealt with further in the longitudinal study of students’ images in Chapter 4.

Movement in an Aqueous Ionic Solution (Key Feature 35)

If we compare the percentages of students in 2000 and 2001 who mentioned movement in the original question in the post-test, we find there is little difference (0% cf. 3%, respectively). However, if we compare this to the percentage of students who mentioned movement in the additional question, there is a significant difference (22%). This suggests that the method of assessment contributed to the lack of response by students, as proposed. The new question,
which asked students to compare their mental image with the image on the page, encouraged some students to reveal their idea about movement. The results, however, are rather disappointing. Do only 22% of students know that there is movement in an aqueous ionic solution? If not, why don’t students mention movement? Similar questions may be asked about the number of students mentioning collisions in gaseous and liquid water.

Perhaps it is because students saw static diagrams, drawings and animation snapshots more often than they viewed the animations. Due to their repetition, these diagrams may have been more instrumental than the animations in developing some students’ mental images of solutions, and these students may therefore mentally visualise static representations. This conclusion is consistent with that made by Williamson and Abraham (1995) regarding the use of pictures in teaching chemistry. They suggested that pictures, as opposed to animations, might encourage the formation of static mental models. This suggests that the animations should be repeated more often, so they have a greater effect on students’ images than do static drawings. Furthermore, there should be some discussion of the limitations of 2D drawings, to ensure that animations are appreciated as a learning tool and not just as a novelty or waste of time.

It is likely, however, that many students know that there is movement, and can perhaps visualise this movement but just don’t think to mention it. As mentioned earlier, this suggests that the idea is not important to them as a feature of ionic solutions and that it was not at the forefront of their minds when responding to a question regarding an aqueous solution. A further hypothesis is that students are so used to thinking about aqueous ionic solutions in static terms, from viewing drawings and diagrams, that they find it difficult to incorporate this new idea into their already existing concept. There is a need to emphasise the idea of movement when showing the animations and to reiterate this point by representing movement in all drawings after the animation has been shown, so that movement is recalled as a significant feature of ionic solutions. Students may need to be instructed in how to indicate movement in two-dimensional diagrams, so that it becomes almost second nature for them to do so. This would also eliminate the need for elaborate methods of assessment to determine if they are aware of these concepts.

There is also evidence that some students store their ideas as propositions rather than as images, and only produce images when they are asked to do so. Three students of the fourteen
interviewed in 2000 reported infrequent use of visual imagery in chemistry and/or suggested that they constructed images only when instructed to do so. An example is given below:

Interviewer: I want you to recall how often you are aware that you create a mental picture in your head when you’re doing any sort of problems in chemistry or when you’re thinking about chemistry and I want you to indicate on this scale how often you think you would imagine the particle level of matter when you’re thinking about chemistry.

Student 2: Actually, unless it’s presented in front of you or put on the whiteboard I’d say it’s…Really, I tend more to think in terms of equations.

Interviewer: …So because that’s rare you probably can’t identify too many topics in chemistry that you would sit down and actually bring up mental pictures?

Student 2: If told to, yes. I’ll bring up a mental picture. Usually I solve problems in other ways.

If movement was not adequately emphasised, these students might not recall the idea.

Students need to be challenged to solve problems that require them to have a dynamic, interactive mental model of a solution and to use their model to make predictions about other chemical phenomena, so that they realise the importance of movement and collisions in chemical processes. This approach should also encourage meaningful storage of the information.

A firm visual idea of these concepts earlier in the course of schooling should provide a solid foundation on which to build the more complex ideas that are dealt with in topics such as collision theory, kinetics and equilibrium. It has been reported that students imagine that chemical reactions are not interactive (Ben-Zvi, Eylon & Silberstein, 1987) and that reactions occur via some "miraculous" process, whereby bonds break spontaneously before reacting to form products (Lee, 1999). Extra emphasis on these aspects of the animations may help to remedy these problems.

2.2.4.2. General Overview

Table 2.26 summarises the results and conclusions derived from follow-up data collected in 2001, regarding the hypotheses drawn from the year 2000 data in relation to particular key features.
Students conceive of spacing in a liquid as relative to solids and gases rather than as absolute. Students once again reported choosing a particular representation based on exclusion of the “solid” and “gas”. Students judge spacing in a liquid relative to solids and gases.

Animations confirm the misconception that particles in a liquid are reasonably spaced. Most students chose a representation where the molecules have some space, but most are touching, in preference to the more widely spaced representation given in the original questionnaire. Animations do not confirm the misconception that particles in a liquid are reasonably spaced.

Students conceive of spacing in a gas as relative to solids and liquids rather than as absolute. Most students did not choose the representation where the molecules were furthest apart. Ideas remained the same after instruction. Students have an absolute idea of the distance between molecules in a gas and tend to underestimate this distance, even after exposure to animations.

Prompting for polarity effects will increase the sensitivity of the questionnaire to this key feature. The percentage of students identifying this key feature in the modified questionnaire rose considerably compared with the original questionnaire. Prompting encouraged more students to mention this feature, thus increasing the sensitivity of the questionnaire to this key feature.

Prompting for movement in ionic solutions will increase the sensitivity of the questionnaire to this key feature. Some students revealed their understanding of movement in ionic solutions when responding to the additional question. Prompting for movement in ionic solutions increased the sensitivity of the questionnaire to this key feature.

<table>
<thead>
<tr>
<th>Hypotheses 2000</th>
<th>Results From 2001 Questionnaires</th>
<th>Conclusions from 2001 Questionnaires</th>
</tr>
</thead>
<tbody>
<tr>
<td>Students conceive of spacing in a liquid as relative to solids and gases rather than as absolute.</td>
<td>Students once again reported choosing a particular representation based on exclusion of the “solid” and “gas”.</td>
<td>Students judge spacing in a liquid relative to solids and gases.</td>
</tr>
<tr>
<td>Animations confirm the misconception that particles in a liquid are reasonably spaced.</td>
<td>Most students chose a representation where the molecules have some space, but most are touching, in preference to the more widely spaced representation given in the original questionnaire.</td>
<td>Animations do not confirm the misconception that particles in a liquid are reasonably spaced.</td>
</tr>
<tr>
<td>Students conceive of spacing in a gas as relative to solids and liquids rather than as absolute.</td>
<td>Most students did not choose the representation where the molecules were furthest apart. Ideas remained the same after instruction.</td>
<td>Students have an absolute idea of the distance between molecules in a gas and tend to underestimate this distance, even after exposure to animations.</td>
</tr>
<tr>
<td>Prompting for polarity effects will increase the sensitivity of the questionnaire to this key feature.</td>
<td>The percentage of students identifying this key feature in the modified questionnaire rose considerably compared with the original questionnaire.</td>
<td>Prompting encouraged more students to mention this feature, thus increasing the sensitivity of the questionnaire to this key feature.</td>
</tr>
<tr>
<td>Prompting for movement in ionic solutions will increase the sensitivity of the questionnaire to this key feature.</td>
<td>Some students revealed their understanding of movement in ionic solutions when responding to the additional question.</td>
<td>Prompting for movement in ionic solutions increased the sensitivity of the questionnaire to this key feature.</td>
</tr>
</tbody>
</table>

Table 2.26 Summary of results and conclusions derived from 2001 data, regarding hypotheses derived from the year 2000 data

2.2.5. **Results and Discussion: Transfer Test 2000**

The direct and applied sections of the transfer test were marked in a similar fashion to the pre- and post-tests, using key features (see Figures 2.4–2.5). Students obtained a total mark for the number of key features they identified in each section of the test: molecular substances (direct transfer), ionic solids (separate scores for direct and applied transfer) and ionic solutions (separate scores for direct and applied transfer). Transfer effects were examined through calculation of Pearson correlation coefficients between sections on the post-test and transfer test. A direct comparison of pre/post key features and transfer key features, to determine transfer affects, is made for some molecular substances key features that were assessed in a similar manner using student drawings. Other key features are not examined in this way due to the different format of the questions used to assess these key features. It is known that
changes to question wording or format can influence students’ responses (Cassels & 

In addition to this, interview data is presented in Section 2.2.6.3 to support the hypothesis that 
students are able to transfer ideas from the animations to new situations.

### 2.2.5.1. Correlation Studies

A Pearson correlation matrix was computed between components of the post-test and transfer 
test (excluding data with missing values, N = 35). Not unexpectedly, there is a large, 
statistically significant correlation between post-test total and transfer total. Those students 
with a greater level of knowledge about substances shown in animations were more likely to 
score highly on the transfer test, as this knowledge is necessary in order to answer problems 
in the transfer test. Importantly, however, the correlation may indicate that students were 
somewhat successful at applying this knowledge.

The results of two main sections of the post-test were responsible for this large correlation: 
"general features of molecular substances" and "ionic solid" (see Table 2.27). These 
correlations suggest that students with an understanding of molecular substances were most 
likely to succeed at direct transfer, applied transfer (ionic solution) and topic transfer 
(concentration) questions. Students with a good understanding of ionic solids were also more 
likely to successfully answer direct transfer, applied transfer and topic transfer (concentration) 
questions. These results indicate that some students did not restrict their understanding of the 
molecular level to the substances portrayed by animations. Whether or not students have 
applied their images of animations cannot be determined from the correlation data.

Considering that the ball-and-stick model seemed to have a significant impact on students’ 
images of sodium chloride, it is just as likely that students have applied this model to new 
situations. Interviews were used to probe whether students were able to apply their images of 
animations to questions on the transfer test (see Section 2.2.5.3).

Knowledge of ionic solutions in the post-test did not significantly correlate with any 
components of the transfer test. This may suggest that some students have a superficial 
understanding of ionic solutions. Students received extensive instruction on ionic solutions 
and were tested on their knowledge in the mid-semester exam. The post-test demonstrates that
such instruction was effective at enabling students to describe the key features of ionic solutions. The lack of correlation with the transfer test suggests, however, that some of these students may have learnt the ideas by rote for assessment purposes without fully incorporating them into their mental models. These students would not be expected to be able to apply their knowledge. Emphasis on and subsequent assessment of key features may encourage students to adopt these ideas, but whether these ideas are learnt meaningfully may depend on the student. Student attributes affecting their ability to apply knowledge are further examined in subsequent chapters.

Lack of correlations with other components of the “Topic Transfer” section suggest that students did not use their knowledge of molecular and ionic substances to answer these questions. Importantly, the lack of correlation with the “Equations” component of Topic Transfer is consistent with previous research showing that students have difficulty moving between molecular and symbolic representations (Johnstone, 1982; Keig & Rubba, 1993) and may be able to answer typical exam-style questions without understanding the concepts at a molecular level (Nurrenbem & Pickering, 1987; Nakhleh, 1993; Nakhleh & Mitchell, 1993).

<table>
<thead>
<tr>
<th></th>
<th>Molecular substances (General)</th>
<th>Ionic Solid</th>
<th>Ionic Solution</th>
<th>POST-TEST TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct: Molecular</td>
<td>0.680**</td>
<td>0.471**</td>
<td>-</td>
<td>0.600**</td>
</tr>
<tr>
<td>Direct: Ionic Solid</td>
<td>0.345*</td>
<td>0.425*</td>
<td>-</td>
<td>0.416*</td>
</tr>
<tr>
<td>Direct: Ionic Solution</td>
<td>0.412*</td>
<td>0.487**</td>
<td>-</td>
<td>0.488**</td>
</tr>
<tr>
<td>Applied: Ionic Solid</td>
<td>-</td>
<td>0.404*</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Applied: Ionic Solution</td>
<td>0.464**</td>
<td>0.623**</td>
<td>-</td>
<td>0.631**</td>
</tr>
<tr>
<td>Topic: Equations</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Topic: Concentration</td>
<td>0.428*</td>
<td>0.475**</td>
<td>-</td>
<td>0.451**</td>
</tr>
<tr>
<td>Topic: Reactions</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Topic: Dissolved Gas</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TRANSFER TOTAL</td>
<td>0.610**</td>
<td>0.651**</td>
<td>-</td>
<td>0.693**</td>
</tr>
</tbody>
</table>

** correlation significant at 0.01 level (2-tailed)
* correlation significant at 0.05 level (2-tailed)

Table 2.27  Significant correlations between components of the post-test and transfer test
2.2.5.2. **Transfer of Molecular Substances Key Features**

This section attempts to look at the transfer of key features of solid, liquid and gaseous water at a molecular level (animations) to solid, liquid and gaseous iodine at a molecular level. Only those key features that were assessed using the same question format are compared. These include key features 4, 5, 7, 8, 9, 10, 11, 12, 13 and 14. For this comparison, only student data with either a 011 pattern (no prior knowledge, post-test knowledge and transfer knowledge) or a 010 (no prior knowledge, post-test knowledge and no transfer knowledge) pattern for key features were included. This served to simplify the interpretation of the data. These students presumably had learnt a key feature during the course of instruction and may or may not have shown transfer of this feature. Therefore, we can examine the extent of transfer. Figure 2.18 shows the number of students obtaining a mark for a particular key feature in the post-test and transfer test. Recall that all these students scored zero in the pre-test for these key features. The total number of students completing all three tests was 39.

![Figure 2.18](image)

**Figure 2.18** Number of students obtaining a mark for a particular key feature in the post-test and transfer test

Table 2.28 presents the extent of transfer as a percentage of students transferring the idea as a function of the number demonstrating awareness of the idea in the post-test. These percentages are somewhat deceptive considering the small number of students in each sample. Nevertheless, reasonable transfer (60% or greater) seemed to occur for the following key features:
Students appear to have a developed understanding of the nature of movement in solids, liquids and gases. It also appears that the instruction has helped to remedy the idea that intramolecular bonds break during phase changes. These students seem to have a general idea about phase changes that can be applied to different systems. A few students developed a general idea about the structured nature of molecular solids.

Little or no transfer was seen for key features:

9: Significant intermolecular attractions in solid
11: Collisions in liquid
12: Significant intermolecular attractions in liquid
14: Collisions in gas

It is little wonder that few students mentioned intermolecular attractions in relation to iodine. Non-polar molecular substances do not show specific orientations or attractions that can be shown easily in a diagram, like water. Transfer of ideas regarding hydrogen bonding is simply not appropriate.

The idea of collisions in liquids and gases does not seem to have been successfully transferred, once again suggesting that students do not consider it an important feature of the liquid and gaseous states of matter.

The majority of students were already aware of the multi-particulate nature of matter (key feature 4) in the pre-test, and hence development and transfer of this idea following instruction was negligible.
Table 2.28 Percentage of students transferring idea from post-test to transfer test

<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Percentage of Students Showing Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>4. The molecular level is multi-particulate</td>
<td>0</td>
</tr>
<tr>
<td>5. Molecular substances contain discrete particles in the solid, liquid and gas states</td>
<td>89</td>
</tr>
<tr>
<td>7. Structured lattice in solid</td>
<td>60</td>
</tr>
<tr>
<td>8. Vibrate in fixed positions in solid</td>
<td>84</td>
</tr>
<tr>
<td>9. Significant intermolecular attractions in solid</td>
<td>14</td>
</tr>
<tr>
<td>10. Movement in liquid</td>
<td>67</td>
</tr>
<tr>
<td>11. Collisions in liquid</td>
<td>20</td>
</tr>
<tr>
<td>12. Significant intermolecular attractions in liquid</td>
<td>0</td>
</tr>
<tr>
<td>13. Movement (translational, vibrational and rotational) in gas</td>
<td>75</td>
</tr>
<tr>
<td>14. Collisions in gas</td>
<td>25</td>
</tr>
</tbody>
</table>

Table 2.28 Percentage of students transferring idea from post-test to transfer test

2.2.5.3. Transfer of Ideas from Animations

The following section presents interview data aimed at determining whether VisChem animations help students visualise chemical substances and systems not depicted by animations, i.e., did students find their recall of VisChem animations useful for or relevant to transfer questions; and could students relate the animations shown to them in interviews to the content of the transfer test? These interview data were collected from the same fourteen students who discussed their responses to the post-test.

When viewing animations again, these fourteen students were asked to consider which questions in the transfer questionnaire the animations were relevant to. Doing this successfully required the ability to recognise suitable transfer of the animation, even if the student did not originally use the animation to answer the question.

Tables 2.29 and 2.30 present evidence for the influence of VisChem animations on students’ responses to the direct (Table 2.29) and applied (Table 2.30) components of the transfer test. Quotes in these tables demonstrate that some students were able to apply some of the ideas they had developed from animations to new chemical substances and systems. The tables list the number of students who either mentioned animations when discussing how they arrived at an answer in the transfer test (“Application of…””) or identified an animation as being related
to a particular question (“Relevance of . . . ”). No quotes are given for the latter, where students identified particular animations as being relevant to certain questions in the transfer test.

2.2.5.3.1. Direct Transfer

Table 2.29 gives evidence of students’ ability to apply concepts from animations to new but similar substances, i.e., they are aware that the information in animations can be generalised.

Interestingly, one student who had not previously mentioned the animations as helping with his mental image of an aqueous solution of sodium chloride, mentioned the animations in relation to an aqueous solution of barium chloride. This student had a reasonably good understanding of ionic solutions prior to starting university (six key features compared with the group average of two). It is interesting to note the level of detail that he noticed and recalled from the animations.

Student 5: I probably think the animations might have helped in the sense that I did know there was ions in water but perhaps the water molecules themselves, I didn’t have a complete understanding of how they, in water acted. I knew about the polar bonds, how they joined to the ions but maybe the rest of them how they sort of they sort of almost exchange as they move through the water, sometimes.

Interviewer: What do you mean, exchange with what?

Student 5: Oh, I think it’s one of the . . . animations had sort of a picture of as this ion sort of moves through water, one of these might sort of float away, another one’ll join and things like that so I guess it was clear understanding of the mechanics of it I suppose as it moves through.

Interviewer: . . . So it’s improved your ideas about the interactions, maybe? . . . at a particle level?

Student 5: Yep, I’d say that. I mean, again when I came out of school I probably would have thought they just went straight into water and that was it, you know straight away they’d just be surrounded and those ones would just stick there until something else comes.

Interviewer: Do you think that you had a static image, at high school?

Student 5: . . . Yeah, I would say that actually . . . no movement, no interactions.

This adds support to the idea that prior knowledge might influence what students "see" in the animations, as pointed out by other researchers in relation to various models in chemistry (Kozma & Russell, 1997; Greca & Moreira, 2000; Jones et al., 2001).
Table 2.29  Evidence of direct transfer of ideas from animations to new but similar substances

### DIRECT TRANSFER

<table>
<thead>
<tr>
<th>Molecular Substance: Iodine</th>
<th>Number of Students</th>
<th>Sample Quotes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application of water animations</td>
<td>6</td>
<td>Student 11: Probably the same animations from before...The ones about the solid, liquid, gas.</td>
</tr>
</tbody>
</table>

### Ionic Solid: Potassium Bromide

| Application of solid sodium chloride animation | 4                  | Student 9: …it needs to be in a regular pattern. |
|                                               |                    | Interviewer: Okay, which animation?         |
|                                               |                    | Student 9: The sodium chloride.              |

### Ionic Solution: Aqueous Solution of Barium Chloride

| Application of animations related to aqueous sodium chloride | 4                  | Student 2: The lattice-work animation, brought up the dissolving animations there |
|                                                               |                    | Interviewer: Do you want to describe to me the dissolving animation?           |
|                                                               |                    | Student 2: There you’d have the solid lattice of barium chloride, water molecules pouring down, water molecules working their way around ions, the barium or chlorine ions, they’re wobbling around and they kind of randomly float off kind of thing one by one or independently. |

| Relevance of aqueous sodium chloride animation to aqueous barium chloride | 4                  |                                                                   |

#### Table 2.29  Evidence of direct transfer of ideas from animations to new but similar substances

2.2.5.3.2.  *Applied Transfer*

Based on Table 2.30, there seems to have been some success in applying images of ionic solutions, taken from animations, to new chemical substances and systems. No student, however, suggested that the animation of solid sodium chloride assisted in their response to the question on the precipitation of copper(II) hydroxide. This is unusual considering that an understanding of ionic solids was found to correlate significantly and positively with the “ionic solid” component of Applied Transfer. It could be argued that most students did not use their recall of the animation to answer questions on ionic solids but, as discussed in Section 2.3.3.3.3 (page 72), may have relied on images gained from other sources, such as the ball-and-stick model, or may have approached questions with concepts about ionic substances rather than images.

Few students mentioned the animations in relation to the products of the reaction between sodium hydroxide and hydrochloric acid, and those that suggested the animations might have
helped (2) were vague and unconvincing. This may have been due to the repetitious nature of the interview questions and students not wishing to repeat themselves, and the fact that this was the last question discussed. This lack of response is surprising, however, considering that the product of the complete reaction would be an aqueous solution of sodium chloride. It may be that students had not made the link between the nature of the products and the solution, keeping their ideas compartmentalised.
<table>
<thead>
<tr>
<th>APPLIED TRANSFER</th>
<th>Number of Students</th>
<th>Sample Quotes</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Precipitation of Copper(II) Hydroxide</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ionic Solution</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Application of aqueous sodium chloride animations | 3 | Interviewer: Do you think that when you were answering that question you thought about animations?  
Student 9: …Yeah, well just all the ions floating around in the water and the water being attracted to them. |
| Relevance of aqueous sodium chloride animations | 1 | |
| **Other** |  | |
| Application of precipitation of silver chloride animation | 1 | Interviewer: Precipitation?  
Student 5: I’d say that was definitely helped by the animations…the one that I mentioned before where you saw them joining two and then four.  
Interviewer:  
Student 5: Yep. I think that was probably was really helpful because I wouldn’t have understood the interactions, like you said before. |
| **Aqueous Solution of Hydrochloric Acid** |  | |
| Ionic Solution | | |
| Application of aqueous sodium chloride animations | 5 | Interviewer: Do you think that any of the animations helped you with that question?  
Student 7: Sodium chloride one with the water molecules stuck to it. |
| Relevance of aqueous sodium chloride animations | 4 | |
| **Products of Reaction Between Hydrochloric Acid and Sodium Hydroxide** |  | |
| Ionic Solution | | |
| Application of aqueous sodium chloride animations | 2 | Interviewer: Do you think that any of the animations helped you with that question?  
Student 7: Sodium chloride one with the water molecules stuck to it…  
Interviewer: …and the products of that reaction after we accidentally put some sodium hydroxide in there?  
Student 7: Yeah, probably about the same thing |
| Relevance of aqueous sodium chloride animations | 2 | |

**Table 2.30** Evidence of applied transfer of ideas from animations to new chemical systems
2.2.5.3.3. **Topic Transfer: Concentration and Volume**

One student mentioned that the animations might have indirectly influenced her ability to visualise changes in concentration and volume at a molecular level.

Interviewer: Okay do you think anything in particular helped you to be able to visualise this sort of a change...with the water evaporating off a sugar solution?

Student 1: I can’t remember if there was anything directly.

Interviewer: Okay, how about indirectly?

Student 1: …Just again that video. You realise that some of the water molecules make the transition or they gain more energy, like that picture I drew before and they move from this area of having not as much energy to up here as having more energy but the sugar molecule wouldn’t because it stays dissolved in the water.

Most students did not feel that the animations assisted them with this question. This is not surprising considering that any influence of the animations here was expected to be due to an increased ability to visualise the particle level of matter, and not a direct result of any particular animations. This expectation is substantiated by the fact that the post-test results correlate significantly and positively with results on this section of the transfer test.

2.2.5.3.4. **Topic Transfer: Ionic Equations**

During interviews, students were not directly asked whether the animations or related mental imagery assisted them in the construction of ionic equations, or their understanding of ionic equations, as tested by the transfer test. One student, however, when asked for specific topics they tended to visualise, mentioned that she spontaneously constructed visual imagery when thinking about ionic equations.

Interviewer: Can you identify any particular topics or areas of chemistry where you specifically can remember doing it? Bringing up some sort of an image?

Student 3: Yeah, when we had to write the net ionic equation things.

2.2.5.3.5. **Topic Transfer: Acid/Base Reaction**

This section basically awarded students extra marks for realising that in the reaction between unequal amounts of sodium hydroxide and hydrochloric acid there was excess hydrochloric acid left in the solution, and then showing what effect this would have on the molecular-level representation. There was an assumption that students would use mental imagery to work
through this situation. Few students scored marks for this section, but those from the interview group who did tended to work in "ratios" and from the equation, rather than visualising the reaction. The drawn image was constructed after the necessary information was derived from this ratio approach. A sample excerpt is given.

Interviewer: Okay, in the final solution, what sort of ratio of sodium to chloride ions would you expect?

Student 5: One to one

Interviewer: Even if there are hydronium ions left?

Student 5: I guess it didn’t really say what concentrations you had to start off with or how much you mixed but if it was accidentally spilled in there I suppose there’d still be hydronium ions left.

Interviewer: Okay, is that solution you have there neutral?

Student 5: Did I put a hydronium ion there too did I?

Interviewer: Mm

Student 5: Oh, I’d still say they’d be one-to-one… Yeah they should because with every one that gets turned to water it would dissociate one…oh hang on, no it wouldn’t…You’ve got me thinking now.

Interviewer: What are you picturing now?

Student 5: You’d probably have a higher concentration of chloride ions because if you’ve only spilt a little bit in you’ve only added a tiny bit of sodium compared to what’s still in there.

Interviewer: Can you tell me, are you visualising anything in your head at the moment?

Student 5: Yeah, yeah.

Interviewer: What are you seeing?

Student 5: Well what I’m seeing is that if you’ve only added a tiny bit of NaOH…you’ve got a ratio in here of probably one-to-one of your sodium and hydroxide and another ratio of one-to-one with your hydronium and chloride ions, so I’m thinking if you only add a little bit of the sodium hydroxide then the hydroxides going to react with the hydronium to that extent and create that many water molecules and if you’ve still got some hydronium left over then it means you’ve still got excess HCl, which means you’ll still have more chloride ions left over so they wouldn’t have reacted with the sodium…well not that it reacts with the sodium but they’d still be more than the sodium.

Interviewer: Okay, now when you were describing that to me, were you picturing molecules, atoms in your head or were you picturing symbols and equations?

... Student 5: More like statistics, I guess, numbers.

This is consistent with the lack of correlations between post-test results and this component of the transfer test.
2.2.5.3.6. **Topic Transfer: Dissolved Gas**

This particular question was not discussed with interviewees, due to the lack of correlations found during statistical analysis.

2.2.5.3.7. **Summary**

Several students found their recall of VisChem animations useful for or relevant to transfer questions. These students seem to have generalised their understanding of animations, enabling them to apply the same ideas to different situations and to recall animations in appropriate circumstances. Furthermore, on being shown the animations again, many students were able to see the relevance of these animations to questions in the transfer test.

2.2.5.4. **Students’ Use of Imagery**

This section reports results relating to the final aim of the interviews: to examine students’ conception of their extent of imagery use in chemistry and relate this to results on the post-test and transfer test. At the end of each interview, students were asked to rate how often they imagined the particle level when studying chemistry. They marked their response on a scale from 1 to 5, five being “almost always”, one being “rarely”. On completing the scale, each student was asked to identify areas of chemistry where they felt they had evoked mental images in an attempt to understand or think about the topic. Table 2.31 shows the visual image rating of each student, and their corresponding marks on the post-test and transfer test.

There do not seem to be any differences between high visualisers and low visualisers in terms of marks on the post-test or transfer test. The Pearson correlation coefficient between the post-test results and imagery ratings was calculated to be −0.115; and −0.119 between the transfer test scores and imagery ratings. These correlations are not statistically significant. Low visualisers did not seem disadvantaged in any way when it came to producing or discussing their images – they just tended not to visualise unless they were asked. In fact, the negative correlation suggests that low imagers may perform slightly better than high imagers. These two approaches to thinking about chemistry, one utilising mental images and the other thinking in more conceptual terms, is consistent with the theory of cognitive styles described by Riding and co-workers (Riding & Cheema, 1991; Riding & Sadler-Smith, 1992; Riding, Dahraei, Grimley & Banner, 2001). Riding describes learners as being either predominantly ‘ imagers”, with a preference for mentally storing information visually or “verbalisers”, with a
tendency to mentally represent information as words or verbal associations. Consistent with
the observations made in this research, Riding suggests that both groups can use either mode
of representation if they make a decision or are asked to do so (Riding et al., 2001). Riding’s
cognitive styles, and their effects on learning in chemistry are further explored in Chapter 3.

<table>
<thead>
<tr>
<th>Student</th>
<th>Visual Images Rating</th>
<th>Post-Test Score</th>
<th>Transfer Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Student 1</td>
<td>4</td>
<td>19</td>
<td>41</td>
</tr>
<tr>
<td>Student 2</td>
<td>1</td>
<td>24</td>
<td>42</td>
</tr>
<tr>
<td>Student 3</td>
<td>5</td>
<td>19</td>
<td>*</td>
</tr>
<tr>
<td>Student 4</td>
<td>4</td>
<td>20</td>
<td>29</td>
</tr>
<tr>
<td>Student 5</td>
<td>4</td>
<td>24</td>
<td>41</td>
</tr>
<tr>
<td>Student 6</td>
<td>2</td>
<td>25</td>
<td>47</td>
</tr>
<tr>
<td>Student 7</td>
<td>4</td>
<td>22</td>
<td>44</td>
</tr>
<tr>
<td>Student 8</td>
<td>3.5</td>
<td>13</td>
<td>29</td>
</tr>
<tr>
<td>Student 9</td>
<td>5</td>
<td>17</td>
<td>*</td>
</tr>
<tr>
<td>Student 10</td>
<td>5</td>
<td>23</td>
<td>27</td>
</tr>
<tr>
<td>Student 11</td>
<td>4</td>
<td>20</td>
<td>29</td>
</tr>
<tr>
<td>Student 12</td>
<td>3</td>
<td>22</td>
<td>44</td>
</tr>
<tr>
<td>Student 13</td>
<td>3</td>
<td>12</td>
<td>17</td>
</tr>
<tr>
<td>Student 14</td>
<td>2</td>
<td>16</td>
<td>18</td>
</tr>
</tbody>
</table>

*transfer test had incomplete sections, hence no total was computed

Table 2.31   Students’ imagery ratings, post-test scores and transfer-test scores

Table 2.32 lists the topics where students claimed to use visual imagery. Students most
commonly identified areas of study where there had been a particular emphasis on molecular-
level representations, such as reactions and structure and bonding. Some of these students
claimed that visualisation was not useful for the more recently taught topics (kinetics,
thermochemistry) and tended to think in a more mathematical way for these topics.

Student 12: To be honest, I think the…concept of heat, I don’t really see an image, I think I just think
of it more, more like a value, more like a statistic, more a number…and similarly with, with the
kinetics, I think, I think it’s more like a numbers thing, than a visual thing.

This is not unexpected considering that calculation-style problems are common in these
topics. However, this has implications for the use of visualisation in teaching. If students are
to utilise visual imagery for more complex topics, it might be necessary to deliberately show them how it is relevant.

<table>
<thead>
<tr>
<th>Topic</th>
<th>No. Responses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td></td>
</tr>
<tr>
<td>Movement</td>
<td>1</td>
</tr>
<tr>
<td>Valence Shells</td>
<td>1</td>
</tr>
<tr>
<td>States of matter</td>
<td>3</td>
</tr>
<tr>
<td>Ideal gas laws</td>
<td>1</td>
</tr>
<tr>
<td>Structure and bonding</td>
<td>5</td>
</tr>
<tr>
<td>Solubility</td>
<td>3</td>
</tr>
<tr>
<td>Precipitation and other reactions</td>
<td>8</td>
</tr>
<tr>
<td>Molecular structure</td>
<td>2</td>
</tr>
<tr>
<td>Equations</td>
<td>2</td>
</tr>
<tr>
<td>Formulae</td>
<td>1</td>
</tr>
<tr>
<td>The mole</td>
<td>1</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>1</td>
</tr>
<tr>
<td>Kinetics</td>
<td>2</td>
</tr>
<tr>
<td>Acids and bases</td>
<td>4</td>
</tr>
<tr>
<td>Titration</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.32  Topics that students identified as involving the use of imagery

2.2.5.5. General Overview

Some general summary comments can be made in regard to the results presented in Section 2.2.6. First, it can be seen that the transfer of features of the common substances water and sodium chloride, to new substances and processes is indeed possible. This was demonstrated through direct comparison of the numbers of students listing certain key features in representations of molecular substances and by the fact that post-test results correlated highly with transfer test results.

More specifically, however, it can be concluded from interview data that some students were able to use ideas and images from VisChem animations to construct appropriate images for new substances and processes. This was particularly evident for the direct transfer section of the test. Students also showed successful transfer of ideas from animations regarding ionic solutions to a precipitation reaction, an acid/base reaction and an acid solution. Evidence of transfer to different topics (topic transfer) was somewhat more tentative. There was evidence
that some students were able to use their understanding of the molecular level to answer a question on concentration, demonstrated by significant correlations between the post-test and concentration section of the transfer test; and by interview evidence. There was little evidence, however, that animations assisted with the other components of “topic transfer”.

Finally, the results for the use of imagery demonstrate that spontaneous visualisation is probably not required for adequate understanding of substances and processes at a molecular level. These students spontaneously produce visual mental images to different extents and this was not related to the quality of the representation that the students produced, when asked. This is likely to be related to the way information is preferentially stored in the minds of students.

### 2.2.6. Conclusions

This study aimed to examine the effectiveness of VisChem animations in the teaching of first-year university chemistry. In line with earlier research on the use of animations in teaching chemistry (Williamson & Abraham, 1995; Russell et al., 1997; Sanger & Greenbowe, 1997; Garnett & Hackling, 2000; Sanger, Phelps & Fienhold, 2000), the results of this study have found benefits in their use; helping students develop mental models that can be used in transfer situations, reducing common misconceptions and building student confidence. The effectiveness of the animations seems to rely heavily on the way in which they are presented. They must be used as part of an overall teaching strategy that conforms to established principles of effective learning. They are simply building blocks from which a chemistry teacher might construct a program of study to help students develop their ideas regarding the molecular level of matter. VisChem animations are not sufficient as a teaching tool in themselves. Recommended guidelines for the use of VisChem animations in teaching are given in Chapter 5.

The most obvious limitation of this study is that it is difficult to isolate the extent of the contribution of the VisChem animations to the development of students’ images because other teaching devices were utilised in the course of the study. However, in a sense, this will be the case in any real educational setting. This study has shown that, when used as a component of an instructional sequence, animations are an effective learning tool and are commonly identified by students as helpful in the development of their images. If other models (e.g.,
ball-and-stick models, symbolic representations, Lewis diagrams) were not also contributing, then students might develop a very narrow view of science and scientific modelling.

Another criticism of the study may be that it does not reveal whether use of animations is more effective than other methods used to teach about the molecular level. This was not an aim of the study. This study only served to determine if the animations are effective in their own right, i.e., do they accomplish what they were designed to achieve, and how can we maximise the effectiveness of this medium? Scientific animations are now widely available. Their use in teaching is inevitable. It is therefore necessary to determine how best to utilise the resource, rather than dwelling on whether or not one medium is better than another. This point has been made by Mayer (1997):

“It is possible to produce effective and ineffective instruction in both computer-based and book-based media; moreover, in both media, ineffective instruction can be changed into effective instruction by applying the same basic instructional principles…the search for media effects dominated early research on media, but the current consensus among educational psychologists is that questions about the relative effectiveness of various media are no longer productive questions.”

One further question regarding this study is whether the benefits of animations would be apparent in other educational settings. For example, at the university in which the study was conducted, the UAI* cut-off for students in science courses is generally lower than that for some other universities in NSW. The benefits of VisChem animations may not be readily extrapolated to more highly academic students. This is an avenue for further research.

A final criticism may be that the questionnaires utilised in the study did not evaluate student understanding but merely looked at whether or not students had knowledge of key features.

Prosser (2000) suggests that “in the context of science education, memorisation can be associated with either a surface or deep approach” depending on “the intention the student has when engaged in memorisation.” Committing to memory the key features can be considered

* University Admissions Index: A number based on students’ academic success during their final year of high school for selection into university courses.
an essential but insufficient component of meaningful learning. In this study, the pre-test and post-test examined whether students had knowledge of key features. The transfer test was designed to see if students had learnt these ideas meaningfully. The ability to apply ideas is an indicator of meaningful learning. As suggested in the discussion, some students *do* perhaps learn ideas and images by rote. The study also demonstrates, however, that other students are able to apply their images of animations to new situations. Animations in themselves are unlikely to promote deep learning. Whether or not students learn meaningfully from animations is likely to be influenced by a number of factors, including how the animations are presented (Milheim, 1993; Russell *et al*., 1997; Burke, Greenbowe & Windschitl, 1998), learning strategies accompanying the animations (Milheim, 1993; Reiber, 1990; Greenbowe, 1994), adoption of a deep-learning style (Prosser, Trigwell, Hazel & Waterhouse, 2000) and sufficient prior knowledge (Prosser *et al*., 2000; Williamson, & Abraham, 1995). Student attributes affecting their ability to transfer ideas from VisChem animations are examined in Chapter 3.

In conclusion, the above study demonstrates that in first-year university chemistry, VisChem animations were intimately involved in:

- Helping students develop more detailed and scientifically acceptable mental models of the molecular world;
- Reinforcing students’ ideas regarding the molecular level and hence improving their confidence in their ideas and the vividness of their images; and
- Enabling some students to appropriately visualise chemical substances and systems not depicted by VisChem animations.
2.3. Further Insight into 2000 Data

Data were collected in the year 2000 that have not yet been discussed. This extra information is worth explaining as it extends the current literature in a number of key areas, and served as the basis of some further research presented in subsequent chapters. All the data presented below were extracted from the pre-test, post-test and transfer test described earlier in this chapter, but not all questions discussed in this section have been referred to in previous analyses.

Section 2.3.1 looks takes a deeper look at key features 17–20, students’ choice of a model of the water molecule and features of water molecules. Some original research into students’ misconceptions and mental models relating to concentration changes and precipitation reactions are presented in Section 2.3.2. Students’ ability to translate between symbolic and molecular representations is explored in Section 2.3.3.

2.3.1. Modelling

Concern has been expressed over the use of vivid computer animations to teach about the molecular level, because of the impact they might have on students’ perception of the reality of models (Harrison & Treagust, 2000). This concern is explored in this section with reference to students’ choices of models to represent water.

2.3.1.1. Questionnaire Data

Table 2.33 presents data on students’ choices of a model of water in the pre-test and the post-test distributed in the year 2000. This choice represents the model believed to best represent the “actual” structure of a water molecule. Numbers of students total more than 48 because some students chose more than one model. One student selected both models 1 and 2 in the pre-test. One student selected both models 1 and 2, and two selected models 1, 2 and 3 in the post-test.

The space-filling model was the most popular choice of representation, growing in popularity after instruction. Harrison and Treagust (1996) also showed this model to be more popular with junior high-school students than the ball-and-stick model for representing a water molecule, and it was most often used by high-school students to represent water molecules, in
Chapter 2  Effectiveness of VisChem Animations

a study by Pereira and Pestana (1991). As shown in Tables 2.5 (page 51) and 2.10 (page 61), six students of the fourteen interviewed mentioned that VisChem animations had influenced their choice of the space-filling model. Other reasons for choice of molecule were discussed with students in interviews and are reviewed in Section 2.3.1.2. A paired one-tailed t-test performed on the total score of key features 18–20 (features of chosen water molecule) shows a significant increase (N = 48, p < 0.001) from pre-test to post-test, suggesting that, on average, students have not just adopted a model on the basis of familiarity and the impact of the animations but also with regard to the information it conveys. This idea is explored in Section 2.3.2.1 by referring to students’ comments in interviews.

<table>
<thead>
<tr>
<th>Model of water</th>
<th>Pre-test (N = 48)</th>
<th>Post-test (N = 48)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Structural (acceptable model)</td>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>2. Space-filling (acceptable model)</td>
<td>29</td>
<td>41</td>
</tr>
<tr>
<td>3. Ball-and-stick (acceptable model)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>4. Incorrect order, linear</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>5. Two-particle</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>6. Linear ball-and-stick</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.33  Models chosen by students as best representing the “actual” structure of a water molecule

Table 2.34 shows the models adopted by students when representing the molecular level of water as a solid, liquid and gas in the pre-test and post-test administered in 2000.

<table>
<thead>
<tr>
<th>Model of water</th>
<th>Pre-test (N = 48)</th>
<th>Post-test (N = 48)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Structural (acceptable model)</td>
<td>12</td>
<td>1</td>
</tr>
<tr>
<td>2. Space-filling (acceptable model)</td>
<td>24</td>
<td>44</td>
</tr>
<tr>
<td>3. Ball-and-stick (acceptable model)</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>4. Incorrect order, linear</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5. Two-particle</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>6. Linear ball-and-stick</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>7. Circle</td>
<td>11</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2.34  Models used by students in their representations of solid, liquid and gaseous water

Once again, numbers do not total 48 because some students used different models for different states. In the pre-test, one student used models 3, 4 and 5 and two students used both model 2 and circles. In the post-test, one student used model 2 and circles.
An overwhelming majority chose to represent the states of water using the space-filling model in the post-test, despite some of these students choosing a different model as best representing the “actual” structure. This is probably due to the fact that the space-filling model was used both in the VisChem animations and in drawings made by the lecturer and the students.

2.3.1.2. Interview Data

During interviews, eight students of fourteen commented on features of the space-filling model that suggested it was closer to the “actual” structure of a water molecule than other models. Table 2.35 shows the features identified, with supporting quotes. Other students were either not directly probed about their choice of model (when there had been no change in their response from pre-test to post-test or their answer in the post-test was sufficiently detailed) or did not favour any particular model.

<table>
<thead>
<tr>
<th>Feature</th>
<th>No. Students</th>
<th>Quote</th>
</tr>
</thead>
<tbody>
<tr>
<td>Three-dimensionality</td>
<td>3</td>
<td>Student 1: It’s also a bit more three dimensional so it’s got a shape to it, it’s not just…flat</td>
</tr>
<tr>
<td>No sticks to represent bonds, hydrogen and oxygen are close together</td>
<td>5</td>
<td>Student 12: The reason why I thought that was more correct is because there’s not actually a space in between the hydrogen and oxygen. They’re actually together. Student 11: If you saw the actual molecules, there wouldn’t be like a little stick joining it</td>
</tr>
<tr>
<td>Size differences of atoms</td>
<td>4</td>
<td>Student 4: It shows well the oxygen being a bigger atom than the hydrogens.</td>
</tr>
<tr>
<td>Spherical atoms</td>
<td>2</td>
<td>Student 7: …the spheres, you know like a Mickey Mouse</td>
</tr>
</tbody>
</table>

Table 2.35  “Realistic” features of the space-filling model of a water molecule

Although five of the eight students cited above suggested that their selection of a water molecule was influenced by the extent of its use in lectures (drawings and animations), they were still able to provide reasoning for their choice based on specific features of the model. Some students discussed different reasons for having multiple models. These included:
• Different models used depending on how clearly they showed certain features, such as shape, the bonding or dipoles
• Different models for different learning styles
• Different models show different aspects, giving a better overall picture
• Some models are quicker and easier to draw

These reasons support the notion that some students do not necessarily blindly accept models as being depictions of reality, but rather representations designed with a particular purpose in mind.

In summary, students seem to believe that the space-filling model best represents the “actual” structure of a water molecule, often having been influenced by it extensive use in lectures. Fortunately, however, some students are able to propose reasons for why this is the case, although this ability may be affected by level of prior knowledge (see Section 2.2.4, page 93). There seem to be different views on the extent of the realism of the space-filling model. One student claimed it was “more life-like” than other models. Another suggested that the space-filling model simply conveyed more information and that he was aware that “in reality, a water molecule does not consist of a ball representing oxygen and a ball representing hydrogen”. Students’ understanding of scientific modelling has been studied by Grosslight and co-workers (1991), who assigned students “modelling ability” based on the extent of realism they attached to a model. Modelling ability is explored further in Chapter 4.

2.3.2. Mental Models and Misconceptions

2.3.2.1. Concentration Changes

A question on concentration featured in the “Topic Transfer” section of the transfer test. It required students to redraw a molecular-level representation after some water had been evaporated and after some water had been spilt, and comment on the comparative amounts of sugar before and after these occurrences. The 39 transfer tests previously reported were analysed for misconceptions or incorrect reasoning regarding concentration changes, at the molecular level. The misconceptions identified have not been reported in the literature.
Evaporation of Sugar Solution

A total of 67% of students had some misconception regarding the evaporation of a sugar solution.

To represent the evaporation of water from a sugar solution in the transfer test, students commonly (46%) removed water molecules from the given representation to give a representation that demonstrated the change in the ratio of water to sugar. This method, however, commonly resulted in having more space between or around particles because fewer particles were drawn in a given space. An example of this error is shown in Figure 2.19 (page 128). Some of these students removed water molecules only from the top of the given representation (5%), suggesting a link to the macroscopic conception.

A couple of students (5%) believed there would be no change to the molecular level of the sugar solution when water was evaporated.

Some stated that the amount of sugar in the solution would increase after evaporation. Various reasons were given for this, including:

• The concentration of the solution had increased. One student correctly drew more sugar molecules in their representation and seemed to extrapolate from this the presence of an increased number in the overall solution (3%).
• Some chemical reaction occurred to produce more sugar molecules (8%).

The latter misconception is shown by the following quotes:

Quote 1:
“The amount of sugar will increase as they break down into simpler forms.”

Quote 2:
“Heat from the sun provides ionised sugar to form back to individual molecules.”

Quote 3:
“Some H₂ has reacted with the sugar to form excess sugar.”
One student suggested a decrease in the amount of sugar resulted from evaporation due to the “H and O atoms in the molecule evaporating with the H₂O molecule”.

A summary of the erroneous responses is given in Table 2.36.

<table>
<thead>
<tr>
<th>Misconceptions Relating to the Evaporation of Sugar Solution</th>
<th>Percentage (no.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Removal of water from original diagram</td>
<td></td>
</tr>
<tr>
<td>Random removal</td>
<td>46% (18)</td>
</tr>
<tr>
<td>Same number of sugar drawn</td>
<td>15% (6)</td>
</tr>
<tr>
<td>More sugar drawn</td>
<td>13% (5)</td>
</tr>
<tr>
<td>Removal from around “hydrated sugar molecule”</td>
<td></td>
</tr>
<tr>
<td>Same number of sugar drawn</td>
<td>10% (4)</td>
</tr>
<tr>
<td>Removal from top of diagram</td>
<td></td>
</tr>
<tr>
<td>Same number of sugar drawn</td>
<td>5% (2)</td>
</tr>
<tr>
<td>Complete Removal</td>
<td></td>
</tr>
<tr>
<td>Same number of sugar drawn</td>
<td>3% (1)</td>
</tr>
<tr>
<td>2. No change to molecular level</td>
<td>5% (2)</td>
</tr>
<tr>
<td>No reason given</td>
<td>1% (1)</td>
</tr>
<tr>
<td>Only volume decreases</td>
<td>1% (1)</td>
</tr>
<tr>
<td>3. The overall amount of sugar in the beaker increases</td>
<td>10% (4)</td>
</tr>
<tr>
<td>Concentration has increased</td>
<td>1% (1)</td>
</tr>
<tr>
<td>Chemical reaction occurred</td>
<td>3% (1)</td>
</tr>
<tr>
<td>4. The overall amount of sugar in the beaker decreases</td>
<td>3% (1)</td>
</tr>
<tr>
<td>Atoms from sugar evaporate together with water</td>
<td>1% (1)</td>
</tr>
<tr>
<td>5. An increase in concentration can be represented by increasing the size of the sugar molecule</td>
<td>3% (1) (in interview)</td>
</tr>
</tbody>
</table>

Table 2.36 Misconceptions relating to evaporation of a sugar solution
Figure 2.19  Misconception 1: Evaporation can be represented by removing water from the molecular-level diagram

In the interviews, some students became quite adamant of the need to show, in the molecular-level representation, that there had been a loss of water molecules (misconception 1). This was achieved by removing water molecules from the original representation. These students did not necessarily believe that there was actually more space between the water molecules following evaporation. Reasoning at a macroscopic level was generally correct, but the desire to demonstrate the changes occurring in the overall solution, at a molecular level, led students to create erroneous representations of the molecular level. Even though some of these students realised that the representation did not adequately represent the molecular level, they felt it represented the change that had occurred. An example is given below.
Interviewer: What’s in all this space here?

Student 3: Nothing. That’s the whole point. Here the water molecules are all sort of, you know, there’s a lot of water molecules but here, after some evaporation has occurred, there is less water molecules.

Interviewer: Okay, which results in more space between the existing water molecules?

Student 3: Yeah less solution, less volume...

Interviewer: Okay, less volume on an observation type level. Does that result in greater spacing between water molecules at this level?

Student 3: No, no.

Interviewer: Okay, so what’s in this space?

Student 3: Water molecules but I haven’t drawn them.

Interviewer: Okay, so if you put water molecules in there aren’t you putting back the one’s you just took out?

Student 3: But we’re not putting them back in, we’re merely just showing here that’s there’s...I think the whole point of leaving space is to show that there’s less volume.

One student correctly suggested an increase in the concentration of sugar on evaporation of water, but suggested this could be represented by increasing the size of the sugar molecule (misconception 5).

Student 13: They should take up a lot more space than what I originally did here.

Interviewer: What do you mean, take up a lot more space?

Student 13: The sugar…that should be bigger, a bigger molecule.

Spillage of Sugar Solution

A total of 42% of students demonstrated misconceptions regarding the spillage of a sugar solution.

To demonstrate a loss of both water and sugar in the overall solution after spillage, students commonly represented the molecular level as containing half (or so) the number of particles as the original solution, once again resulting in fewer particles within a given space and more space between the particles. This was done by 23% of students. An example is given in Figure 2.20.
Two students (5%) appeared to indicate a decrease in the amount of sugar present after spillage by halving the size of the sugar molecule (see Figure 2.21).

Two students (5%) suggested that the amount of sugar in the beaker had not changed after spillage. One suggested that this was because the concentration had not changed (there was the same amount of sugar in the molecular representations); the other just commented that only the volume of the solution had changed. These comments indicate a confusion over the terms “amount” and “concentration”.

Some students (8%) suggested that mostly water would be lost from the solution, as the sugar was likely to have settled out or precipitated, leaving the solution effectively more concentrated. This is demonstrated by the following response:

“The sugar would appear more as it would have settled and most of the spillage would have been water.”

These students did not mention that this precipitation of sugar was due to the earlier evaporation, but appeared to believe that the sugar would just settle out as a matter of course. This once again points to a static image of a solution at the molecular level. The misconception perhaps arose due to knowledge relating to sugar and sugar solutions. For
example, students may be used to sugar being a solid, or may have observed leftover sugar in a mug after drinking a cup of coffee.

Misconceptions are summarised in Table 2.37.

<table>
<thead>
<tr>
<th>Misconceptions Relating to Spillage of Sugar Solution</th>
<th>Percentage (no.) (N = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6. Loss of solution through spillage can be represented by removing water and sugar molecules from the initial representation</td>
<td>23% (9)</td>
</tr>
<tr>
<td>7. A reduced amount of sugar in the solution due to spillage can be represented by halving the size of the sugar molecule</td>
<td>5% (2)</td>
</tr>
<tr>
<td>8. There is no change to the amount of sugar present in the overall solution.</td>
<td></td>
</tr>
<tr>
<td>• Concentration unchanged</td>
<td>3% (1)</td>
</tr>
<tr>
<td>• Only volume decreased</td>
<td>3% (1)</td>
</tr>
<tr>
<td>9. Sugar will settle out from the solution and hence spillage will result in mostly water being lost</td>
<td>8% (3)</td>
</tr>
</tbody>
</table>

Table 2.37  Misconceptions relating to spillage of sugar solution

![Student representation before spillage](image1.png)  ![Student representation after spillage](image2.png)

Figure 2.21  Misconception 7: A reduced amount of sugar in the solution due to spillage can be represented by halving the size of the sugar molecule

A large percentage of students demonstrated difficulty in representing the seemingly simple concepts of concentration and volume changes, at a molecular level. Commonly, misrepresentations of the molecular level seemed to involve assigning characteristics of the
macroscopic level onto the molecular-level representation. This has been previously reported in the context of students giving atoms and molecules physical properties of the substance (see Chapter 1, Section 1.3). Students’ responses also suggest that many students did not use a dynamic mental image of the molecular level to solve the problems given.

Considering that many students cannot construct these basic images, it is little wonder they experience difficulty with stoichiometric problems involving concentrations, volumes and moles. It is suggested that more attention be given to helping students construct suitable images of these changes at the molecular level, with a strong emphasis on the fact that sometimes changes at the macroscopic level do not directly correspond to the changes thought to occur at a molecular level. Simply emphasising the molecular-level via use of animations appears insufficient.

2.3.2.2. Precipitation Reactions

In the pre-test and the post-test, students were required to respond to a question on precipitation. This question was excluded from the analysis of key features presented in Section 2.2.3 because it was the final question and therefore was sometimes not completed or completed poorly. It could not be determined whether this was due to time constraints or the perceived difficulty of the question. Answered questions, however, revealed interesting findings regarding students’ mental models of precipitation reactions. Some of these ideas were probed further in interviews. Comparatively little research has been done into students’ mental models of complete reactions. In Sections 2.3.2.2.1 and 2.3.2.2.2, an alternative framework which emerged for precipitation is presented. Although limited, these data open the door for further research into alternative mental models of precipitation reactions.

2.3.2.2.1. Questionnaire Results

A common error emerged from the responses provided. Students sometimes represented reactants and/or products using molecules, rather than ions. Some students represented the equation in molecular terms, suggesting a swapping of partners as the mechanism for the reaction. In the pre-test, two students elaborated on this idea by incorporating the idea of ions. One student’s response is shown in Figure 2.22. These data may indicate the presence of a generalisable alternative conceptual framework for precipitation reactions.
Figure 2.22  Example 2: Alternative conceptual framework for precipitation of lead(II) iodide

The basic ideas of the proposed alternative framework can be summarised as follows:

1. We start with molecules of two different substances
2. When the molecules of each substance are mixed, they split to form “ions”
3. “Ions” “swap partners” to produce the products
4. The products exist as molecules
5. One of these molecules is a solid

Both of the above students had moved towards more scientific models by the post-test, suggesting that this alternative model may be the result of high-school teaching methods.

2.3.2.2.  Interview Data

Probably because all the students interviewed (14) had been taught about precipitation reactions, their mental models do not correspond fully to the above framework. These students instead tend to demonstrate a migration towards the more scientifically acceptable framework typical in conceptual development (Pines & West, 1986), by producing composites of the above framework and the scientifically acceptable model. In the majority of cases, students were more familiar with the structure of the products than the reactants. Examples of students’ descriptions that exhibit aspects of this alternative model are given in the following.
**Student 3**

This student demonstrated components 1–3 of the proposed model, and was unsure about the exact nature of the products; specifically whether or not the spectator ions bond together.

Student 3: Say the lead and the nitrate are somehow stuck together and the potassium and the iodide are stuck together but when they are mixed together in solution the, this is how I always think of it. The positive ion goes with the negative ion, negative goes with the positive but then there’s going to be two that are, what are they called, spectator ions, so they don’t do anything, they just stay in the solution whereas the other two form the solid or whatever it is that we want after they’re…mixed.

Interviewer: …Do you have some sort of a mental image of this solid?

Student 3: Afterwards? Yeah…Oh okay hang on, the bonds break here. How do the bonds break? Maybe through heat, through something else, something that breaks the bonds and then they form new bonds with the new ions…and the spectator ions, do they form a bond to that or did I just say that? …

Interviewer: …Do you have a picture of this part of the solution at the end?

Student 3: Yes, they’re either separate or they’re together but they have no significance being together.

Interviewer: What do you mean they have no significance being together?

Student 3: Because they’re spectator ions. They don’t affect the solution in any way or maybe in a little way but

Interviewer: Okay, I see what you mean. Okay, and so what’s your image of the solid?

Student 3: …It’s back in I think in some sort of lattice, well it doesn’t have to be in a lattice but they’re all sort of connected together, ball-and-stick wise.

**Student 5**

Student 5’s representation showed both reactants and products as molecules. He indicated that the reactants and one of the products would be dissociated in water and the other product would be a solid. He was questioned as to why he had represented all species as molecules. He suggests that the substances are molecules before being placed in water.

Student 5: I think I’m just sort of mentally drawing down what I thought the equation would have looked like.

Interviewer: So you’ve got underneath all of those – dissociates in water, dissociates in water…So at what point are they structured like this…?

Student 5: Well when they’re not in solution, not in water, I guess.

Interviewer: So there are molecules?

Student 5: Yeah
When probed about his description, he was able to give quite a detailed description of the precipitation process, derived from the precipitation animation. This suggests that he mentally stored both scientific and non-scientific mental models of precipitation reactions simultaneously.

Student 5: I guess you get your potassium and your nitrate which would remain in the water as dissociated ions and they don’t join at all...your lead and iodine ions they would join up into more or less a lattice, molecule by molecule and then, and well again I get that picture of the computer animation that [the lecturer] showed...I think that probably did help with the perception, just maybe one molecule and another molecule up to about four molecules and then maybe two of those lots of four and two of those lots of eight and then eventually it’s a solid.

Student 9

While this student could also adequately describe the products in terms of there being a solid lattice structure and separate spectator ions, he suggested that initially the reactants were molecules.

Student 9: They're spectator ions and they're still floating around, while these form together in a solid at the bottom of the solution

Interviewer: Okay, can you describe the solid?

Student 9: The solid? It'd just be the lead and iodide together, bonded together.

Interviewer: ...What do you mean like lead and iodide bonded together in molecules? You've got "molecules form the solid" here...Draw a little picture down there of the solid.

Student 9: [Draws ball-and-stick representation of ionic solid]...that all would've sunk to the bottom and the solution would be the other ions floating around in the solution, spectator ions...

Interviewer: And how about your reactant solutions? Is that a potassium iodide molecule there?

Student 9: Yep.

Interviewer: So you start off with molecules in your aqueous solution?

Student 9: Yeah.

Interviewer: I don't know. You've got the charges on there but you've got them grouped together, I was just wondering what that symbol...means to you?

Student 9: It means that they'd be together...I'm just showing the charges of each.
Student 11

This student’s model seemed to feature aspects of components 1 and 2 from the model above, suggesting that dissociation of ions occurs somewhere along the process. This student did understand, however, that the spectator ions remain as ions in solution.

Student 11: Probably a whole bunch of beakers like, the first one you put the two substances together, the second one you show dissociated ions and then the last one would be the…solid formed and the yellow solution but the other ions still in solution other than being bonded.

*  

Having studied first-year chemistry, students appeared to be developing the correct notion of a precipitation reaction. Some students made errors, however, which may be explained by the adoption of an alternative conceptual framework.

The fact that most of these students developed the correct image of the products is reassuring and can be explained by the fact that instruction concentrated more on the resulting solution. The animation used in the instruction only showed the reactants after they were mixed and the products being formed. This left the initial structure of the separate reactants open to interpretation. Students seemed to find it difficult to apply their model of an aqueous solution of sodium chloride to the reactant solutions. Explicit teaching and discussion may be required to help students draw links between their ideas about ionic solutions and precipitation reactions.

It seems likely that this framework may have come about through the misinterpretation of “molecular” and ionic equations. Students are commonly presented with both a molecular and ionic version of an equation. Students may interpret these as being two steps in an overall process rather than two representations of the same reaction, taking the equations quite literally as representations of the molecular-level process. Sleet (1993) recommends avoiding use of “molecular” equations to represent such processes and avoiding the use of the term “molecular equation” to describe an overall equation or representation.

Alternatively, the problem may lie in the strategies employed by high-school teachers to teach about chemical reactions. In a paper by Loughran and co-workers (2001), a teacher explained her deliberate use of erroneous chemistry to teach year 9 students about chemical equations.
"I know that Magnesium and Chloride are joined in a lattice rather than a 1:1 linkage but I don’t worry here about that or getting the charge right or the actual formula right. What is more important to me at this stage is helping my students to get the idea that different atoms rearrange their groupings to form new molecules, and that is what a chemical reaction is. Sometimes it is ok to teach “wrong” science if it helps to illustrate an important concept."

Simple models such as this might be strongly held by students and pose problems when the correct ideas are presented or when appropriate knowledge relating to chemical reactions is assumed. The negative and perhaps long-term effects of using “wrong” science to illustrate important concepts should not be overlooked.

More research is needed to establish the presence of this framework. Further examples are presented in Chapter 4, regarding students’ mental models of precipitation reactions, and their interpretation of “molecular” and ionic equations of the same reaction. This provides further evidence of this alternative conceptual framework.

2.3.3. Translating Between Molecular and Symbolic Representations

Questions in the pre-test, post-test and transfer test examined students’ ability to translate between molecular and symbolic representations of different substances. In the pre-test and the post-test students were required to distinguish between the substances, NO₂ and N₂O₄, when asked to draw a molecular representation of 2NO₂ and write a formula for a molecular depiction of N₂O₄. Some students seemed to find this task difficult. Further probing of these skills was carried out via the transfer test.

Table 2.38 demonstrates the range of responses on the pre-test and the post-test (N = 48) for the translation questions. Although there was an improvement from pre-test to post-test, the percentage of students giving correct responses, especially for the translation from the molecular representation, is disappointing. A third of the students were unable to adequately represent 2NO₂ at the molecular level after instruction. Most of these students represented a single molecule of N₂O₄. This suggests a misunderstanding of the meaning of coefficients in front of formulae. Even more astonishing, just over half the students were unable to produce the correct formula for the given molecular representation. Once again, the confusion lay with the coefficient in front of the formula. Some students seemed to believe there could be two
different molecular representations for the one formula, as suggested by the fact that they correctly represented the formula $2\text{NO}_2$ in Question 1, as separate $\text{NO}_2$ molecules but labelled the molecular representation of $\text{N}_2\text{O}_4$ in Question 2 as $2\text{NO}_2$. The difficulty seemed to lie in the fact that the molecule had a molecular formula that was different from its empirical formula. Garnett and Hackling (2000) reported similar difficulties in interpreting formulae and molecular representations of substances with empirical formulae, even after instruction specifically designed to teach students how to interpret chemical equations. The persistence of this misconception is cause for concern.

To further probe this difficulty, some questions were included in the transfer test. Students were required to write formulae for two substances where the empirical formula was different from the molecular formula, and for two substances where the molecular and empirical formulae were identical. The results of these questions are given in Table 2.39. A third of students were unable to provide correct formulae for the substances with an alternative empirical formula. The most common error involved the incorrect use of a coefficient, as in the responses to the question in the post-test. The percentage of students able to produce formulae rose considerably for representations where the empirical and molecular formulae were the same.

Other errors in translating between formulae and molecular representations in the pre-test, post-test and transfer test that were less common included:

- A belief that the coefficient indicated the number of atoms of the first element in the formula and
- Inappropriate use of brackets, for example, writing $(\text{OH})_2$ rather than $\text{H}_2\text{O}_2$.

During interviews, three students were asked to discuss their rules for writing formulae for molecular representations. This was done in regard to responses provided in the transfer test. The first student seemed to use the familiarity of compounds to name some structures.

Student 1: Okay, well, I would look at the picture and say well there’s two oxygens and each of them has got a hydrogen on it, so there’s two OHs and I guess I just recall that OH has a negative.

This is consistent with the finding by Keig and Rubba (1993) that students may use familiarity to assess whether or not a proposed formula or representation is plausible.
The second student used coefficients incorrectly, suggesting that the coefficient indicated the number of atoms of the species directly after it, rather than the whole molecule.

Student 14: Just how many there are and sort of put ‘em to wherever they’re going, so you’ve got two oxygens to two hydrogens

Interviewer: Okay, so a two out the front means that there are two oxygens?

Student 14: Yeah

This misconception has also been reported previously (Smith & Metz, 1996).

The third student demonstrated confusion between empirical and molecular formulae, demonstrating the misconception that bracketing with the appropriate subscript can be used to show that there are more than one of the empirical units bonded.

Student 4: …You put the two outside the brackets instead of writing two of those and two of those…just put (OH)₂.

Interviewer: So why’s this one not (CH₃)₂?

Student 4: Yeah…you don’t do them that way? I think that’s called an empirical formula, when…you do it like that.

Interviewer: You do it like which?

Student 4: If you call that (CH₃)₂. Maybe you just don’t do that at all, I don’t really know.

The results of this section suggest that it should not be assumed that students adequately understand the symbolic notation used as the main communication tool in chemistry. It seems more attention needs to be given to establishing this basic knowledge early in education (junior high school), perhaps through the use of multi-media programs such as “Balancing and Interpreting Equations” designed by Garnett, Hackling and Oliver (1998).
### Questions and Responses

<table>
<thead>
<tr>
<th>Questions and Responses</th>
<th>Percentage of Students providing Response on the Pre-test (N = 48)</th>
<th>Percentage of Students providing Response on the Post-test (N = 48)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Question 1: Draw and describe 2NO₂</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Two molecules of NO₂ (Correct response)</td>
<td>29.2</td>
<td>66.7</td>
</tr>
<tr>
<td>Molecule of N₂O₄ drawn</td>
<td>41.7</td>
<td>20.8</td>
</tr>
<tr>
<td>Molecule of N₂O₂ drawn</td>
<td>4.2</td>
<td>0</td>
</tr>
<tr>
<td>Two moles of NO₂</td>
<td>4.2</td>
<td>0</td>
</tr>
<tr>
<td>Other/no response</td>
<td>20.8</td>
<td>12.5</td>
</tr>
<tr>
<td><strong>Question 2. Write a formula for:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen (O)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen (N)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N₂O₄ (correct response)</td>
<td>37.5</td>
<td>45.8</td>
</tr>
<tr>
<td>2NO₂</td>
<td>54.2</td>
<td>45.8</td>
</tr>
<tr>
<td>2NO₄</td>
<td>2.1</td>
<td>2.1</td>
</tr>
<tr>
<td>(NO₂)₂</td>
<td>0</td>
<td>2.1</td>
</tr>
<tr>
<td>NO₂</td>
<td>2.1</td>
<td>0</td>
</tr>
<tr>
<td>Other/no response</td>
<td>4.2</td>
<td>4.2</td>
</tr>
</tbody>
</table>

**Table 2.38**  Students’ responses to translation questions from the pre-test and post-test
### Questions and Responses³

<table>
<thead>
<tr>
<th>Questions</th>
<th>Percentage of Students providing Response on the Transfer Test (N = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5(a) Write a molecular formula for:</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Molecular formula" /></td>
<td></td>
</tr>
<tr>
<td>H₂O₂ (correct response)</td>
<td><strong>66.7</strong></td>
</tr>
<tr>
<td>2OH</td>
<td><strong>20.5</strong></td>
</tr>
<tr>
<td>OH⁻</td>
<td><strong>7.7</strong></td>
</tr>
<tr>
<td>2HO₂ (or 2OH₂)</td>
<td><strong>2.6</strong></td>
</tr>
<tr>
<td>(OH)₂</td>
<td><strong>2.6</strong></td>
</tr>
<tr>
<td>5(b) Write a molecular formula for:</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Molecular formula" /></td>
<td></td>
</tr>
<tr>
<td>NO₂ (correct response)</td>
<td><strong>97.4</strong></td>
</tr>
<tr>
<td>other</td>
<td><strong>2.6</strong></td>
</tr>
<tr>
<td>5(c) Write a molecular formula for:</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Molecular formula" /></td>
<td></td>
</tr>
<tr>
<td>C₂H₆ (correct response)</td>
<td><strong>66.7</strong></td>
</tr>
<tr>
<td>2CH₃</td>
<td><strong>15.4</strong></td>
</tr>
<tr>
<td>2CH₆</td>
<td><strong>2.6</strong></td>
</tr>
<tr>
<td>CH₆</td>
<td><strong>7.7</strong></td>
</tr>
<tr>
<td>other</td>
<td><strong>7.7</strong></td>
</tr>
<tr>
<td>5(d) Write a molecular formula for:</td>
<td></td>
</tr>
<tr>
<td><img src="image" alt="Molecular formula" /></td>
<td></td>
</tr>
<tr>
<td>SeCl₄ (correct response)</td>
<td><strong>89.7</strong></td>
</tr>
<tr>
<td>other</td>
<td><strong>10.3</strong></td>
</tr>
</tbody>
</table>

Table 2.39  Students’ responses to translation questions from the transfer test

³ A key was provided for these questions in the transfer test. See Appendix A.
2.4. Long-Term Effects of Exposure to VisChem Animations

2.4.1. Aims

This study aimed to examine some of the long-term effects of exposure to VisChem animations. This was achieved by:

- Probing the images and ideas of third-year students who had been exposed to animations in their first year of university chemistry;
- Comparing the images and ideas of third-year students who had been taught using animations in first-year university chemistry with those who had not;
- Examining students recall of animations;
- Determining how beneficial students found the animations in first-year chemistry and subsequent years of study; and
- Examining students’ ability to interpret animations upon re-exposure.

2.4.2. Methodology

2.4.2.1. Sampling

The study involved the distribution of two questionnaires, an “Images Questionnaire” and an “Attitude Survey”, with follow-up interviews.

Third-year chemistry students (N = 20) from a metropolitan university in NSW, Australia, completed a questionnaire to assess their mental images of some chemical substances (Images Questionnaire). Fourteen of these students had seen VisChem animations in first-year university chemistry (animation group). Twelve students from the animation group also completed an attitudinal survey. The remaining six students did not complete first-year chemistry at the university where the study was conducted (non-animation). Four volunteers from the animation group participated in one-to-one follow-up interviews.

Slightly modified versions (see Appendix A for copies of each version) of the questionnaire and attitudinal survey were administered the following year to another group of third-year
chemistry students (N = 23). Sixteen of these students had been exposed to VisChem animations in first-year university chemistry (animation group) and the other seven had not (non-animation). Three students from the animation group were interviewed separately following the completion of the questionnaires.

Administration of both questionnaires took about one hour. The attitudinal survey was not administered until the images questionnaire had been submitted. This was done because the mention of “animations” in the Attitudes Survey might have biased responses on the Images Questionnaire. Interviews with students lasted approximately 20 minutes.

Data from both groups of third-year students were combined for statistical analysis. Therefore, the animation group totalled 30 students and the non-animation group, 13 students.

2.4.2.2. Images Questionnaire

The Images Questionnaire examined students’ mental images and ideas by requesting them to draw and explain solid water, liquid water, gaseous water, an aqueous solution of barium chloride and a saturated solution of silver chloride at the molecular level. To guide the level and extent of detail the students provided, they were instructed to provide all the information they would point out to a beginning student, if they were a tutor. The students from the animation group had been exposed to animations of water, ionic solutions and precipitation during their first year of university chemistry.

Questionnaires were marked in a similar style to that described in Section 2.2. A set of key features was constructed for images under the categories: molecular substances (14 key features), ionic solutions (8 key features) and saturated solutions (15 key features) (see Table 2.4.2.2). Students’ chosen models for representing water were also noted.

The content examined in the questionnaire did not change from one administration to the next. Only slight changes were made to the original questionnaire to improve the clarity of the instructions. For example, “Molecular-level drawing(s) and description” was added above each blank space where students were required to draw.
2.4.2.3. Attitudes Survey

The Attitudes Survey was designed to determine how vividly students felt they recalled animations and to determine any perceived benefits of having seen the animations. Students were asked to rate how well they recalled animations shown to them in first year. They were asked to describe their most memorable images of the animations, to say if and how they felt the animations benefited them in first year and/or subsequent years, and to discuss any effects the animations had on the way they thought about chemistry or the world around them.

Once again, minor changes were made to the questionnaire following the first administration. For example, a modified scale to determine their recall of animations was used (see Figure 2.23).

2.4.2.4. Interview Protocol

The interviews were used to further probe some students’ images by encouraging them to discuss their responses to certain questions on the Images Questionnaire. Students were asked whether they recalled images from animations when answering the questionnaire. They were then re-exposed to the animation(s) relevant to the question and allowed to make modifications to their original representation. The interview protocols for the first and second groups of students differed slightly in their approach to showing the animations. The first group of students were told what the animation represented. They watched the animation, made modifications to their representation, watched the animation again with key features pointed out to them and made further modifications to their representation. The second group were left to interpret animations without assistance from the interviewer. They were then allowed to make modifications to their representation(s). The interview protocols can be found in Appendix C.
**Original Question:**

In your first year lectures, you were shown a number of animations of the molecular world. **Do you remember them?** *(please circle one response)*

**YES / NO / VAGUELY**

**Modified Question:**

In your **FIRST YEAR LECTURES** you were shown a number of animations of the molecular world. As a whole, **how vivid is your memory (visual mental image) of them?** *(please tick one response)*

- [ ] Perfectly clear and as vivid as normal vision
- [ ] Clear and reasonably vivid
- [ ] Moderately clear and vivid
- [ ] Vague and dim
- [ ] No image at all, you cannot remember them or you only "know" that you are thinking of them

---

**2.4.3. Results and Discussion**

**2.4.3.1. Images Questionnaire**

Students’ questionnaires were scored such that indication or mention of a key feature received a mark. Students received a total mark out of 37, with separate marks for questions on molecular substances, ionic solutions and saturated solutions. A list of key features is given in Table 2.40.

**2.4.3.1.1. Statistical Data**

The percentages of students from the animation and non-animation groups obtaining a mark for each key feature are shown in Table 2.40. All percentages for the animation group are higher than those for the non-animation group, although some of these differences are small. Differences are discussed in Section 2.4.3.1.2.

---

*4 Question adapted from Mark’s Vividness of Visual Imagery Questionnaire (1973).*
Table 2.41 gives a comparison of average scores obtained by the animation and non-animation groups on sections of the Images Questionnaire. Scores obtained by the animation group are significantly higher ($p < 0.05$) than those obtained by the non-animation group, on all sections of the questionnaire.

It seems instruction aimed at encouraging students to develop their understanding of the molecular level at a first-year level has had a lasting and significant impact on students’ images. Students not taught with this emphasis on the molecular level seem less likely to develop and/or retain certain ideas. Despite this, even the animation group’s averages were low compared with the maximum marks allocated, suggesting that students have not retained some ideas from first year or did not develop them initially.

It should be noted that these conclusions are somewhat tentative. Sample sizes were small and the experiment was not controlled for factors such as the differences in academic ability between the two groups.
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>A: Animation Group Percentages (N = 30)</th>
<th>N: Non-animation Group Percentages (N = 13)</th>
<th>A minus N N</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOLECULAR SUBSTANCES - general</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecules in a liquid are closely crowded</td>
<td>17</td>
<td>0</td>
<td>17</td>
</tr>
<tr>
<td>Molecules in a gas are widely spaced</td>
<td>67</td>
<td>23</td>
<td>44</td>
</tr>
<tr>
<td>The molecular level is multi-particulate</td>
<td>93</td>
<td>54</td>
<td>39</td>
</tr>
<tr>
<td>Molecular substances contain discrete particles in the solid, liquid and gas states</td>
<td>77</td>
<td>54</td>
<td>23</td>
</tr>
<tr>
<td>Solid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structured lattice</td>
<td>47</td>
<td>38</td>
<td>9</td>
</tr>
<tr>
<td>Vibrate in fixed positions</td>
<td>37</td>
<td>0</td>
<td>37</td>
</tr>
<tr>
<td>Significant intermolecular attractions</td>
<td>30</td>
<td>23</td>
<td>7</td>
</tr>
<tr>
<td>Liquid</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement</td>
<td>50</td>
<td>15</td>
<td>35</td>
</tr>
<tr>
<td>Collisions</td>
<td>13</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>Significant intermolecular attractions</td>
<td>37</td>
<td>31</td>
<td>6</td>
</tr>
<tr>
<td>Gas</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement (translational, vibrational and rotational)</td>
<td>60</td>
<td>31</td>
<td>29</td>
</tr>
<tr>
<td>Collisions</td>
<td>33</td>
<td>8</td>
<td>25</td>
</tr>
<tr>
<td>SPECIFIC FEATURES of WATER</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Greater spacing in solid than liquid due to H-bonding</td>
<td>7</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Water molecules can react with each other to form hydronium ions and hydroxide ions</td>
<td>13</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>IONIC SOLUTIONS</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Contains water</td>
<td>67</td>
<td>31</td>
<td>36</td>
</tr>
<tr>
<td>High water-to-salt ratio</td>
<td>13</td>
<td>0</td>
<td>13</td>
</tr>
<tr>
<td>Hydration of ions</td>
<td>17</td>
<td>0</td>
<td>17</td>
</tr>
<tr>
<td>There is an electrostatic attraction between water molecules and ions</td>
<td>20</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>The solution is electrically neutral</td>
<td>50</td>
<td>38</td>
<td>12</td>
</tr>
<tr>
<td>Ions, not molecules</td>
<td>60</td>
<td>23</td>
<td>37</td>
</tr>
<tr>
<td>Ions, not atoms</td>
<td>67</td>
<td>46</td>
<td>21</td>
</tr>
<tr>
<td>Dynamic (movement, collisions, water exchange etc)</td>
<td>37</td>
<td>15</td>
<td>22</td>
</tr>
</tbody>
</table>
**SATURATED SOLUTIONS**

**Ionic Solid**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Average (standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ions, not molecules</td>
<td>27 (0)</td>
</tr>
<tr>
<td>Ions, not atoms</td>
<td>47 (15)</td>
</tr>
<tr>
<td>Correct ratio of ions</td>
<td>60 (46)</td>
</tr>
<tr>
<td>Structured</td>
<td>17 (15)</td>
</tr>
<tr>
<td>Closely packed</td>
<td>47 (15)</td>
</tr>
<tr>
<td>Vibrations in fixed positions</td>
<td>7 (0)</td>
</tr>
</tbody>
</table>

** Ionic Solution**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Average (standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contains water</td>
<td>43 (0)</td>
</tr>
<tr>
<td>Hydration of ions</td>
<td>10 (0)</td>
</tr>
<tr>
<td>There is an electrostatic attraction between water molecules and ions</td>
<td>7 (0)</td>
</tr>
<tr>
<td>The solution is electrically neutral</td>
<td>40 (38)</td>
</tr>
<tr>
<td>Ions, not molecules</td>
<td>43 (31)</td>
</tr>
<tr>
<td>Ions, not atoms</td>
<td>40 (38)</td>
</tr>
</tbody>
</table>

**Equilibrium**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Average (standard deviation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equilibrium represented</td>
<td>33 (23)</td>
</tr>
<tr>
<td>Interactive process</td>
<td>7 (0)</td>
</tr>
<tr>
<td>Ion-pair formation</td>
<td>3 (0)</td>
</tr>
</tbody>
</table>

**Table 2.40**  Percentage of students identifying key features in the animation and non-animation groups

<table>
<thead>
<tr>
<th>Section</th>
<th>Animation Group Average (standard deviation) (N = 30)</th>
<th>Non-animation Group Average (standard deviation) (N = 13)</th>
<th>Difference Between Animation and Non-animation Averages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Substances (out of 14)</td>
<td>5.8 (2.4)</td>
<td>2.8 (2.5)</td>
<td>3.0***</td>
</tr>
<tr>
<td>Ionic Solution (out of 8)</td>
<td>3.3 (1.8)</td>
<td>1.6 (1.4)</td>
<td>1.7**</td>
</tr>
<tr>
<td>Saturated Solution (out of 15)</td>
<td>4.3 (3.1)</td>
<td>2.2 (2.2)</td>
<td>2.1*</td>
</tr>
<tr>
<td>Test Total (out of 37)</td>
<td><strong>13.4 (5.3)</strong></td>
<td><strong>6.6 (4.3)</strong></td>
<td><strong>6.8</strong>*</td>
</tr>
</tbody>
</table>

*** significant at 0.001 level (1-tailed unpaired t-test)

** Table 2.41 Average scores obtained by the animation and non-animation groups on sections of the Images Questionnaire**

**Note:** The table provides a comparison of average scores between the animation and non-animation groups for different sections of the Images Questionnaire. The significance levels are indicated using asterisks: *** for p < 0.001, ** for p < 0.01, and * for p < 0.05.
2.4.3.1.2. Discussion of Key Features

Molecular Substances

In relation to molecular substances, the animation group was more likely to have dynamic, interactive, multi-particulate images than the non-animation group. Negligible differences occurred for key features relating to intermolecular attractions. This is consistent with the lack of effect of the VisChem animations on this particular key feature, for first-year chemistry students (See Table 2.17, page 91). Other features showing only small difference were the structure of ice and the comparative spacing in ice and water. Once again, these results are consistent with the results from the first-year study, which showed minimal progress from pre-test to post-test for these key features and perhaps lack of an animation effect (See Table 2.17, page 91). It appears that, for these key features, other methods of instruction are equally effective.

Ionic Solutions

The animation group performed significantly better than the non-animation group on the ionic solutions question. The greatest differences occurred for the key features of separate ions in solution and the presence of water molecules. Although higher than the non-animation group, the percentage of students in the animation group showing features of hydration, ion-dipole forces and a high water-to-salt ratio was rather low. Animations have been shown to be effective at portraying these features. It might be that some students only learnt these features by rote or did not fully integrate them into their mental models of a solution at the first-year level, and hence did not think to mention them. Hydration of ions and ion-dipole forces are important in higher levels of inorganic and organic chemistry. It may be that the animations need to be shown again to students in the context of relevant concepts beyond first-year chemistry, to help them maintain and develop their mental models.

Saturated Solutions

Once again, the animation group performed significantly better than the non-animation group on this question. However, differences between the groups were small for several key features. The difference in the percentages of students representing solid silver chloride as a structured lattice was negligible, and percentages were low for both sets of students. It is distressing to think that by third year, many students may not have developed the image of a
structured ionic lattice, despite some being exposed to VisChem animations. Perhaps not so surprising is the fact that very few students mentioned lattice vibrations, but those who did were from the animation group. The lack of mention of this feature may result from:

- The idea is not part of the students’ mental models;
- The fact that they were representing a saturated solution, and were not asked to directly focus on features of the ionic solid; therefore, they deemed other details more important to mention; or
- A common reluctance to mention movement.

The animation group’s representations and descriptions of the ionic solution were less detailed than they had been for an aqueous solution of barium chloride. This may have occurred for different reasons:

- The students had already represented an ionic solution and some did not feel it was necessary to put the same level of detail in again;
- There were many more ideas to cover for the saturated solution; therefore, students may have produced a simplified diagram with just the main ideas;
- Students were unable to transfer their ideas about ionic solutions to a saturated solution of silver chloride or were not sure what a saturated solution was; or
- Students were restricted for time and so represented just some key ideas.

The decrease in percentages for the solution key features also occurred for the non-animation group for some key features, but not to the extent that occurred for the animation group.

The equilibrium process occurring in a saturated solution was not shown in VisChem animations. It is, therefore, perhaps not surprising that there was little difference between the animation and non-animation groups for the “equilibrium” features. Students required knowledge of the concept and did not have an animation image to assist its recall.
2.4.3.1.3. Choice of Model for Representation of Water

Students’ choice of a model (see Table 2.42) to represent water suggests an animation effect, with the space-filling model being the most popular among the animation group. The symbolic representation was most common among the non-animation group, perhaps suggesting an instructional emphasis on the symbolic level.

<table>
<thead>
<tr>
<th>Model</th>
<th>Percentage of Students using Model from Animation Group (N = 30)</th>
<th>Percentage of Students using Model from Non-Animation Group (N = 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space-filling</td>
<td>70</td>
<td>15</td>
</tr>
<tr>
<td>Ball-and-stick</td>
<td>33</td>
<td>38</td>
</tr>
<tr>
<td>Symbolic</td>
<td>10</td>
<td>54</td>
</tr>
<tr>
<td>Circles</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Orbital</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Wedge</td>
<td>0</td>
<td>8</td>
</tr>
</tbody>
</table>

Table 2.42 Models adopted by students to represent solid, liquid and gaseous water

2.4.3.2. Attitudes Questionnaire

Table 2.43 shows the responses from the first group of third-year students relating to whether they recalled the animations shown to them in first year. Of 12 students, 10 could remember them, one had a vague recollection, and one could not recall them.

<table>
<thead>
<tr>
<th>Recall of animations?</th>
<th>Number of Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>YES</td>
<td>10</td>
</tr>
<tr>
<td>VAGUELY</td>
<td>1</td>
</tr>
<tr>
<td>NO</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.43 Number of third-year students from the first group able to recall animations from first-year chemistry

To obtain a clearer indication of how well students recalled the animations, the modified scale was used in the survey administered the following year. Table 2.44 shows the number of responses for each category on the scale. All 16 students claimed at least moderately clear and vivid recollection of the animations.
Clarity and Vividness of Recall of Animations | Number of students
--- | ---
Perfectly clear and as vivid as normal vision | 2
Clear and reasonably vivid | 9
Moderately clear and vivid | 5
Vague and dim | 0
No image at all, you cannot remember them or you only "know" that you are thinking of them. | 0

<table>
<thead>
<tr>
<th>Animation</th>
<th>Number of Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water/states of matter</td>
<td>8</td>
</tr>
<tr>
<td>Liquid water</td>
<td>1</td>
</tr>
<tr>
<td>Solid water</td>
<td>1</td>
</tr>
<tr>
<td>A gaseous collision</td>
<td>1</td>
</tr>
<tr>
<td>A water molecule</td>
<td>1</td>
</tr>
<tr>
<td>Vibration of a water molecule</td>
<td>1</td>
</tr>
<tr>
<td>Sodium chloride lattice</td>
<td>4</td>
</tr>
<tr>
<td>Sodium chloride dissolving</td>
<td>2</td>
</tr>
<tr>
<td>Hydrated ions</td>
<td>1</td>
</tr>
<tr>
<td>Autoprotolysis of water</td>
<td>2</td>
</tr>
<tr>
<td>Copper metal</td>
<td>1</td>
</tr>
<tr>
<td>Precipitation of silver chloride</td>
<td>1</td>
</tr>
<tr>
<td>Spectator ions</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.44 Recall of animations of third-year students in 2000

The remaining discussion incorporates data collected from both sets of third-year students (N = 28). Responses to all remaining questions on the survey were sorted into the following categories:

1. Most memorable VisChem animations
2. Areas of study where animations were beneficial
3. Proposed benefits of VisChem animations
4. Proposed limitations of VisChem animations

**Most Memorable VisChem Animations**

Animations most vividly recalled by students are listed in Table 2.45. Students most commonly recalled animations relating to water. Some students listed more than one animation.
Some students also mentioned memorable general features of animations: rotating or moving molecules (6), collisions (1) and three-dimensionality (1).

**Areas of Study Where Animations Were Found Beneficial**

All students who could recall the animations felt that they had helped them in first year and subsequent years. The areas of study where students perceived them to be useful are outlined in the following sections. Some students mentioned more than one topic or concept.

*Topics and Concepts in First-Year Chemistry*

Students identified a number of topic areas in first-year chemistry where they felt the animations had assisted their learning. These are listed in the following table.

<table>
<thead>
<tr>
<th>TOPIC</th>
<th>Number of Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical equations</td>
<td>3</td>
</tr>
<tr>
<td>Chemical reactions</td>
<td>3</td>
</tr>
<tr>
<td>States of matter</td>
<td>2</td>
</tr>
<tr>
<td>Structure</td>
<td>1</td>
</tr>
<tr>
<td>Bonding</td>
<td>1</td>
</tr>
<tr>
<td>Acids and bases</td>
<td>1</td>
</tr>
<tr>
<td>Kinetics</td>
<td>1</td>
</tr>
<tr>
<td>Periodicity</td>
<td>1</td>
</tr>
<tr>
<td><strong>CONCEPT</strong></td>
<td></td>
</tr>
<tr>
<td>Three-dimensionality</td>
<td>3</td>
</tr>
<tr>
<td>Interactions</td>
<td>3</td>
</tr>
<tr>
<td>Hydrogen bonding/clusters in water</td>
<td>2</td>
</tr>
<tr>
<td>Vibrations</td>
<td>2</td>
</tr>
<tr>
<td>Multi-particulate nature of matter</td>
<td>1</td>
</tr>
<tr>
<td>Solvent effects in organic chemistry</td>
<td>1</td>
</tr>
<tr>
<td>Cloud-like appearance of atoms</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.46  Topics and concepts in first-year chemistry assisted by the VisChem animations
Subjects, Topics and Concepts in Subsequent Years of Study

Students identified various areas of study from subsequent years of their science degree where they felt their recall of VisChem animations had assisted them. These areas of study are listed in Table 2.47.

<table>
<thead>
<tr>
<th>SUBJECT</th>
<th>Number of Students</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inorganic Chemistry</td>
<td></td>
</tr>
<tr>
<td>Transition metals and d-orbitals</td>
<td>1</td>
</tr>
<tr>
<td>Complexation</td>
<td>1</td>
</tr>
<tr>
<td>Organic Chemistry</td>
<td></td>
</tr>
<tr>
<td>Mechanisms</td>
<td>2</td>
</tr>
<tr>
<td>Intermediates</td>
<td>1</td>
</tr>
<tr>
<td>Molecular structure</td>
<td>1</td>
</tr>
<tr>
<td>Steric crowding</td>
<td>1</td>
</tr>
<tr>
<td>Physical Chemistry</td>
<td></td>
</tr>
<tr>
<td>Kinetics: effect of molecular shape on reaction rates</td>
<td>1</td>
</tr>
<tr>
<td>Analytical Chemistry</td>
<td></td>
</tr>
<tr>
<td>NMR</td>
<td>1</td>
</tr>
<tr>
<td>IR spectroscopy</td>
<td>1</td>
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<tr>
<td>Biochemistry</td>
<td>1</td>
</tr>
<tr>
<td>Materials science</td>
<td>1</td>
</tr>
<tr>
<td>Geochemistry</td>
<td>1</td>
</tr>
</tbody>
</table>

| CONCEPT                        |                    |
| Behaviour of particles and chemical reactions | 5 |
| Multi-particulate nature of matter | 1 |
| Equilibrium                    | 1                  |
| Polarity                       | 1                  |

Table 2.47  Subjects, topics and concepts in subsequent years of study assisted by the VisChem animations

Potential Benefits

Table 2.48 summarises the benefits, identified by students, of exposure to VisChem animations. Each benefit is supported by a sample quote. The number of students indicates how many students mentioned this idea, at least once, somewhere in their attitude survey. Most benefits seem to be related to an improved ability to visualise the molecular world of matter. A complete list of quotes is given in Appendix D.
Chapter 2  Effectiveness of VisChem Animations

<table>
<thead>
<tr>
<th>Proposed Benefit</th>
<th>No. students</th>
<th>Sample Quote</th>
</tr>
</thead>
<tbody>
<tr>
<td>Improved Visualisation</td>
<td>14</td>
<td>“helped in developing visual images”</td>
</tr>
<tr>
<td>Assisted with Idea of Movement and Interactions</td>
<td>13</td>
<td>&quot;They helped me visualise interactions of different molecules.”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>“It is a constantly moving environment.”</td>
</tr>
<tr>
<td>Improved Understanding</td>
<td>10</td>
<td>“increased my ability to understand concepts”</td>
</tr>
<tr>
<td>Made Learning Easier</td>
<td>8</td>
<td>“visualising made chemistry easier”</td>
</tr>
<tr>
<td>Interpretation of Macroscopic Phenomena</td>
<td>8</td>
<td>“You can imagine the molecules, atoms, structures, on a molecular level instead of just a macro level.”</td>
</tr>
<tr>
<td>Aroused Interest/Curiosity</td>
<td>6</td>
<td>“increased interest in chemistry”</td>
</tr>
<tr>
<td>Improved 3D Thinking</td>
<td>4</td>
<td>“Animations helped me think in a 3-dimensional way with all molecules.”</td>
</tr>
<tr>
<td>Good Foundation for Further Study</td>
<td>4</td>
<td>“Understanding of first-year chemistry ideas and concepts made a good foundation for years that followed.”</td>
</tr>
<tr>
<td>Application</td>
<td>2</td>
<td>&quot;The animations give a guide that can be applied in other situations, it’s the visualising and thinking about them which made them most useful.”</td>
</tr>
<tr>
<td>Improved Ability to Draw Molecules</td>
<td>1</td>
<td>“They helped me to draw molecules.”</td>
</tr>
</tbody>
</table>

Table 2.48  Proposed benefits of exposure to VisChem animations

Potential Limitations

Two students felt that the animations may have been more beneficial in subsequent years of chemistry had they been used beyond first-year chemistry, as the following quote shows:

“The visual communication was not supplemented in further years (animations)”

Quite astutely, one student also made the following point:

“Whilst I think the animations were helpful to me in understanding chemistry, they weren’t sufficient on their own in communicating other important concepts.”

*  

The above data suggest that students overwhelmingly support the use of VisChem animations in the teaching of chemistry. Animations are believed to help in a number of key topic areas in both first year and subsequent years of chemistry. Proposed benefits suggest the possible
incorporation of animations into instruction to improve the popularity and decrease the difficulty of chemistry. Changes in students’ attitudes towards chemistry after exposure to VisChem animations, including enjoyment or interest in the subject and perceived difficulty, are examined in Chapter 3. Animations had a positive effect on helping students develop multi-particulate, dynamic and interactive images. Students’ comments on the limitations of their use are also positive, supporting the development of further animations for higher level chemistry and continued use of these animations in new contexts in advanced chemistry classes. This re-exposure may help students maintain or develop the detail in their mental models.

2.4.3.3. Interview Analysis

In total, seven students who had seen VisChem animations in first-year chemistry participated in interviews. Students 1–4 (L1–L4) were from the first group of third-year students; Students 5–7 (L5–L7) from the second group. Each interview will be discussed separately. Students’ responses are sorted according to the following categories:

1. Images and Ideas
2. Recall of Animations
3. Animation Interpretation
4. Modifications to Representations

L1.

L1 studied first-year chemistry two years prior to completing the questionnaire. He claimed to remember animations from first year. This student identified a total of 10 key features on the questionnaire: five for molecular substances, three for ionic solutions and two for saturated solutions. During the interview, he was asked about his image of a saturated solution and was shown the animation of AgCl precipitating.

Images and Ideas

In his questionnaire, L1 drew the representation of a saturated solution shown in Figure 2.24. He did not provide a key for his diagram. When questioned about his representation, L1 labelled the smaller circles as silver and the larger ones chloride.
During the interview, the student described the bonding in the solid as being ionic, yet seems to have represented the silver and chloride as “molecules”.

When probed about the meaning of the term “saturated solution”, L1 realised he had not represented water molecules, and recalled the electrostatic attractions between water molecules and ions.

L1: that's another thing I didn't think of. You'll have water molecules surrounding so the oxygen being the negative surrounding the silver ion, positive, and ripping it away from the or inhibiting the chloride ions from interacting with it...But then you'd have the occasional bumping of the silver and ions in solution but also that'll be pulled apart by the water molecules.

Figure 2.24 shows the modification L1 made to his drawing to represent this idea.

The above quote also demonstrates this student’s ability to conceive of molecular-level processes as being interactive and dynamic. This student, however, was apparently not aware of the equilibrium process occurring between the solid and solution, but instead believed that the solid would just continue to dissolve until the solution became saturated.

L1: I thought the water molecules would come to the solid surface in the solution…and actually collide with the surface and the collision would cause breaking away of the silver and the chloride and then slowly, slowly the silver chloride, the solid would become saturated.

Figure 2.24 L1’s representation of saturated silver chloride solution: initial representation (blue, black, red), modifications (green)
Recall of Animations

L1 claimed to recall only the animations of water.

L1: I can remember very vividly the water, the H$_2$O molecule and also the solid structure of the solid ice of water. Yeah, I can remember that vividly.

He did not use the recall of animations to help him answer the question on silver chloride.

Animation Interpretation

When viewing the animation of AgCl precipitation, L1 pointed out the orientation of the water molecules around the ions.

L1: You’ve got the hydrogen bonds attached to the chloride…hydrogen bonds on the water attached to the chloride. You got oxygen attached to the silver…

Modifications to Representations

After a first viewing of the animation, L1 decided that rather than solid silver chloride continuing to dissolve into the solution, silver and chloride ions from the solution would be precipitating out. Only after extensive discussion did he come to the understanding that both occur at equal rates.

L1: So as these leave, some more will come in. So the bombardment of water will take some off…but it will also replace some.

L2.

L2 first studied first-year chemistry three years prior to completing the questionnaire. He claimed to remember animations from first year. He identified a total of seven key features on the questionnaire: five for molecular substances, one for ionic solutions and one for saturated solutions. During the interview, he was asked about his image of an aqueous solution of barium chloride and was shown the animation of an aqueous solution of sodium chloride.

Images and Ideas

In the questionnaire, L2 represented an aqueous solution of barium chloride as a collection of bent barium chloride molecules as shown in Figure 2.25. He was questioned about the meaning of the term “aqueous”.
Interviewer: What do you understand by the term “aqueous”?

L2: Aqueous, okay...it’s a...liquid.

Interviewer: A liquid?

L2: Yep, which is very close to a solution or like...another word? ...water...like a mixture of water or some other things like so, aqueous, it’s basically liquid.

Interviewer: ...What’s the difference between liquid and a solution?

L2: A solution is like a mixture of things...a liquid is...similar to water, its pure, pure liquid... This is not pure...It is a mixture of two things.

Interviewer: What are the two things?

L2: The barium and the chloride.

This student seemed confused by the differences between the terms “liquid”, “aqueous” and “solution”, as well as the difference between pure substances and mixtures. Confusion over the former perhaps resulted in his inability to correctly represent an aqueous solution.

Figure 2.25  L2’s representation of an aqueous solution of barium chloride

Recall of Animations

This student claimed to recall animations of water when filling out the questionnaire.

L2: ...the one that I really remember the most is water.
He did not recall any animations when constructing his image of an aqueous solution of barium chloride.

Animation Interpretation
L2 struggled with the interpretation of the animation of an aqueous solution of sodium chloride. He could recall being shown the animation, but could not discuss what it represented, being unable to identify a chloride ion. Interestingly, he did not even recognise a water molecule. This may have been due to the fact that he did not expect water molecules to be present, considering his existing notion of an aqueous solution.

Interviewer: Do you remember this animation at all?
L2: I think so yeah…cause I remember the green thing, when he like sort of pointed...he mentioned it…pointed on the green molecule [chloride ion].
Interviewer: green sphere? And do you remember what he might have said about it?
L2: …not really but like I can remember from that that green sphere he pointed at it at that time and started talking about it.
Interviewer: What features do you notice about this solution?
L2: What's that exactly? [points to water molecule] Is that the same as those or…?
Interviewer: There’s a green and a silver one. This is sodium chloride. What do you think the silver and green might be?
L2: …Green could be sodium and the silver… You know the red and white…is that?
Interviewer: This is a water molecule.
L2: A water molecule, okay.

Modifications to Representations
After initially viewing the animation of an aqueous solution of sodium chloride during his interview, L2 proposed that he could modify his drawing by adding water molecules, and would include a high ratio of water to ions.

L2: I would say there are some other water molecules around, going around there…the amount of chloride present in the solution as well…like it’s not as we can see here, like you know, water molecules is less than chloride.

The student was shown the animation again, with all the relevant features pointed out for him. He was then asked to draw a final representation of an aqueous solution of barium chloride.
His representation is given in Figure 2.26. It shows the separation of the barium and chloride. He explained his modifications as follows:

L2: I would say it’s going to be a similar type of thing, except in water all around and you’ve got the barium and the chlorine moving around the system as well.

Figure 2.26  L2’s modified representation of an aqueous solution of barium chloride

L3.

L3 first studied first-year chemistry three years prior to completing the questionnaire. She claimed to remember the animations from first year. This student identified a total of 21 key features on the questionnaire: seven for molecular substances, five for ionic solutions and nine for saturated solutions. During the interview, she was asked about her image of a saturated solution, and was shown the animations of silver chloride precipitating and an aqueous solution of sodium chloride.

Images and Ideas

Although L3 represented a number of important key features in her representation of a saturated solution (see Figure 2.27), she did not mention the occurrence of an equilibrium process. In her representations of ionic solutions, she did not show hydration.

L3 was asked about bonding in the solution. She made a distinction between bonding and attraction.
L3: There’s just attraction in the solution… the water comes in and grabs…the solid at the interface you have molecules more attracted to the water and that’s why they break free…and that breaks the bonding so… maybe there’s an attraction, but I’m not sure if there’s a bonding… they’re just really… free in the solution.

When probed about how the water breaks free some of the ions, she elaborated on her response, and mentioned electrostatic interactions between silver and chloride ions and water. However, it was not clear if she understood that each water molecule is polar or whether she believed that the positively charged hydronium ions and negatively charged hydroxide ion pulled ions from the lattice. Ultimately though, she believed that sodium and chloride float “free in the solution”.

L3: Because you have the water, the oxygen… is negatively charged and it will come in and it will attack your silver which is positively charged and it’ll have a greater attraction than the silver will have with the chloride and so the silver can break free and similarly the hydrogens of the water if it’s, if you get H_3^+ and it’s very positive or like you get an OH molecule which is very negative and it gets attracted to… that’s because you’ve got to remember water is like at pH 7 for a reason because… there’s… the hydroxide ion and the hydronium ion… And that’s how I thought of it. So you get the hydronium ions trying to go for the chloride and you get the hydroxide ions going for the [sodium] and that attractions greater and hence they break free. That’s how I always thought of it.

Although this student did not seem to realise that an equilibrium process occurs in a saturated solution, she certainly did not perceive it as a static system.

L3: Every time they go to rejoin, the water comes and pulls them off and that’s why you get this. Most of the reaction happens at the interface. You don’t get much in the two layers. But when you mix the solution see you give water a chance to get in between the lattice and break it and it breaks again and sometimes it dissolves. It’s just it… it’s all about attraction.
Figure 2.27  L3’s representations of saturated silver chloride solution: initial representation (black), first modification (green), second modification (blue)

Recall of Animations

Once again, this student most vividly recalled the animations of water.

L3: From then on, I started viewing things like this…especially water molecules.

She did not recall any animations relevant to the aqueous solution of barium chloride. She felt that the animations had been particularly useful in helping her visualise chemical systems in chemistry and biochemistry. They helped her to believe the ideas being taught.

Quote 1:

L3: From when he was talking about water and ice and he had the two different lattices and you could see the differences.

Interviewer: Do you think you would have ever developed that image of the vibrating…if you hadn’t seen the animations?

L3: No, they were really good. It’s good to visualise chemistry, otherwise it’s just too…radical. I can’t sit here and think, oh yeah, there’s a water molecule doing this. You don’t believe it until you…

Interviewer: How have these helped then? They’ve helped you…

L3: Believe
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Quote 2:

Interviewer: Well prior to seeing these animations, did you attempt to visualise chemistry?

L3: I tried but no, not like that…You need a push then now I do…It’s really helpful in biochemistry too.

Animation Interpretation

On the first viewing of the animation of silver chloride precipitating, this student concentrated on the idea of solubility, as the discussion just prior focused on the solubility of silver chloride. She concluded that silver chloride is insoluble. This prompted her to reconsider her conception of a saturated solution of silver chloride.

After some discussion, L3 was shown the same animation again, with some key features pointed out (movement and orientation of water molecules). The animation of an aqueous solution of sodium chloride was also shown to emphasise the orientation of the water molecules. The student recognised this animation.

Modifications to Representations

After viewing the animation of silver chloride precipitating, this student decided to modify her representation of a saturated solution by adjusting the ratio of ions to water in the solution. More water and fewer ions were represented, to accommodate the idea that silver chloride is insoluble (See Figure 2.27). The student explained why there might still be some ions in solution as follows:

L3: Maybe they didn't bump into each other. Maybe you'd have a lot of water in the top layer then cause that's what keeps them apart and that's why you get the occasional ions.

She seemed unsure of whether or not all the ions would eventually precipitate out.

L3: Eventually I guess, yeah. Yeah, they'll just, maybe they'll just form crystals. Yeah and in the end you'll just maybe get two layers.

After key features of the animations were pointed out to this student, she added the hydration and orientation of water to her representation (see Figure 2.27).
L4.

L4 first studied first-year chemistry three years prior to completing the questionnaire. She claimed to remember animations from first year. This student identified a total of 14 key features on the questionnaire: eight for molecular substances, three for ionic solutions and three for saturated solutions. During the interview, she was asked about her image of an aqueous solution of barium chloride and was shown the animation of an aqueous solution of sodium chloride.

Images and Ideas

This student represented an aqueous solution of barium chloride simply as separate barium and chloride ions (see Figure 2.28). She was, therefore, asked about her understanding of the term “aqueous”.

L4: It's a liquid medium of…whatever ions it's in like there's no water, it's just liquid.

There was obvious confusion between a pure liquid and an aqueous solution. She was, therefore, asked about differences between the meanings of the terms solution, aqueous and liquid.

L4: Liquid can be anything that can, that has particles that can move freely…it can occupy a container or takes the shape of the container…you add water to make a solution…a sugar solution…that dissolves into it so that becomes the solution and if you have aqueous, if you talk about, like take sugar and melt it. That's the aqueous bit of sugar.

This statement revealed a misunderstanding of the differences between melting and dissolving.

This student did, however, conceive of the solution as a dynamic system.

L4: That’d be free to move but like that’d be sliding over each other, like the ions would be still around the barium.
Recall ofAnimations

L4 claimed to recall the animations of water when answering the water questions in the questionnaire.

L4: He actually showed us the, what do you call it, the bent shape… It was [the lecturer] that was showing that it could move in any direction because it was in a liquid format…they could slide over each other and that’s how he showed it to us.

She also thought about an animation of sodium chloride when answering the question about an aqueous solution of barium chloride

L4: sodium chloride…they had the sodium ions were smaller than the chloride ions...

Interviewer: And you were thinking about that animation when you were thinking about this one? [BaCl₂]

L4: Yeah.

Animation Interpretation

This student was told what each species in the animation represented. She pointed out some rather subtle points in the animation, and provided explanations for what she was seeing.
L4: It's the water molecules that keep them separate isn't it? And the other water molecules in the solution that kick off the other water molecules that are attached to the chloride ions or the sodium ions and then gets themselves attached to the chloride ions...they're trying to bump into the water molecule that's attached to it and then get themselves attached...That bit is the bonds between the sodium and chloride is weak than compared to the bonds between the water molecules and the sodium ions and the chloride ions and the water molecules. So that's why they keep them away...They do get attracted but they, the water molecules keep them separated.

After she modified her drawing, the animation was shown again, with key features pointed out. The student immediately sought to discover how many water molecules surrounded each ion. She misinterpreted the voice-over and concluded that there were three. The interviewer corrected this misinterpretation and pointed out the six hydrating water molecules. The student was then asked to explain the hydration.

L4: Oxygen is negatively charged and...unlike poles attract...unlike charges attract and that would mean chloride, it's negative, the positive, the hydrogen ions would be attracted.

The interviewer then pointed out all the other relevant key features.

**Modifications to Representations**

This student radically reconstructed her drawing in light of the animation. She drew a dynamic system in which water molecules exchanged with other water molecules around the ions, and barium and chloride ions attracted one another. She described her representation as follows:

L4: ...I would put in water molecules and yeah exactly presentation like. That would be chloride molecules coming to barium. That animation would be shown and then there'd be water molecules around the chloride ions and water molecules around the barium ions...separating them...I don’t know how many water molecules are supposed to be around there but, I didn’t check that.

Although she represented hydrating water molecules, she did not consider the orientation of these molecules around each ion (see Figure 2.28).

After the second viewing of the animation, with key features pointed out, the student drew another representation, orientating the water molecules around the barium and chloride ions. However, she represented the orientations incorrectly (see Figure 2.28).
L5.

L5 first completed first-year chemistry two years prior to completing the questionnaire. He claimed to have clear and reasonably vivid recall of the animations from first year. He identified a total of 27 key features on the questionnaire: seven for molecular substances, eight for ionic solutions and 12 for saturated solutions. Considering the sophistication of this student’s images, he was not asked to discuss any particular response(s) further nor whether he wanted to modify his drawings after seeing animations. He was shown animations of sodium chloride dissolving, aqueous solution of sodium chloride and silver chloride precipitation.

Recall of Animations

This student was asked to identify some of the resources responsible for helping to develop his images. He spontaneously brought up animations from first-year chemistry.

L5: Well, this one, the silver chloride…I remember an animation in first year that [the lecturer] did and I don't think it was silver chloride, I forget what it was. I think it might have actually been a liquid turning into a gas, like liquid H₂O… I really think that I based that diagram on what I saw on that screen, because that image just came back to me as soon as I read the question.

L5: I remember a similar sort of thing for barium and chlorine, but I don't think it was barium chloride. I think it was either silver chloride or sodium chloride in solution. Yeah, the hexagonal water. All I remember is that there was a hexagonal pattern and the animations would havezoomed around and there were hexagonal tunnels all throughout the ice structure.

He felt though that subsequent study had helped him develop his images further.

L5: I remember those animations but I think probably the stuff I’ve learnt since then has sort of helped me build up a better mental picture of it.

Animation Interpretation

This student was first shown the animation of sodium chloride dissolving. Although he could not recall having seen this animation before, he was able to readily describe what it represented.

L5: I can see already that that's an ionic salt of some sort. Yeah, it’s vibrating cause, the idea is that they do vibrate cause of the thermal energy… Okay, it's dissolving. Yeah the positive and the negative charges of the water are lining up, so that positive is attracted to negative, pulling it off.
He was then shown the animation of an aqueous solution of sodium chloride, which he recollected. He referred to the attraction of a sodium and a chloride ion in solution as an equilibrium whereby a “solid NaCl molecule” is formed, stating that, “the likelihood of seeing those two come together at the molecular level is absolutely tiny and small.”

L5: I think this is the equilibrium one of the dissolved salt and there’s water floating around and the positives [mumbles] and the water’s attracted to the negatives and yeah that was, what that was was equilibrium of the solid forming rather than the dissolved one. I remember this animation… The positives and negatives attracting to each other again.

Interviewer: Which ones?

L5: Of the waters together and of the, there was some, you could sort of see the green ion in the background and I wasn’t paying attention to which end of the water molecule’s attracting to it. Just right at the very start.

Interviewer: Okay

L5: There, that one. It sort of, it’s come into view since it began. I can’t really see which sides of the water molecule’s attracted to it though.

Interviewer: What do you think that green thing is?

L5: Probably a negative ion…because I tend to visualise all these things as sodium chloride… Chloride’s bigger than the sodium.

Finally, L5 was shown the animation of silver chloride precipitation, which he also claimed to recall. He quickly identified what the animation was trying to show, pointing out a number of important features. Features that he did not recognise instantly, such as the presence of the spectator ion, did not confuse him for long. He was able to use his existing knowledge to interpret such details.

L5: This is water again. This is the precipitation. I remember this one as well. Not very clearly though… Yeah, the water molecules are clumping the ions together through all the electrostatic attractions and grouping them together. There was some big blue thing there but I don’t know what it was… Oxygen… Nitrate?

Interviewer: Okay, perhaps it’s a nitrate ion. What would that be doing in there?

L5: Well you’d have to, if that salt’s insoluble you’d have to mix one solution of one ion with one solution of another and… all nitrates salts are soluble… so if that was say silver chloride and you put in silver nitrate, you’d have some nitrate floating around.

Interviewer: Okay. What do we call those sort of ions?

L5: Spectator ions.

Interviewer: Yeah.

L5: Yeah again the electrostatic attraction and the vibrating… I have a recollection of this animation but I don’t remember the vibrating. I just remember the things grouping together.
L6.

L6 first passed first-year chemistry five years prior to completing the questionnaire. He claimed to have clear and reasonably vivid recollection of the animations from first year, although he believed that only a few animations were shown in the year he completed first year as it was not long after the lecturer began to use them. He identified a total of 14 key features on the questionnaire: five for molecular substances, three for ionic solutions and six for saturated solutions. During the interview, he was asked about his images of an aqueous solution of barium chloride and saturated solution of silver chloride. He was shown the animations of sodium chloride dissolving, an aqueous solution of sodium chloride and silver chloride precipitating.

*Images and Ideas*

In the questionnaire, L6 represented an aqueous solution of barium chloride as separate ions each surrounded by water molecules (see Figure 2.29). The orientation of the water molecules was incorrect, however. This was the first thing that L6 noticed when shown his representation.

L6: Basically the only thing wrong with this is I’ve got the…negative van der Waal’s forces in the oxygen, attached to the…chlorine.

He described his image of the solution as follows:

L6: …I’d describe the, is it atoms of barium, chlorine as little balls or circles…Then I’d have water attached to each of them.

Interviewer: Are you counting, what?

L6: I’m trying to remember whether it’s…whether there’s four attached or six, …whether it’s square planar or hexagonal, square planar or something else…

Interviewer: …So basically what you’ve described to me is what you’ve drawn here. Separate ions of barium and chloride surrounded by water molecules and you mentioned earlier as well that the water molecules are attached in a certain way. Can you describe that?

L6: …There’s actually three places on a…water molecule with charges. Like the oxygen carries a slight negative charge and the two hydrogens carry a slight positive charge…in the diagram you try to have the hydrogen attached to a negative ion, with the oxygen represented as being attached to a positive ion.

Interviewer: Okay. Now besides these two complex ions, is there anything else in there?

L6: Lots of water, bits of other things.
Figure 2.29  L6’s representation of an aqueous solution of barium chloride

L6 was also asked to describe his image of a saturated solution of silver chloride (Figure 2.30). He immediately pointed out that he hadn’t represented the water molecules.

L6:  This one I did fairly basically because I didn’t have them all surrounded by hydrogen, water.

In his original drawing, this student represented the solid silver chloride with a line and the label “Solid AgCl”. He was therefore asked to describe his image of solid silver chloride at the molecular level. He explained that the structure would be different depending on whether the solid was a powder or “actual solid”, due to different lattice planes and different angles. He was asked to describe a perfect crystal.

L6:  …Just a solid chunk of it like a single crystal you’d have a fairly ordered lattice structure.

Interviewer:  Okay, well imagine that it’s a perfect crystal and you’ve got that fairly ordered lattice structure. Can you describe to me what that looks like? … Just like basic, first-year level type description.

L6:  Okay, from what I can remember is silver and chlorine ions have fairly similar ionic radius, so I’d try and demonstrate that by having the little circle things the same size.

Interviewer:  Okay, do you want to draw it again for me with the red pen?

L6:  Something like this. If you want to get really fancy you have like little holes and stuff like that.

He made the modification shown in Figure 2.30. He was then questioned about the bonding in silver chloride.
Interviewer: Would the bonding between that chloride and that silver ion be different from the bonding between that chloride and that silver ion?

L6: It shouldn’t be but sometimes it could be.

Interviewer: When could it be?

L6: …Just like a fracture of a cell surface or its actually at the edge because you won’t get the same balancing as you would in like the centre.

It is obvious that during his study, this student had developed his images beyond a first-year level.

Recall of Animations

When first asked about his recall of the animations, this student showed only vague recollection of “a little water molecule bouncing all over the screen…The water molecule just like vibrating and bouncing all over the place”. Later, he seemed to remember a little more about the animations of water and stated that the animation of ice sprung to mind when answering the questionnaire.

L6: One of the ones he showed us was a pile of water molecules and he went through all the different, different phases, like ice, liquid and gas.

L6: Yeah, the only one that really sprung to mind was the ice one…how it all forms like little hexagonal tube type things…I was just amazed how it went from disordered mass to a very ordered mass.

He did not recall any animations relevant to the aqueous solution of barium chloride.

Figure 2.30 L6’s representation of saturated silver chloride solution: initial representation (blue), modifications (red)
Animation Interpretation

L6 was shown the animation of sodium chloride dissolving. He provided a good overview of the animation, pointed out lattice vibrations and discussed what was occurring in terms of energy. He could not recall seeing this animation before.

L6: Okay. Well this just looks like the surface of a cell...just indicating lattice vibrations. Just looks like water dissolving the lattice, breaking it up and forming complexes.

Interviewer: Okay. That was a good sort of overview of what’s going on. Do you want to point out any more specific details that you notice?

L6: Like the lattice vibrations.

Interviewer: Yep, you pointed that out. That was good.

L6: ...how the water molecules attach from the outside in...not just in any old way and it takes a fair bit of energy to actually rip the ions off the lattice itself.

Interviewer: So what suggests that it takes a fair bit of energy?

L6: ...the fact that it takes a long time for... It’s like a tug of war really.

Next, L6 was shown the animation of an aqueous solution of sodium chloride. He pointed out some rather obscure details such as the exchange of water molecules around the ions and hydrogen bonding.

L6: Yeah, bouncing around...that looks like an, is it, a complex and every now and then its actually swapping a water molecule.

Interviewer: Okay, so you’re noticing the water molecule exchange, that’s pretty good.

L6: Some of the water molecules are actually floating around in pairs as well. I saw a couple of pairs in there.

Interviewer: ...What do you think it might be an animation of?

L6: A solution of some description... I think it’s showing how difficult it is for a fairly soluble ion, ah molecule to actually crystallise out.

He also noticed that the number of water molecules that could surround each ion was restricted. When questioned, he was able to identify the positive and negative ions.
L6: They’re more likely, by the looks of it, they’re isolated from the rest of the water molecules. Only a set number can actually interact with them.

Interviewer: …Can you tell what charge that might have?

L6: That one looks like negative…because the hydrogens are actually attached to it.

Interviewer: Okay, yep and the other one…

L6: Positive.

Finally, L6 was shown the animation of silver chloride precipitating. His description of this animation was rather vague. He could not recall having seen the animation before. He once again explained what he was seeing in terms of energy.

L6: This…a solution…a chemical actually dissolving out of solution…that’s the wrong way so, it’s solidifying, it’s coming out of solution.

Interviewer: So you’ve got a lattice structure forming…Why might that happen?

L6: If the lattice energy is a lot less than the energy of the complex…energy of formation, that’s the one I was looking for, not lattice energy, the energy of formation for the molecule is less than the complex. It’s actually energetically favourable.

Interviewer: …Is there anything else you notice in there?

L6: Well, apart from the, what’s it, that really weird little red one.

The student did not recognise the spectator ion. Even after extensive questioning relating to precipitation reactions, he believed the particle to be an impurity that “could be from the water itself, you could have started off with impure solutions, it could have come off the actual glass or glassware if you hadn’t washed it properly.” Finally, he suggested it might be a nitrate because “you’d expect a…nitrate to be floating around in the solution” after having mixed two solutions together to form a precipitate.

*Modifications to Representations*

This student did not wish to make any modifications to his representations.

L7.

L7 first studied first-year chemistry two years prior to completing the questionnaire. He claimed to have clear and reasonably vivid recollection of the animations from first year. This student identified a total of 14 key features on the questionnaire: eight for molecular substances and six for ionic solutions. He did not have time to attempt a representation of a
saturated solution. During the interview, he was asked about his images of the three states of water and an aqueous solution of barium chloride. He was shown animations of sodium chloride dissolving, an aqueous solution of sodium chloride and silver chloride precipitating.

Images and Ideas

This student had quite detailed images of the liquid and gaseous states of water, although he confessed that his concept of solid water was not clear.

He had a dynamic image of liquid water.

L7: I imagine liquid water as being, okay, I imagine it in a container and in the middle of it all, if you like, I imagine individual water molecules moving around in random directions, different speeds and bumping into one another…and at the surface, some of them are escaping into the atmosphere.

He described gaseous water as:

L7: Water molecules with more space in between them than you would have in the liquid case, again moving in different directions at different speed and bumping into each other a lot less frequently…moving faster cause they’ve got more energy.

He stated that solid water was highly structured and vibrated, but he was not sure why it adopted that structure.

L7: Like a three-dimensional structure where I suppose there would be some little motion, vibration of the molecules in the structure but why, the question that I ask myself is why does it form that structure and I don’t have an answer.

When asked about his image of an aqueous solution of barium chloride (see Figure 2.31), he provided the following description:

L7: mainly comprised of barium ions that are surrounded by water molecules that have been attracted to it and chloride ions surrounded by water molecules that have been attracted to them…because it’s an aqueous solution most of the particles in the image in my mind are water molecules with only a few of them being barium ions and chloride ions.
Recall of Animations

L7 discussed his opinion and recall of the animations quite extensively. He felt that he had used his memory of the animation of ice to answer the relevant question in the questionnaire.

L7: I think I only encountered it once in a textbook… the discussion of solid water and I didn’t really pay that much attention and so I remember the animation that was shown to me in first year and the main features of that that I remember is that it was highly structured.

Like a previous student, he felt that his images were developed from a combination of having seen the animations and his exposure to other resources.

Interviewer: Do you think when you were answering this and when you were describing the liquid and the gas to me that you also thought about those animations? …

L7: …Yeah, I think so. It’s hard to tell. It’s hard to know whether I would’ve actually… because those animations weren’t the only source of information that I received of course because I read books as well and it’s hard to know whether I imagine those things or whether it’s a combi, I’m sure it’s probably a combination of things.

He could not recall an animation relevant to the aqueous solution of barium chloride question and, like other students, most vividly recalled animations of water.

L7: I’m pretty sure we were shown some but…first year… for me was a while ago and… the animations I do remember are mainly… water.

He did acknowledge, however, that the animations might have contributed to the development of his image.
This student also made some other pertinent comments regarding the animations. He felt that they were useful for confirming images one had developed oneself, and for demonstrating chemical change.

L7: I think probably the main benefit of animations is that they, they confirm things that, they confirm an impression that you get from reading a book. You can read a book and build up an impression of what’s going on and then when you see an animation you think yeah…my impression is correct or it’s not correct. In my case, it was correct so that’s good. That’s quite encouraging.

L7: Certainly there are things which some of the more, for instance, like when a water molecule ionises to become a hydroxide ion or a hydronium ion, you know that that’s easier I think to convey in an animation than it is in a textbook…that’s what animations are particular good for. Showing changes.

In criticising the animations, he felt that they were misleading because they appeared to represent chemical reactions as mechanical and deterministic processes, lacking the element of randomness.

L7: The one thing actually, that I do remember quite distinctly now, when I first saw these animations it gave me, it gave rise to the question in my minds…how do all these things happen? As in looking at this animation for instance, it shows water molecules, or this is what I think when I see it, sort of carrying this structure along…like a bunch of little robots…the animation depicts something that…I think really happens by chance as a very deliberate and deterministic sort of process and I think that’s slightly misleading.

L7: Surely it must be possible to make it look less deliberate, less mechanical. Maybe by showing, you know, various complexes heading off in different directions and not, not going straight into the structure. Yeah, the odd one or two going into the structure but not, not all of them.

**Animation Interpretation**

This student gave a relatively comprehensive overview of the animation of sodium chloride dissolving, pointing out many important key features. Seeing the animation again triggered his recall of it.

L7: That’s sodium chloride crystal…the big green balls I think are…the big green balls are the chloride ions and the little balls are the sodium ions…and the obviously those things are water molecules being poured on top of the crystal and this is the process of dissolution. The water’s dissolving the salt crystal.

L7: the orientation of the water molecules toward the various ions…on this side of the water molecule these are the two hydrogen ions and that’s ah the positive, positively charged side of the molecule and…that makes sense that they should attach to the chloride ion in that orientation because the chloride ion’s negatively charged and when you look at the way the water molecules attach to the sodium ion, they do so in the reverse sense because sodium ions are positively charged and that’s the negatively charged side of the water molecule… The other feature that I noticed is that the ions in the crystal are vibrating.
This student’s description of the aqueous solution of sodium chloride animation was also quite detailed.

L7: I’m seeing dissolved sodium chloride in water…so an aqueous solution of sodium chloride and again the ah chloride ions and sodium ions have formed complexes with the water molecules…The feature of these complexes that I can recognise is what I was speaking about in the last animation and that was the orientation of the water molecules with respect to different ions… One of the other things that is apparent in this animation is that the…water molecules that have formed the complex with the ions are being replaced…and also there’s one episode in the animation which the, it appears that a sodium ion and a chloride ion are brought together and then move apart again…there…I imagine they’re attracted to one another because of their opposite charges.

As with other students, the level of description was lower for the animation of silver chloride precipitating, even though he recalled the animation. This student was also bewildered as to what the blue particle represented.

L7: It’s trying to depict the precipitation of the salt… I don’t know what that is though… that blue bit.

After much deliberation, this student still had not worked out what the blue particle represented. When he was told what solutions were mixed, he worked out that the blue particle must be a nitrate ion.

**Modifications to Representations**

Viewing the animations only clarified one point for this student, regarding the number of hydrating water molecules around the chloride ion.

L7: It answers my doubt about how many water molecules complex with chloride ions although I must admit I wasn’t actually counting…six by the look of it.

## 2.4.3.4. Summary of Interview Findings

**Images and Ideas**

The sophistication of individual students’ images varied considerably, from being comprehensive, with an understanding of the underlying principles, to having a quite limited understanding with misconceptions.

Several students (L1, L3, L4 and L7) showed evidence of having interactive and or dynamic images. L5 and L7 showed evidence of having built up their mental models of the substances
shown in animations beyond a first-year level, supporting the idea that animations can serve as a foundation for further study.

During the interviews, some students recalled features they had failed to include in their questionnaire responses, such as the inclusion of water molecules in solutions (L1 and L6) and the orientation of water molecules around ions (L1 and L4).

Despite having been taught with animations in first year, two students (L2 and L4) had misconceptions regarding the difference between liquids and aqueous solutions. This attests to the fact that some misconceptions can be deeply held and difficult to remedy (Pines & Leith, 1981).

**Recall of Animations**

As suggested by the survey data, the animations of water were most easily recalled. All interviewed students claimed that recall of the water animations assisted with their responses to the relevant questions on the images questionnaire. The animation of an aqueous solution of sodium chloride was cited by one student (L5) as helping with his image of an aqueous solution of barium chloride.

**Animation Interpretation**

Most students made sense of the animations of sodium chloride, excluding L2 whose mental model of a solution was too far removed from the animation. Two students (L6 and L7) who were shown the animation of silver chloride precipitation without being told what it represented had difficulty interpreting it, perhaps suggesting that their mental models of precipitation were poor.

Students L4–L7 referred to concepts underlying the processes occurring in the animations, such as electrostatic attractions, energy differences and requirements, thermal energy, equilibrium and bonding. This would be expected from students moving towards expertise (relative to first-year students) in chemistry (Kozma & Russell, 1997).

**Modifications to Representations**

Re-exposure to the animation of an aqueous solution of sodium chloride prompted appropriate modifications to the students’ images of an aqueous solution of barium chloride. This was
particularly significant for the two students (L2 and L4) who were confused about the differences between aqueous solutions and liquids.

### 2.4.4. Conclusions

The following points summarise the conclusions of the longitudinal study.

- Students exposed to animations in first year developed more detailed mental models than those not exposed to animations.
- Animations seem to encourage and aid students in developing mental pictures of the molecular level that are multi-particulate, dynamic, interactive and three-dimensional.
- Students claimed long-term recall of animations, especially those of water.
- Students felt that exposure to animations helped throughout their degrees.
- Students felt that animations improved their ability to visualise the molecular world.
- Benefits may be improved by the inclusion of animations beyond first-year chemistry.
- Misconceptions are resistant to change. Exposure to animations in first year did not eliminate misconceptions associated with aqueous solutions.

### 2.5. Chapter Summary

This chapter aimed to discuss the effectiveness of VisChem animations in helping students develop mental models of molecular and ionic substances. Overall, the studies suggest that the use of VisChem animations in the teaching of chemistry may be beneficial in helping students develop multi-particulate, dynamic, interactive images of the molecular level, as well as helping them learn specific details about substance types. It is concluded that VisChem animations could make an invaluable contribution to an overall teaching strategy in chemistry, if used in a manner that facilitates students’ ability to learn from them.

The following chapter presents findings regarding the attributes that contribute to an individual’s ability to learn from animations and to form scientifically acceptable mental models of chemical phenomena.
Chapter 3

Factors Affecting Students' Mental Models

3.1. Introduction

The research presented in this chapter was carried out in parallel with the study described in Chapter 2. Data were collected over two years (2000–2001), with research in the second year designed to support and extend the results from the first year.

The purpose of the studies was to examine the effects of a number of independent variables on student performance on a post-test and transfer test. This was done to identify factors influencing students’ ability to form mental models with the aid of animations. To identify possible or likely influences on the mental processes involved in perceiving animations, a mental model of the perceptual process was developed.\(^\text{1}\)

3.1.1. Proposed Model of Mental Processes Involved in Perceiving an Animation

Constructivism has had an extraordinary influence on science education and is widely accepted, although not all educationalists accept the movement. Matthews (unpublished) claims that “in substituting viability for truth, and sense-making for science, constructivism undercuts the basis on which objective public knowledge can be built and identified” (p. 2). Despite this criticism, it cannot be denied that constructivism offers some worthwhile advice in regard to teaching and learning, as Matthews admits. He describes a number of positive aspects, including the need to find out what pupils think and teach accordingly, and to teach for understanding. What is perhaps needed, however, is an educational theory grounded in science by which these recommendations can be explained. Neuroscience may well provide this foundation. This chapter describes a model of perception derived from scientific evidence of how the brain processes visual information. In taking into account the importance of prior

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\(^{1}\) The model was developed in collaboration with Dr Ray Sleet.
knowledge and meaningful learning, this model does not undermine the positive ideas emanating from constructivism, but instead provides a more objective basis for the claims.

Figure 3.1 Proposed model of mental processes involved in perceiving an animation

Figure 3.2 Areas of brain activated during perception of an animation

The proposed model of perception (shown in Figure 3.1) is based on earlier information on processing models (Baddley, 1992; Johnstone, 1994) and the model of visual perception developed by Treisman and Gormican (1988). It is predominantly a top-down processing
model, *i.e.*, the processes involved are generated internally and involve active attention, as opposed to bottom-up processing, which occurs automatically or reflexively. It is proposed that, for a person to have the most effective learning experience in perceiving an animation, it is necessary for all the mental processes described by this model (for example, attention networks and working memory) to be activated.

The components of this model are described below. The relationship between neuropsychology and the proposed model is highlighted in Figure 3.2, which shows the areas of the brain activated in each mental process.

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**Figure 3.3** Lateral view of the human brain showing the four lobes of the left cerebral hemisphere (adapted from Squire and Kandel [1999], p. 11)

**Block 2: Auto-registration of Visual Features**

The initial stage in perceiving a visual stimulus involves automatic registration of surface features (for example, colour, orientation, size and direction of movement) of the image. The cortical processing of information from the eyes begins in the primary visual cortex (see Figure 3.2) located at the rear of the occipital lobe (see Figure 3.3). The visual information received in the primary visual cortex is distributed to other cortical regions for further processing. There are two separate neural pathways for processing what the stimulus is (“what” pathway) and where it is located (“where” pathway) (Posner & Raichle, 1997; Le Doux, 1998). Specialised regions along the “what” and “where” pathways are responsible for analysing the different surface features of the perceived image. The “what” pathway travels from the primary visual cortex to the temporal lobes and the “where” pathway travels from
the primary visual cortex to the parietal lobes (see Figure 3.4). To interpret the visual pattern from the “what” and “where” pathways, this pattern must be held in the working memory and matched or compared with information in the long-term memory. “We have conscious access to the outcome of the computation but not to the computation itself” (Le Doux, 1998, p. 30).

Figure 3.4  “What” and “where” pathways (adapted from Posner and Raichle [1997], p. 15)

Block 3 and 4: Attention Networks and Working Memory
Working memory (WM) “refers to a brain system that provides temporary storage and manipulation of the information necessary for such complex cognitive tasks as language comprehension, learning and reasoning” (Baddeley, 1992, p. 556). Two kinds of WM have been described: the phonological loop and the visuospatial sketch pad (Baddeley & Logie, 1999). The phonological loop consists of a passive phonological store, for storing verbal material, and an active rehearsal system, to maintain the contents of the phonological store via mental repetition. The visuospatial sketch pad is divided into separate visual and spatial components. It consists of a passive visual cache and a spatial rehearsal system, the inner scribe (Baddeley & Logie, 1999). The visual cache is used for retaining visual patterns. The inner scribe is the spatial component and is responsible for retaining sequences of movements. It does not rely on visual perceptual input.

Keeping in mind and reasoning with the information in the WM depends on the frontal cortex and the sensory cortices in the brain interacting with one another as a neuronal system. The frontal cortex has reciprocal anatomical connections with many areas of the visual cortex. In particular, areas of the prefrontal cortex (see Figure 3.2) appear to guide the visual system to
attend to features or items in a visual scene and to maintain those items in the WM (Le Doux, 1998; Rowe, Toni, Josephs, Frackowiak, & Passingham, 2000).

Another cortical area of the frontal lobes, the anterior cingulate cortex (ACC), is a region of the brain associated with the attention networks (see Figure 3.5). It exerts an important control over the functions of the WM. The strong arrow linking blocks 3 and 4 in Figure 3.1 indicates the close anatomical and functional relationships between the working memory and the attention networks.

Posner and Raichle (1997) propose that a role of the ACC is to bring an object into conscious awareness, allowing for recognition of the object or perhaps “the realization that the object fulfils a sought-after goal” (p. 169).

MacDonald and co-workers (2000) presented evidence that the ACC has a role in performance monitoring; that is, the ACC is “likely to be involved in evaluative processes indicating when control needs to be more strongly engaged”. This function of the ACC seems to be consistent with other reports about the role of the ACC in controlling the way the brain attends to visual information. For example, Posner and Raichle (1997) consider the ACC is a site of an “executive attention network” which controls many of the mental processes involved in visual perception. Gazzaniga, Ivry and Mangun (1998) state that “the anterior cingulate is a higher-level attentional system required to ensure that our behaviour is efficient and flexible” (p. 463). Le Doux (1998) points out that the ACC and the lateral prefrontal cortex are anatomically interconnected and that “both regions are part of what has been called the frontal lobe attentional network…” (p. 277).
Figure 3.5 The attention networks are involved in control of the working memory, visual orienting and processing of visual features (adapted from Posner and Raichle [1997], p. 173)

Smith and Jonides (1999) summarise five generally accepted functions of the attention networks:

“(i) focusing attention on relevant information and processes and inhibiting irrelevant ones (“attention and inhibition”);
(ii) scheduling processes in complex tasks, which requires the switching of focused attention between tasks (“task management”);
(iii) planning a sequence of subtasks to accomlish some goal (“planning”);
(iv) updating and checking the contents of the working memory to determine the next step in a sequential task (“monitoring”); and
(v) coding representations in the working memory for time and place of appearance (“coding”)” (p. 1659).

Block 6: Long-Term Memory
The long-term memory (LTM) is considered to be a storage system of unlimited capacity and duration. The way the different features received by the visual cortex are integrated and the way the whole visual scene or pattern is perceived in the working memory depends on information coming from the LTM (Gazzaniga et al., 1998; Crick & Koch, 1997). As Greenfield (2000) puts it “We see the world in terms of what we have seen already” (p. 65).

The development of a deep understanding of the visual perception depends on the degree of interest the person has in the content of the visual perception and the extent to which the
person relates that content to existing knowledge in the LTM. Greenfield (2000) suggests that “understanding differs from rote learning in that it is predicated on pre-existing, additional knowledge of some sort or other, a personal context within which the new fact or process is interpreted or evaluated” (p. 31).

The medial temporal lobes of the brain (including the hippocampus) are involved in transforming a visual perception into a lasting memory (encoding), by first storing aspects of the developing memory. The ultimate storage of long-term memories is thought to be in the various areas of the cerebral cortex responsible for the initial processing of the information (Squire & Kandel, 1999).

3.1.2. Variables Studied

The independent variables examined in this study include: prior knowledge, attitudes, visual imaging ability, study style, disembedding ability and visuospatial working-memory capacity. Their relationship to the proposed model is examined in the following section. This information is summarised in Figure 3.6 (page 194).

3.1.2.1. Prior Knowledge

Prior knowledge is considered to describe the information stored in the LTM. According to the model, it will influence the interpretation of visual stimuli and the consequent storage of any resulting memories. The influence of prior knowledge on learning has been well documented in the chemical education literature (for example see: Pines & West, 1986; Haidar & Abraham, 1991; Boujaoude, 1992; Johnstone, 1997; Prosser et al., 2000) and the above model provides a reason, in terms of neuroscience, for why this is so. The importance of considering prior knowledge in the learning process has been stressed in the recent study by Prosser and co-workers (2000).
“This study confirms the vital role of prior knowledge and understanding in the quality of student learning outcomes… the key issue is to determine the nature of students’ prior knowledge and understanding and to help students build an appropriate structure of prior knowledge so that students can focus on their studies in an integrated way… we would also contend that in recent years, not enough attention has been paid to the role of prior knowledge and understanding on science learning in higher education.” (p. 71)

Chemical education research also supports the notion that the extent of relevant prior knowledge has an effect on whether or not students adopt meaningful study styles. Russell et al. (1997) suggested that lack of relevant prior knowledge may inhibit students’ ability to make the links necessary for deep understanding of certain chemical phenomena. Prosser et al. (2000) demonstrated that prior knowledge influences a student’s adopted approach to learning:

"Students with well developed prior knowledge are likely to be aware of those aspects of the context affording a deep approach, to adopt a deep approach and to have well developed post knowledge." (p. 71)

A questionnaire was administered to probe students’ existing mental models of certain substances at a molecular level prior to modelling the same substances with animations. Sufficient prior knowledge is expected to enable students to interpret animations appropriately, resulting in the development of more sophisticated mental models that can be applied to new situations.

3.1.2.2. **Attitudes**

A person’s attitudes and interests play a role in directing attention in learning and in the coding of new information in the LTM, as Squire and Kandel (1999) explain.
“We remember better the more fully we process new subject matter. Memory is better the more we have a reason to study, the more we like what we are studying and the more we can bring the full breadth of our personality to the moment of learning…When no particular effort is being made to record experiences for later, our interests and preferences direct our attention and determine the quality and quantity of encoding. Our interests and preferences thereby influence the nature and the strength of the resulting memory.” (pp. 71–72)

Therefore, a positive attitude is likely to encourage a deep approach to learning. In accordance with this, Novak (1988) found that science students express negative feelings towards learning if their “cognitive involvement is essentially rote learning” and positive feelings “when involvement is meaningful”.

In this study, we use a questionnaire to measure students’ attitudes to chemistry: how relevant or important they feel chemistry is (reason to study), their enjoyment in the subject (“like what we are studying”) and how difficult they perceive the subject to be. Positive attitudes to chemistry may suggest a willingness to attend actively to animations, with concomitant activation of the attention networks. Furthermore, positive attitudes are expected to encourage meaningful learning from animations.

3.1.2.3. Visual Imaging Ability

The image formed in a person’s brain from perceiving an actual visible stimulus is called a ‘percept’ (Posner & Raichle, 1997), to distinguish it from the image created by a person in his/her brain when the stimulus is not visible. From a review of neuroimaging studies, Posner and Raichle (1997) concluded that the areas of the brain activated during visual perception are closely related to the areas of the brain activated during the task of creating a visual image. This evidence from neuroscience suggests that the capacity of students to develop clear and accurate percepts of animations of the molecular world is likely to be closely related to their capacity to create clear and accurate images of the animations when they reflect on their experiences of viewing animations. To learn effectively and meaningfully from the animations, the model implies that a necessary, but not sufficient, condition is that the students develop vivid percepts and create vivid images of the animations.
A questionnaire requiring students to mentally visualise and interpret common scenes was used to obtain a rating of students’ imaging ability. The vividness of their images of these scenes was considered an indication of their capacity to create vivid images and to develop vivid percepts of the animations.

3.1.2.4. Study Style

How a student approaches their study has an impact on how meaningfully new information is stored in the long-term memory. Students may be considered deep learners or surface learners, in relation to a particular subject or topic. Whether a student adopts a deep or surface approach is a reaction to a particular learning environment, in order to cope with certain situations and tasks (Riding & Sadler-Smith, 1992; Prosser et al., 2000). This is influenced by a student’s level of relevant background knowledge and level of interest in the task (Ramsden, 1979).

Deep learners (Ramsden, 1979; Biggs, 1987; Prosser, 2000) are characterised by their attempts to bring meaning and personal understanding to new information. They try to relate new ideas to previous knowledge and relate concepts to everyday experiences.

Surface learners (Ramsden, 1979; Biggs, 1987; Prosser, 2000), on the other hand, restrict their learning to the minimum required to pass. They approach learning passively and perceive learning to be the rote memorisation of information, in order to reproduce it in exams. They rarely attempt to understand or integrate the material.

Various studies demonstrate a relationship between learning style and learning outcome, with deep-learning strategies promoting higher achievement on tasks requiring an understanding of the material (Trigwell & Sleet, 1990; Hegarty-Hazel & Prosser, 1991; Boujaoude, 1992; Prosser et al., 2000). This research can be explained using the above perceptual model. Squire and Kandel (1999) point out that “the extent to which we can organise [what is perceived] and relate it to knowledge that we already have” influences “the nature and extent of the encoding that occurs at the time of the initial learning and how effectively a new event or a new fact results in neuronal change in the brain”. Furthermore, “when encoding is elaborate and deep, memory is much better than when encoding is limited and superficial” (p. 71).
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A questionnaire was administered to determine the extent to which students believed they engaged in meaningful learning activities in chemistry, such as relating new material to old, compared to how often they adopted more surface-learning strategies. Because a deep understanding relies on students’ linking new information to knowledge that already exists in the LTM, deep learners should perform well on transfer tasks.

3.1.2.5.  Disembedding Ability

Disembedding ability, also commonly known as field-dependence/field-independence or the global/ articulated (or analytical) style, refers to the ability to extract details from a complex background.

The field-dependence/field-independence styles derived from experiments examining how people locate upright in space; for example, whether they position a rod relative to the position of a visual field (in this case a frame) regardless of the position of the frame relative to upright (field-dependent) or whether they position the rod upright, regardless of the position of the visual field (field-independent). Most people fall between the two extremes. Another situation was found to measure this same perceptual tendency. This involves locating a simple figure within a complex field and therefore also measures the "extent to which the surrounding visual framework dominates perception of the item within it" (Witkin, Moore, Goodenough & Cox, 1977, p. 6). Field-independent subjects were those who were able to find the simple figures with relative ease within a designated amount of time.

The higher a person’s disembedding ability (field-independent, articulated), the more likely that person is to perceive material analytically. A person with a tendency to think analytically is more likely to focus on the details of what they are seeing. They will tend to impose structure on material that lacks it. A person with lower disembedding ability (field-dependent, global) is more likely to take a global (overall) perspective, enabling them to see the "big picture" of a situation. They tend to view material "as is".

Relationships between disembedding ability and problem solving in chemistry have been documented (Bodner & McMillen, 1986; Johnstone & Al-Naeme, 1991, 1995; Niaz, 1996) but thus far no-one has examined the effects of this cognitive trait on students’ development of imagery in chemistry.
Kwon and Lawson (2000) propose that tests of “disembedding ability” measure prefrontal lobe activity. This suggests a connection with the working memory and/or the attention networks. Smith and Jonides (1999) suggest that “focusing attention on relevant information and processes and inhibiting irrelevant ones” is a function of the attention networks. Johnstone and Al-Naeme (1991) state that the search for relevant information requires working-memory space, especially for a novice. Disembedding ability is, therefore, taken to be a measure of the extent of prefrontal lobe activity, indicating the activation of the working memory and attention networks. Because animations are complex multi-particulate representations which are continually changing, an ability to focus on the relevant information would be vital to successful learning from animations. It is, therefore, proposed that students with high disembedding ability will be better able to notice the intricate details in an animation.

3.1.2.6. **Visuospatial Working Memory Capacity (VSWMC)**

The working memory has limited capacity, yet all information we wish to learn must be processed by the working memory before being permanently stored in the long-term memory (Cooper, 1997). Obviously, this has serious implications for successful learning. Various authors claim a link between working-memory capacity and learning success, mainly in the area of problem solving in chemistry and mathematics (Frazer & Sleet, 1984; Johnstone & El-Banna, 1986, 1989; Johnstone & Al-Naeme, 1991; Sweller, 1993; Niaz, 1996; Cooper, 1997; Sleet, 1998). The effect of visuospatial working-memory capacity on students’ development of mental models in chemistry has not been studied.

A questionnaire was distributed to determine students’ relative visuospatial working-memory capacity. This was used to gain an idea of students’ abilities to hold and manipulate, in WM, a number of different visual details. Students with high VSWMC are expected to cope better with complex animated displays, and more easily and effectively co-ordinate or manipulate different features shown in the animations, than those students with low VSWMC. Like disembedding ability, visuospatial working memory can be considered a measure of prefrontal lobe activity. It is expected that there will be some overlap in the effects of disembedding ability and those of visuospatial working memory.
3.1.2.7. Post-test, Transfer Test and Pre–Post Gain

The effects of the above variables were examined by determining their influence on outcomes in a post-test and a transfer test, as well as the improvement from pre-test to post-test. The post-test, identical to the pre-test, was used to examine the clarity and accuracy of the images students had stored in long-term memory following instruction. The transfer test examined the extent to which students were able to relate the percept (animation) to existing knowledge in their long-term memory or relate their images of animations in the LTM to new situations. The pre–post test gain gives an indication of the extent to which students assimilated the new information presented to them.
Figure 3.6  Relationship between processing model and questionnaires used to evaluate student attributes
3.2. Research Hypotheses 2000

The following hypotheses were constructed and are expected to be true based on the proposed model.

1. Prior knowledge will correlate positively with performance on the post-test and pre–post gain, as it should enable students to more fully interpret animations.

2. Prior knowledge will correlate positively with performance on the transfer test because prior knowledge will allow more meaningful storage of images in the LTM and hence will enable students to effectively apply their knowledge.

   By corollary, students’ prior knowledge in chemistry is also expected to correlate significantly and positively with students’ deep-learning scores.

3. Students’ attitudes to chemistry on entering university will correlate positively with post-test and transfer test results, and pre–post gain, as more positive attitudes should imply a willingness to actively attend to animations, and a tendency to adopt a deep approach to learning.

   By corollary, students’ attitudes to chemistry are also expected to correlate positively with students’ deep-learning scores.

4. Visual imaging ability will correlate positively with post-test and transfer test results, and pre–post gain, because it is assumed that an ability to create clear and vivid visual images is necessary for interpreting and recalling animations.

5. Students whose study style is aimed at deep learning will understand the relevance of animations in new situations, so deep-learning scores will correlate significantly and positively with transfer-test scores.

6. Conversely, those students showing a tendency to adopt surface approaches to learning, will be less likely to see the relevance of animations, so surface-learning scores will correlate significantly and negatively with transfer test scores.
7. Disembedding ability will correlate positively with post-test scores and pre–post gain. It is proposed that, in order to notice the intricate details contained in animations, students will need to be able to extract this information from the complex visual field.

8. Visuospatial working-memory capacity will correlate positively with the results on the post-test and with pre–post gain. A high visuospatial working-memory capacity is necessary to maintain and manipulate mental images and hold a number of different details of an animation at one time.

3.3. Methodology 2000

Student performance was assessed both before and after instruction, but the instruction itself was not a variable. A sub-group of students from the sample described in Chapter 2, Section 2.2.2.1, were administered a variety of questionnaires to evaluate various individual attributes. A total of 22 students\(^2\) (11 male, 11 female; median age 18) completed all questionnaires\(^3\). Of the 22 students, 17 had previously completed chemistry at HSC level (two-unit Chemistry, three-unit Science or equivalent), four had not studied beyond junior (Year 9/10) chemistry and one had studied Year 11 chemistry only. Questionnaires were administered at varying times throughout the year, as time allowed. Table 3.1 lists the semesters and weeks the various questionnaires were completed, whether they were distributed in lectures, laboratories or tutorials, and the estimated time for completion (including instructions). Questionnaires, or sample items from questionnaires, are available for perusal in Appendix B. Statistical analysis was carried out using SPSS 11.

\(^2\) Sample size was considerably less than anticipated due to the number of absentees when questionnaires were distributed.

\(^3\) excluding the FIT which was completed by only 13 students.
Chapter 3 Factors Affecting Students’ Mental Models

<table>
<thead>
<tr>
<th>Questionnaire</th>
<th>Week/Semester</th>
<th>Class distributed</th>
<th>Approximate time for completion (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test</td>
<td>1/1</td>
<td>Lecture</td>
<td>50</td>
</tr>
<tr>
<td>Attitudes</td>
<td>2/1</td>
<td>Laboratory</td>
<td>10</td>
</tr>
<tr>
<td>VVIQ</td>
<td>6/1</td>
<td>Lecture</td>
<td>20</td>
</tr>
<tr>
<td>Study Style</td>
<td>12/1</td>
<td>Laboratory</td>
<td>10</td>
</tr>
<tr>
<td>Post-test</td>
<td>13/1</td>
<td>Lecture</td>
<td>50</td>
</tr>
<tr>
<td>Transfer Test</td>
<td>2/2</td>
<td>Lecture</td>
<td>50</td>
</tr>
<tr>
<td>GEFT</td>
<td>4/2</td>
<td>Laboratory</td>
<td>20</td>
</tr>
<tr>
<td>FIT</td>
<td>13/2</td>
<td>Scheduled times</td>
<td>60</td>
</tr>
</tbody>
</table>

Table 3.1 Questionnaire distribution timetable (2000)

3.3.1. Independent Variables

3.3.1.1. Prior Knowledge (Pre-test)

This variable was assessed using the pre-test described in Chapter 2, Section 2.2.2.2, and marked according the marking scheme outlined in Chapter 2, Section 2.2.2.3, such that each student received an overall mark out of 35 for the overall test. A copy of the test and the marking scheme are available in Appendix A.

3.3.1.2. Attitudes

To measure student attitudes, a simple semantic differential was used. The semantic differential was comprised of nine pairs of bipolar adjectives, shown in Figure 3.7. Each adjectival pair was separated by a seven-point rating scale. Students were asked to rate their feelings towards chemistry by placing a cross on the appropriate space along the scale. Students’ responses for each scale were scored from 1 to 7 so that the higher the score, the more positive the attitude. A copy of the complete questionnaire can be found in Appendix B.
Factors Affecting Students’ Mental Models

An identical questionnaire was used by Shannon, Sleet and Stern (1982) to measure students' attitudes towards biology, chemistry, geology and physics. They found, using factor analysis, that the questionnaire evaluated three factors (each consisting of three items) which they labelled "enjoyment", "difficulty" and "importance".

### 3.3.1.3. Visual Imaging Ability (VVIQ)

Visual imaging ability was measured using a slightly modified version of Marks’ (1973) Vividness of Visual Imagery Questionnaire (VVIQ). This is a self-rating questionnaire requiring students to mentally visualise a number of familiar scenes and then rate the vividness of these experiences, with eyes open and then closed, on a five-point scale (see Figure 3.8). The scale used was reversed relative to the original questionnaire, on the advice of McKelvie (1995).

**Figure 3.8  Rating scale used for the modified Vividness of Visual Imagery Questionnaire**

The VVIQ is comprised of 16 items. The wording of some of the items was changed slightly to remove the more obscure words and so minimise the chance of misinterpretation (see Table 3.1).
3.2). The items in the questionnaire were verbally recorded and played to participants in a lecture theatre, with sufficient time between items for participants to write down their ratings. Students were also provided with a visual overhead projection indicating the relative vividness and clarity of the statements on the five-point scale (see Appendix B). This was done in an effort to standardise students' responses, making the questionnaire more objective (McKelvie, 1995). The higher ratings from either the “eyes open” or “eyes closed” options were taken as the scores for each item and these scores were totalled to give an overall score out of 80. Other researchers have taken a comparative approach, allowing students to adopt their preferred (more vivid) mode of visualisation at the time of completing the questionnaire (Hishitani, 1995). Marks reported a Cronbach’s alpha reliability coefficient of 0.74 and a split-half reliability coefficient of 0.85 for the questionnaire. A review of the extensive use of this questionnaire in research (McKelvie, 1995) concluded that "the evidence favours the construct validity of the VVIQ". A copy of the questionnaire can be found in Appendix B.

<table>
<thead>
<tr>
<th>Item</th>
<th>Original Wording</th>
<th>Modified Wording</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Contour</td>
<td>Outline</td>
</tr>
<tr>
<td>3</td>
<td>Carriage</td>
<td>Posture</td>
</tr>
<tr>
<td>13</td>
<td>The contours of the landscape</td>
<td>The overall country scene with trees, mountains and a lake</td>
</tr>
</tbody>
</table>

Table 3.2 Modifications to the VVIQ

3.3.1.4. Study Style (CSPQ)

The study style questionnaire utilised in this research was derived from Bigg’s (1987) Study Processes Questionnaire (SPQ). A slightly modified version of the questionnaire extensively used by Prosser (for example, see Prosser et al., 2000) was employed, which includes surface and deep motives and strategies, but not the achieving factor from the original SPQ. The elimination of this factor can be justified with reference to research suggesting that “achieving” is a sub-factor of deep and surface approaches rather than a discrete factor (Kember & Leung, 1998). The modifications made to Prosser's questionnaire involved tailoring it for the subject of chemistry. Phrases such as "this section" or "this topic" were replaced by "chemistry" or "this subject". Similar changes have been made by Prosser (2000) and others (Sachs & Gao, 2000) and are not thought to reduce the reliability of the test. Only one major change was made, because the original statement was appropriate for a topic but not a complete subject. The surface motive "Whether I like it or not, I can see that doing well in this section is a way for me to get a good grade in my course" was replaced with "When
Chapter 3  Factors Affecting Students’ Mental Models

doing assessment tasks, I consider the percentage it contributes to my overall grade and put in the appropriate amount of time and effort". The original statement was interpreted as a method of prioritising ones' efforts in certain topics in order to maximise the overall grade achieved. The replacement item was assumed to similarly indicate a surface motive. This questionnaire will be referred to as the Chemistry Study Processes Questionnaire or CSPQ.

The questionnaire consists of 28 items. Items 1, 5, 9, etc. refer to surface motives; 2, 6, 10, etc. refer to deep motives; 3, 7, 11, etc. refer to surface strategies, and 4, 8, 12, etc. refer to deep strategies. Students were required to indicate how often each statement in the questionnaire was true, on a Likert-style five-point scale from "only rarely" (1) to "almost always" (5). Scores for each item were simply the numbers circled on the scales. A copy of the questionnaire can be found in Appendix B.

3.3.1.5. Disembedding Ability (GEFT)

Disembedding ability (field-dependence/-independence) was measured using the "Group Embedded Figures Test" (GEFT). The GEFT requires students to find a simple shape within a more complex figure. The simple shapes are represented on the back of a booklet and students are required to look back and forth from the simple shapes to the complex figures. The questionnaire contains seven practice items which students are given two minutes to complete, followed by two sets of nine questions, each with time allocations of five minutes. The score is calculated by adding up the number of correct responses to the 18 questions. The higher the number of correct answers, the greater the level of disembedding ability.

Although this questionnaire was not administered prior to instruction, it was assumed that the disembedding ability of students would not have changed significantly over the time of this study. Witkin, Oltman, Raskin and Karp (1971) claim that disembedding ability levels off at the age of 15 and shows absolute stability in young adulthood. Considering the median age of these students (18), it is reasonable to make this assumption.

Reliability and validity data are discussed in the manual provided with the questionnaires (Witkin et al., 1971). Sample questions from the GEFT are given in Appendix B.
3.3.1.6. **Visuospatial Working-Memory Capacity**

This variable was assessed using the "Figural Intersection Test" (FIT) (Pascual-Leone, 1969; Johnson, 1982a). Receipt of the test and permission to use it were obtained from the designer, Pascual-Leone. Although designed to measure overall working-memory capacity, Cornoldi, Vecchia and Tressoldi (1995) suggest that the FIT gives a raw measure of visuospatial working-memory capacity (VSWMC), through comparisons with other tests of VSWM. The FIT has an advantage over other measures of VSWMC in that it can be administered to a group of students.

In this questionnaire, students are provided with a set of shapes on the right of a page (presentation set) and a set of overlapping shapes on the left (test set). The test requires subjects to find the common area of intersection in the test set, from the shapes from the presentation set (most shapes are common). In some items, a misleading irrelevant shape (not present in the presentation set) is included among the test set. Altogether, there are 36 items on the test. The number of shapes in the presentation set varies from two to eight; the number in the test set from two to nine. The number of shapes in the test set is equal to the score given if the item is marked correct. The test is untimed.

For the purposes of correlational analysis, the FIT was scored by totalling the score given for each correct answer in the FIT (Johnson, 1982b). The highest possible score was 186. This provided relative data rather than absolute values for working-memory capacity.

Sample questions from the FIT are given in Appendix B.

### 3.3.2. **Dependent Variables**

The post-test and transfer test served as the dependent variables in this study. The design, content and marking of these tests is outlined in Chapter 2, Sections 2.2.2.2 to 2.2.2.5.

Students received an overall mark out of 35 for the post-test. For the transfer test, students received marks for **direct transfer** (total 30), **applied transfer** (total 22) and **topic transfer** (total 17) (see Chapter 2, Figures 2.6 to 2.8). A copy of the tests and marking schemes are available in Appendix A. Gain from pre-test to post-test was also a dependent variable.
The dependent variables evaluated increasing levels of ability in applying the ideas shown in the animations, as shown in Table 3.3.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Level of Transfer from Animations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-test</td>
<td>Direct use of ideas from animations</td>
</tr>
<tr>
<td>Pre–Post Gain</td>
<td>Direct use of ideas from animations</td>
</tr>
<tr>
<td>Direct Transfer</td>
<td>Application to similar substances</td>
</tr>
<tr>
<td>Applied Transfer</td>
<td>Application to new systems</td>
</tr>
<tr>
<td>Topic Transfer</td>
<td>Application to new topics</td>
</tr>
</tbody>
</table>

Table 3.3  Relationship between dependent variables and level of transfer from animations

### 3.4. Results 2000

The structures of certain tests were elucidated using principal components analysis, and the reliability of tests measuring student characteristics was determined using Cronbach’s alpha or Spearman Brown’s split-half reliability coefficient. Hypotheses were examined principally by multiple regression analysis. The data were first analysed to ascertain whether they met the assumptions of regression analysis. Normality and linearity were confirmed by histograms, scattergrams and calculation of the Shapiro-Wilks statistic. Corrections were made to data where necessary. Multicollinearity was confirmed by testing the correlations between the independent variables and tolerance levels. Multiple regression analysis was used to examine the effects of the independent variables\(^4\) on the post-test, transfer test and pre–post gain. Only data from those students who had completed all questionnaires were included (N = 22) in the regressions. The relationships between working-memory capacity and the dependent variables were examined separately using Pearson correlation coefficients, because the sample size for this variable was further restricted. Data generated using SPSS 11 are given in Appendix E.

### 3.4.1. Structure

Two of the questionnaires were designed as multidimensional constructs, the attitudes questionnaire and the CSPQ. Principal components analysis was performed on these questionnaires to examine the component structure.

---

\(^4\) excluding working memory capacity
3.4.1.1. Attitudes

Unrotated principal components analysis (see Appendix E) was performed on the attitudinal data collected (N = 22). This analysis yielded a two-factor model, as shown in Table 3.4. This model accounts for 73% of the variance in the scores.

<table>
<thead>
<tr>
<th>Item</th>
<th>Component 1</th>
<th>Component 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.749</td>
<td>-0.148</td>
</tr>
<tr>
<td>3</td>
<td>0.848</td>
<td>0.432</td>
</tr>
<tr>
<td>4</td>
<td>0.753</td>
<td>0.317</td>
</tr>
<tr>
<td>6</td>
<td>0.686</td>
<td>-0.456</td>
</tr>
<tr>
<td>7</td>
<td>0.843</td>
<td>0.234</td>
</tr>
<tr>
<td>9</td>
<td>0.751</td>
<td>-0.0999</td>
</tr>
<tr>
<td>1</td>
<td>-0.141</td>
<td>0.872</td>
</tr>
<tr>
<td>5</td>
<td>-0.174</td>
<td>0.885</td>
</tr>
<tr>
<td>8</td>
<td>-0.0318</td>
<td>0.880</td>
</tr>
<tr>
<td>Eigenvalues</td>
<td>3.645</td>
<td>2.899</td>
</tr>
<tr>
<td>% Variance</td>
<td>40.497</td>
<td>32.212</td>
</tr>
<tr>
<td>Cumulative %</td>
<td>40.497</td>
<td>72.709</td>
</tr>
</tbody>
</table>

Table 3.4 Component matrix resulting from principle components analysis of items on the attitudes questionnaire

Component 1 comprises the items from the “enjoyment” and “importance” factors from Shannon, Sleet and Stern’s (1982) study (items 2, 3, 4, 6, 7, 9). The lack of discrimination between these factors is likely to result from the limited sample size used in this study. This factor will be referred to as “attitude” in the present study.

Component 2, consisting of items 1, 5 and 8, is consistent with Shannon, Sleet and Stern’s (1982) “difficulty” component. In this study, this component is referred to as “simplicity” because higher ratings correspond to positive attitudes, so that a high rating for this factor indicates that a student perceived the subject to be relatively easy.

Students were allocated scores generated in SPSS 11 for “attitude” and “simplicity” based on the relative contributions of each item to the overall factor. Scores were calculated to give a mean of zero with a standard deviation of one for each component, and a correlation
coefficient of zero between the two components. These scores were used in the regression analysis.

### 3.4.1.2. Study Style

Unrotated principal components analysis was carried out on the data from the CSPQ. This analysis revealed nine components with significant cross-loadings across components (see Appendix E). The deep and surface motives and strategies did not emerge as separate factors. For the purposes of this study, a decision was made to split the data into ‘surface’ and ‘deep’ factors by summing over the odd and even items of the test, respectively. Each student, therefore, received a score out of 70 for surface learning and a score out of 70 for deep learning. This approach has been used by Prosser et al. (2000) who also combined motive and strategy items to produce overall surface and deep scores. The surface and deep factors showed high internal consistency (see Table 3.5), and compare favourably with results of Prosser’s (2000) study. The multi-dimensionality of the test suggests, however, that it might be flawed. This is discussed further in Section 3.5.2.

### 3.4.2. Reliability

Reliability coefficients (Spearman Brown’s split-half reliability coefficient and/or Cronbach’s alpha) were calculated for the measures of student characteristics. Table 3.5 gives a comparison of the reliabilities of parameters in this study with those from the literature (where available). All reliability coefficients are moderate-to-high, indicating good internal consistency, and compare favourably with the available literature values.
Table 3.5  Reliability coefficients for independent and dependent variables

<table>
<thead>
<tr>
<th>Test</th>
<th>Cronbach’s alpha coefficient (N = 22)</th>
<th>Literature Comparison</th>
<th>Spearman Brown split-half reliability coefficient (N = 22)</th>
<th>Literature Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attitude</td>
<td>0.89</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Simplicity</td>
<td>0.87</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>VVIQ</td>
<td>0.94</td>
<td>0.870 to 0.906 (95% confidence, McKelvie, 1995)</td>
<td>0.90</td>
<td>0.85 (Marks, 1973) 0.856 to 0.902 (95% confidence, McKelvie, 1995)</td>
</tr>
<tr>
<td>Surface Learning</td>
<td>0.86</td>
<td>0.72 (Prosser et al., 2000)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Deep Learning</td>
<td>0.86</td>
<td>0.87 (Prosser et al., 2000)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>GEFT</td>
<td>0.86</td>
<td>0.89 (Staver &amp; Jacks, 1988)</td>
<td>0.93</td>
<td>0.82 (Witkin et al. 1971)</td>
</tr>
<tr>
<td>FIT(^5)</td>
<td>-</td>
<td>-</td>
<td>0.87</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^5\) N = 13

3.4.3.  Basic Statistics

Some descriptive statistics were computed for each of the final variables. These are given in Table 3.6.
### Table 3.6  Basic Statistics for dependent and independent variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Possible Range</th>
<th>Observed Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test</td>
<td>12.0</td>
<td>4.65</td>
<td>13.0</td>
<td>–35</td>
<td>1–20</td>
</tr>
<tr>
<td>Attitude(^6)</td>
<td>0.00</td>
<td>1.00</td>
<td>–0.0659</td>
<td>-</td>
<td>–2.25–1.62</td>
</tr>
<tr>
<td>Simplicity(^7)</td>
<td>0.00</td>
<td>1.00</td>
<td>0.0167</td>
<td>-</td>
<td>–1.73–2.02</td>
</tr>
<tr>
<td>VVIQ</td>
<td>67.1</td>
<td>10.2</td>
<td>65.0</td>
<td>14–70</td>
<td>51–80</td>
</tr>
<tr>
<td>Surface Learning</td>
<td>47.3</td>
<td>9.00</td>
<td>47.0</td>
<td>14–70</td>
<td>26–66</td>
</tr>
<tr>
<td>Deep Learning</td>
<td>49.3</td>
<td>8.10</td>
<td>48.5</td>
<td>14–70</td>
<td>36–68</td>
</tr>
<tr>
<td>GEFT</td>
<td>14.6</td>
<td>3.62</td>
<td>16.5</td>
<td>0–18</td>
<td>6–18</td>
</tr>
<tr>
<td>Post-test</td>
<td>19.5</td>
<td>4.66</td>
<td>20.0</td>
<td>0–35</td>
<td>10–26</td>
</tr>
<tr>
<td>Pre–post Gain</td>
<td>7.55</td>
<td>3.10</td>
<td>7.50</td>
<td>-</td>
<td>0–13</td>
</tr>
<tr>
<td>Direct Transfer</td>
<td>15.8</td>
<td>5.20</td>
<td>15.5</td>
<td>0–30</td>
<td>4–24</td>
</tr>
<tr>
<td>Applied Transfer</td>
<td>7.45</td>
<td>3.83</td>
<td>7.50</td>
<td>0–22</td>
<td>1–13</td>
</tr>
<tr>
<td>Topic Transfer</td>
<td>7.32</td>
<td>2.73</td>
<td>7.00</td>
<td>0–17</td>
<td>4–15</td>
</tr>
</tbody>
</table>

3.4.4.  Assumptions

3.4.4.1. Outliers

Box-plots were used to examine the incidence of outliers in the data. Outliers were present in pre-test total data, surface-learning data, direct-transfer data and topic-transfer data (see Appendix E). For the pre-test, surface-learning and direct-transfer tests, the trimmed means (see Table 3.7) did not differ greatly from the actual means (Pallant, 2001), the distributions were normal according to the Shapiro-Wilks test (see Table 3.8) and the outliers did not appear to be extreme from the observation of histograms (see Appendix E). Therefore, these data points were retained in further analysis. However, a negative skew was present in the topic-transfer test data, due to the outlier (see Figure 3.9, page 209). Rather than removing this outlier and further reducing the sample size, the data were transformed (see Section 3.4.4.2).

---

\(^6\) Scores generated from the Principle Components Analysis in SPSS.

\(^7\) Scores generated from the Principle Components Analysis in SPSS.
### Chapter 3  
Factors Affecting Students’ Mental Models

<table>
<thead>
<tr>
<th>Test</th>
<th>Actual Mean</th>
<th>5% Trimmed Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test</td>
<td>12.0</td>
<td>12.1</td>
</tr>
<tr>
<td>Surface Learning</td>
<td>47.3</td>
<td>47.4</td>
</tr>
<tr>
<td>Pre–post Gain</td>
<td>7.5</td>
<td>7.7</td>
</tr>
<tr>
<td>Direct Transfer</td>
<td>15.8</td>
<td>16.0</td>
</tr>
</tbody>
</table>

Table 3.7  
Comparison of actual means and trimmed means

#### 3.4.4.2. Normality

Normality was checked by observation of histograms (see Appendix E) in conjunction with calculation of the Shapiro-Wilks statistic\(^8\) (see Table 3.8).

Data from the VVIQ were not normally distributed (see Table 3.8, Figure 3.9). The total scores were, therefore, collapsed into a bipolar variable using a median split (median = 65, N = 22). Students with imagery ratings between 50 and 65 were given a score of 1, and those with an imagery rating between 66 and 80 were given a score of 2.

Data from the GEFT were negatively skewed (see Figure 3.9). The data were transformed using reflect and logarithm to reduce the skewing. Although improved, the resulting distribution still deviated from normality (see Table 3.7, Figure 3.9). Nothing further could be done to correct the distribution. The transformed data were used in further analyses. Reflecting the scores reverses the order of the scores such that a high score represents a low disembedding ability.

Topic transfer was found to have a positive skew (see Figure 3.9). A log10 transformation was performed on these data, resulting in a normal distribution (see Table 3.8, Figure 3.9).

---

\(^8\) This statistic is suitable for testing normality of small samples, N < 20 (Shapiro & Wilk, 1965).
<table>
<thead>
<tr>
<th>Test</th>
<th>Shapiro-Wilks Statistic</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE-TEST</td>
<td>0.970</td>
<td>0.716</td>
</tr>
<tr>
<td>ATTITUDE</td>
<td>0.968</td>
<td>0.662</td>
</tr>
<tr>
<td>SIMPLICITY</td>
<td>0.971</td>
<td>0.730</td>
</tr>
<tr>
<td>VVIQ</td>
<td>0.886</td>
<td><strong>0.016</strong></td>
</tr>
<tr>
<td>SURFACE</td>
<td>0.978</td>
<td>0.876</td>
</tr>
<tr>
<td>DEEP</td>
<td>0.969</td>
<td>0.694</td>
</tr>
<tr>
<td>GEFT</td>
<td>0.853</td>
<td><strong>0.004</strong></td>
</tr>
<tr>
<td>POST-TEST</td>
<td>0.927</td>
<td>0.108</td>
</tr>
<tr>
<td>PRE–POST GAIN</td>
<td>0.959</td>
<td>0.468</td>
</tr>
<tr>
<td>DIRECT TRANSFER</td>
<td>0.954</td>
<td>0.378</td>
</tr>
<tr>
<td>APPLIED TRANSFER</td>
<td>0.942</td>
<td>0.220</td>
</tr>
<tr>
<td>TOPIC TRANSFER</td>
<td>0.893</td>
<td><strong>0.022</strong></td>
</tr>
<tr>
<td><strong>Transformations</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reflect and Log10 GEFT</td>
<td>0.904</td>
<td><strong>0.036</strong></td>
</tr>
<tr>
<td>Log10 TOPIC TRANSFER</td>
<td>0.946</td>
<td>0.264</td>
</tr>
</tbody>
</table>

Table 3.8    Shapiro-Wilks test for normality
Chapter 3  Factors Affecting Students’ Mental Models

### Figure 3.9  Histograms of original and transformed data

<table>
<thead>
<tr>
<th>Original Data</th>
<th>Transformed Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>VVIQTOT</td>
<td></td>
</tr>
<tr>
<td>Histogram</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>5</td>
<td>7</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Std. Dev = 10.17</td>
<td>Mean = 67.1</td>
</tr>
<tr>
<td>N = 22.00</td>
<td></td>
</tr>
<tr>
<td>VVIQ</td>
<td></td>
</tr>
<tr>
<td>Histogram</td>
<td></td>
</tr>
<tr>
<td>Frequency</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>12</td>
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<td>3</td>
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<td>6</td>
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<tr>
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<td>4</td>
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<td>6</td>
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<tr>
<td>7</td>
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<tr>
<td>Std. Dev = .51</td>
<td>Mean = 1.50</td>
</tr>
<tr>
<td>N = 22.00</td>
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<tr>
<td>GEFT</td>
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<tr>
<td>Histogram</td>
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<tr>
<td>Frequency</td>
<td></td>
</tr>
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<td>12</td>
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<td>10</td>
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<td>5</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
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<tr>
<td>Std. Dev = 3.62</td>
<td>Mean = 14.6</td>
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<tr>
<td>LOGGEFT</td>
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<tr>
<td>Histogram</td>
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<td>Frequency</td>
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<tr>
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<td>Histogram</td>
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<td>Frequency</td>
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<td>Mean = 7.3</td>
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<td>LOGTOPIC</td>
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<td>Histogram</td>
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<td>Frequency</td>
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<td>10</td>
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<td>8</td>
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<td>4</td>
<td>2</td>
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<td>0</td>
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<tr>
<td>Std. Dev = .15</td>
<td>Mean = .84</td>
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<tr>
<td>N = 22.00</td>
<td></td>
</tr>
</tbody>
</table>

**Median Split**

**Reflect and Log10**

**Log10**

**Topic Transfer**
3.4.4.3. Multicollinearity

Pearson correlation coefficients were calculated between independent variables to check for possible multicollinearity. The correlations also allowed for testing of hypotheses relating to the relationships between attitudes in chemistry, prior knowledge and deep learning.

<table>
<thead>
<tr>
<th></th>
<th>Pre-test</th>
<th>Attitude</th>
<th>Simplicity</th>
<th>VVIQ</th>
<th>Surface</th>
<th>Deep</th>
<th>GEFT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Attitude</td>
<td>-0.047</td>
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<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Simplicity</td>
<td>0.148</td>
<td>0.000</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VVIQ</td>
<td>-0.310</td>
<td>-0.070</td>
<td>0.012</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface</td>
<td>-0.436*</td>
<td>-0.081</td>
<td>-0.113</td>
<td>0.333</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Deep</td>
<td>-0.232</td>
<td>0.283</td>
<td>-0.068</td>
<td>0.307</td>
<td>0.777**</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>GEFT⁹</td>
<td>0.307</td>
<td>-0.300</td>
<td>-0.035</td>
<td>-0.085</td>
<td>-0.227</td>
<td>-0.362</td>
<td>1</td>
</tr>
</tbody>
</table>

**Correlation significant at 0.01 level (2-tailed)
* Correlation significant at 0.05 level (2-tailed)

Table 3.9 Pearson correlation coefficients between independent variables

The magnitude of the correlation between surface and deep learning is cause for concern. Tolerance levels were checked to determine if this correlation might cause multicollinearity. A regression analysis was performed using all the independent variables and the post-test as the dependent variable. The collinearity statistics are given in Table 3.9.

<table>
<thead>
<tr>
<th>Test</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test</td>
<td>0.622</td>
</tr>
<tr>
<td>Attitude</td>
<td>0.624</td>
</tr>
<tr>
<td>Simplicity</td>
<td>0.959</td>
</tr>
<tr>
<td>VVIQ</td>
<td>0.810</td>
</tr>
<tr>
<td>Surface</td>
<td>0.228</td>
</tr>
<tr>
<td>Deep Learning</td>
<td>0.229</td>
</tr>
<tr>
<td>GEFT</td>
<td>0.750</td>
</tr>
</tbody>
</table>

Table 3.10 Tolerance levels with post-test as the dependent variable

⁹Correlations were calculated with the transformed data for the GEFT. Reflecting the scores reverses their order hence the signs of correlation coefficients have been changed to reflect the true directionality of the relationship between the variables.
Tolerance levels are above 0.1 (Pallant, 2001), suggesting that there are no multicollinearity problems with the data and specifically that the correlation between deep and surface learning does not cause significant multicollinearity.

The statistically significant positive correlation between deep and surface learning appears somewhat counterintuitive. It is possible that some students utilise both surface and deep strategies in their learning, and that the more deep learning that occurs, the more surface strategies need to be employed. Research has shown that Asian students, in particular, utilise surface-like strategies, such as memorisation, in conjunction with meaningful learning (Kember, Wong & Leung, 1999). This correlation, however, tends to further weaken the questionnaire as a measure of deep and surface learning.

The correlation between prior knowledge (pre-test) and deep learning was not significant, counter to that predicted by hypothesis 2 (page 195). There was, however, a statistically significant negative correlation between prior knowledge and surface learning, consistent with hypothesis 2. This may suggest that limited prior knowledge encourages a surface approach to learning and students with high prior knowledge are less likely to adopt surface approaches to learning.

The correlation between deep learning and attitude towards chemistry was positive but not statistically significant, contrary to the prediction of hypothesis 3 (page 195).

### 3.4.4.4. **Linearity**

Scattergrams were plotted between dependent and independent variables to examine the assumption of linearity (see Appendix E). There appear to be curvilinear relationships between transformed GEFT scores and some dependent variables, in particular post-test scores (see Figure 3.10). Whether or not these are true relationships requires closer examination in further research. The lack of normality in the transformed GEFT scores may contribute to a lack of linearity in these relationships. Furthermore, there seem to be two data points (transformed GEFT scores of 0) that distort the general shape of the relationships. It cannot be assumed that these outliers are not valid data points. Therefore, it is not justifiable to remove them from the sample. No further transformations could be performed on the data to remedy the non-linearity.
The relationship between deep learning and transformed topic-transfer scores (see Figure 3.10) also appeared to be non-linear, with the spread of topic-transfer scores increasing with higher deep-learning scores.

Rather than invalidating the analysis, the lack of linearity may result in an underestimation of $R^2$ values in the linear regressions (Miles & Shevlin, 2001).

### Figure 3.10 Examples of non-linear relationships between dependent and independent variables. Independent variables are plotted on the x-axis.

#### 3.4.5. Multiple Regression Analysis

Multiple linear regression employing the backward elimination method\(^\text{10}\) was used to examine the effects of the independent variables on the post-test, transfer-test components and pre–post gain. Factors with a probability of less than 0.1 were retained in the equation, to yield “best models” for predicting outcome on the dependent variables. Analyses were performed using SPSS 11. Assumptions were once again checked in relation to the variate, by examining normal probability plots and scatterplots of the standard residuals, in order to evaluate the robustness of the analysis. Figure 3.11 and Figure 3.12 show sample plots in which the assumptions are met and in which they are violated, for comparison.

---

\(^{10}\) This method was adopted in order to reduce the number of variables in the final regression equation, which was necessary due to the small sample size.
Figure 3.11  Normal probability plots (Hair, Anderson, Tatham and Black, 1998)

(a) Homoscedastic     (b) Non-normal     (c) Non-linear     (d) Heteroscedastic

Figure 3.12  Scatterplots of standard residuals (Tabacknick and Fidell, 2001)
3.4.5.1. **Post-test**

Regression analyses using the post-test as the dependent variable yielded the statistics shown in Table 3.10. Prior knowledge (+), disembedding ability (+)\(^{11}\), surface learning (-) and deep learning (+) were found to account for 76% of the variance in the post-test scores. This value is high suggesting a good model fit, but as suggested earlier, the apparent non-linear relationship between disembedding ability and post-test scores may have led to an underestimation of the extent of the true relationship.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standardised coefficient (Beta)</th>
<th>Significance (p)</th>
<th>Adjusted(^{12}) R(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prior knowledge</td>
<td>0.575</td>
<td>&lt; 0.0001</td>
<td></td>
</tr>
<tr>
<td>Disembedding ability</td>
<td>(-) 0.428</td>
<td>&lt; 0.005</td>
<td></td>
</tr>
<tr>
<td>Surface Learning</td>
<td>- 0.494</td>
<td>&lt; 0.05</td>
<td></td>
</tr>
<tr>
<td>Deep learning</td>
<td>0.617</td>
<td>&lt; 0.005</td>
<td>0.758</td>
</tr>
</tbody>
</table>

**Table 3.11** Linear regression model - post-test scores as a function of prior knowledge, disembedding ability, surface learning and deep learning

The normal probability plot of the regression-standardised residuals (Figure 3.13) demonstrates some slight departure from normality, as shown by the deviation of some data points from the diagonal. This may be a result of the lack of normality of the GEFT data; therefore, nothing can be done to remedy this situation short of repeating the experiment with a larger sample. These results, therefore, should be treated with some caution.

---

\(^{11}\) Regressions were performed with the transformed data for the GEFT. Reflecting the scores reverses their order hence the sign of the coefficient in the regression equation shown in Table 3.11 does not reflect the true directionality of the relationship between the variables.

\(^{12}\) For a small sample the R\(^2\) value tends to be an overestimation of the true value in the population (Pallant, 2001). The adjusted R\(^2\) value gives an estimate of the value of R\(^2\) in the population, rather than the sample.
Figure 3.13 Normal probability plot of regression-standardised residuals, with post-test as the dependent variable

Figure 3.14 Scatterplot of the standardised residuals with post-test as the dependent variable

The scatterplot of the standardised residuals (Figure 3.14) is difficult to interpret because of the limited number of data points. The uneven distribution of scores above and below the zero standard residual once again demonstrates some deviation from normality. Non-linearity may also be present, as indicated by the curvature of the data points. Violation of these assumptions does not invalidate the analysis so much as weaken it. Violation of these assumptions may indicate that there is a more complex relationship between the variables than has been considered. There may, for example, be interactions between the variables in the model such that these variables act together to produce a certain result on the post-test (Miles & Shelvin, 2001).
3.4.5.2. Pre–Post Gain

A similar regression analysis was performed with pre–post gain as the dependent variable. Prior knowledge (−), disembedding ability (+), surface learning (−) and deep learning (+) were found to be the most significant factors affecting pre–post change, accounting for 45% of the variance, but in this case, prior knowledge had a negative impact on the outcome.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standardised coefficient (Beta)</th>
<th>Significance (p)</th>
<th>Adjusted R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior knowledge</td>
<td>−0.638</td>
<td>&lt;0.005</td>
<td></td>
</tr>
<tr>
<td>Disembedding ability</td>
<td>0.643</td>
<td>&lt;0.005</td>
<td>0.453</td>
</tr>
<tr>
<td>Surface learning</td>
<td>−0.743</td>
<td>&lt;0.05</td>
<td></td>
</tr>
<tr>
<td>Deep learning</td>
<td>0.928</td>
<td>&lt;0.005</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.12 Linear regression model - pre–post gain as a function of prior knowledge, disembedding ability, surface learning or deep learning

The normality plot, with pre–post gain as the dependent variable, is identical to that for the post-test and hence indicates some deviation from normality. The uneven distribution of scores above and below the zero residual in the standardised residuals (Appendix E) plot also indicates non-normality.

3.4.5.3. Transfer Test

Regression analyses were performed to examine the effects of the independent variables on each section of the transfer test. Prior knowledge (+) was found to be the only variable affecting outcome in the direct and applied sections of the test, accounting for 29% and 36% of the variance, respectively. Deep learning (+), surface learning (−) and, to a lesser extent, disembedding ability (+), were found to account for 27% of the variance in the topic-transfer scores.
<table>
<thead>
<tr>
<th>Variable</th>
<th>Standardised coefficient (Beta)</th>
<th>Significance (p)</th>
<th>Adjusted R²</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direct Transfer</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prior knowledge</td>
<td>0.570</td>
<td>&lt; 0.01</td>
<td>0.291</td>
</tr>
<tr>
<td><strong>Applied Transfer</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Prior knowledge</td>
<td>0.624</td>
<td>&lt; 0.005</td>
<td>0.359</td>
</tr>
<tr>
<td><strong>Topic Transfer</strong></td>
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<td></td>
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</tr>
<tr>
<td>Disembedding ability</td>
<td>(–) 0.396</td>
<td>&lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>Deep learning</td>
<td>0.629</td>
<td>&lt; 0.1</td>
<td></td>
</tr>
<tr>
<td>Surface learning</td>
<td>– 0.801</td>
<td>&lt; 0.05</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.13  Linear regression models – factors affecting outcome on direct, applied and topic-transfer tests

The variate for direct transfer had a normal distribution but showed some slight heteroscedasticity, perhaps indicating interaction with a variable not included in the analysis. Data for the applied-transfer section did not appear to substantially violate the assumptions of normality, linearity or homoscedasticity based on observation of the residual plots (Appendix E).

For the topic-transfer regression analysis, the normality assumption was met. There was perhaps some slight heteroscedasticity (Appendix E). This may be partially a result of the non-linear relationships between GEFT and topic transfer, as well as between deep learning and topic transfer, or some interaction with a variable not represented in the regression equation. The low $R^2$ value may be partially a result of the violation of this assumption. Therefore, once again, the results are only tentative and must be treated with caution. Follow-up studies are required to substantiate the findings of this study.

### 3.4.5.4. Generalisability of Results

In this study, two issues threaten the generalisability of the results: the small sample size and the violation of some assumptions. Whether or not results can be extrapolated to the population depends on the ratio of the sample size to the number of independent variables, and whether or not the sample is representative of the population. A small sample size can lead to overfitting of the data and hence a lack of generalisability. The absolute minimum requirement is that there be five cases for each independent variable (Hair et al., 1998). The minimum criteria were satisfied in the regression equations derived from this study, with a
maximum of four independent variables and a sample size of 22. Furthermore, the adjusted $R^2$ values rather than the $R^2$ values were quoted to give an estimated value for the population rather than the sample. This was done in order to provide a better idea of the generalisability of results. Tabacknick and Fidell (2001), however, suggest that an appropriate sample size to ensure generalisability and statistical power should be calculated from the following equation:

$$ N \geq 50 + 8m \text{ (where m is the number of independent variables) } $$

Moreover, even larger sample sizes are needed where small effect sizes are anticipated. In terms of this definition, the sample size in this study is grossly inadequate.

Small sample sizes also require rigorous attention to assumptions. Large sample sizes, on the other hand, “diminish the detrimental effects of non-normality” (Hair et al., 1998) and reduce the impact of occasional outliers. In this study, assumptions of non-normality, linearity and homoscedasticity were violated to some extent and influential data points remained in the data set to avoid further reduction of the sample size, effectively weakening the analysis.

This study is worth replicating with a larger sample size to validate the results of this study.

3.4.6. **Working-Memory Capacity**

Analysis of working-memory capacity was completed separately due to the restricted sample size for this variable (N = 13, seven male, six female; median age of 18; nine had completed HSC chemistry, one had completed year 11 chemistry only, and three had not studied HSC chemistry). The relationship between working-memory capacity and the dependent variables was explored using Pearson correlation coefficients. The relationship between working memory and disembedding ability was also examined.

Spearman-Brown’s split-half reliability coefficient for the FIT was calculated to be 0.87 (N = 13). Therefore, the FIT has good internal consistency. The normality of the variables was checked using the Shapiro-Wilks statistic (see Appendix E). All variables, excluding disembedding ability, showed normal distributions. The GEFT scores were transformed using reflect then logarithm to produce a normal distribution.
Table 3.14 shows Pearson correlations between FIT scores and the dependent variables. There was a statistically significant correlation between FIT scores and post-test scores ($p < 0.05$) but not between FIT scores and pre–post gain, partially supporting hypothesis 8 (page 196). A very highly statistically significant correlation was found between FIT scores and topic transfer ($p < 0.01$). The inclusion of working-memory capacity as a predictor of topic-transfer scores would likely improve the model fit substantially.

<table>
<thead>
<tr>
<th></th>
<th>Post-test</th>
<th>Pre–post Gain</th>
<th>Direct Transfer</th>
<th>Applied Transfer</th>
<th>Topic Transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td>FIT</td>
<td>0.594*</td>
<td>0.227</td>
<td>0.390</td>
<td>0.345</td>
<td>0.815**</td>
</tr>
</tbody>
</table>

*correlation significant at 0.05 level (2-tailed)
**correlation significant at 0.01 level (2-tailed)

Table 3.14  Pearson correlation coefficients between FIT scores and dependent variables

FIT scores were also found to correlate significantly ($r = -0.592$, $p < 0.05$) with transformed GEFT scores, such that disembedding ability correlates positively with working-memory capacity. This would be expected if the GEFT measures, at least in part, working-memory capacity.

### 3.5. Discussion 2000

Regression analysis involves the construction of an equation that can be used to predict an outcome. It cannot be inferred from this that the variables forming the equation cause the outcome. The following discussion, therefore, incorporates interpretations of the results in terms of cause and effect rather than statements of fact. Furthermore, due to the small sample size, small effect sizes would not be detected. Furthermore, some assumptions of regression analysis were violated, possibly weakening the results. Conclusions are, therefore, tentative but pave the way for future research in the area.

#### 3.5.1. Hypotheses

*Prior knowledge will correlate positively with performance on the post-test and pre–post gain.*

Prior knowledge was found to be the most significant factor influencing the post-test results. This finding is consistent with much earlier research on the effect of prior knowledge on
learning and understanding. It confirms the role of the long-term memory in learning new information and suggests that prior knowledge of images has influenced students’ ability to interpret certain details in the animations.

Prior knowledge, however, correlated negatively with gains from pre-test to post-test, suggesting that students with low prior knowledge in fact learnt more from the instruction than those with high prior knowledge. This is perhaps not surprising considering that students with low prior knowledge had less-developed images before instruction and, therefore, more potential for progress. This observation is consistent with research by Mayer (1997) showing that students with low prior knowledge experienced greatest gains from exposure to instruction using animations.

Furthermore, the way the animations were presented, with key features directly pointed out, meant that students did not have to rely entirely on prior knowledge to interpret them. This method of instruction using the animations appears successful in helping novices develop basic mental models.

*Prior knowledge will correlate positively with performance on the transfer test.*

Prior knowledge was also a significant factor predicting the results on the direct and applied sections of the transfer test, confirming this hypothesis. Prior knowledge may allow students to create links between new information and old in the LTM, establishing a structured cognitive network that can be accessed in transfer situations. Prior knowledge of basic molecular and ionic substances did not assist students when dealing with more distantly related topics. It therefore appears that, for prior knowledge to be useful, it must be deemed relevant to the transfer situation. As also demonstrated in Chapter 2, Section 2.2.5.3, students, in general, did not see a direct relationship between the animations and the topic-transfer questions, so it is perhaps not surprising that prior knowledge had little effect.

*As a consequence of this, students’ prior knowledge in chemistry will also correlate significantly and positively with students’ deep-learning scores.*

A non-significant negative correlation was demonstrated between prior knowledge and deep learning, suggesting that a high level of prior knowledge does not necessarily encourage a
deep approach to learning. Many factors are thought to influence a student’s choice of study style. Biggs (1987) explained that personal factors, such as age and control over one's learning, or situational factors, such as stress and imposed expectations, influence students' approaches to learning. Trigwell and Sleet (1990) discussed how the nature of assessment can encourage different approaches to learning. Prosser (2000) claimed students' previous experiences and understanding, together with the nature of the teaching, influenced students’ perceptions of the context (e.g., clear goals, good teaching, heaviness of workload), which in turn influenced their approaches to learning. In this study, any effect of prior knowledge on students’ adoption of deep learning approaches may have been obscured by other important factors.

Surface learning, on the other hand, was found to correlate significantly and negatively with prior knowledge, consistent with this hypothesis. This suggests that students with a high level of prior knowledge adopt surface strategies less often than those with a low level of prior knowledge. The adoption of surface strategies by novices may be a means of reducing the cognitive load of the information being learnt. Students with high prior knowledge are more likely to have more highly structured conceptual frameworks that enable them to see some information in “chunks”, thereby reducing the cognitive load of new information (Sweller, 1993). If this is the case, then it might be expected that students with low working-memory capacity might also adopt surface strategies. To check this inference, the Pearson correlation coefficient between surface learning and working-memory capacity was calculated. The correlation was found to be statistically significant ($r = -0.739, p < 0.01$), with use of surface strategies increasing with a decrease in working-memory capacity.

Students’ attitudes to chemistry on entering university correlate positively with post-test and transfer test results, and pre–post gain.

Attitudes to chemistry did not seem to serve as a contributing factor in the development of students’ mental models, with neither component (attitude or simplicity) retained in the regression models. The effect size of attitudes on the development of students’ mental models is likely to be small, hence larger sample sizes may be needed to detect a relationship.

As a consequence of this, students’ attitudes to chemistry will correlate positively with students' deep-learning scores.
Accordingly, attitude to chemistry did not correlate significantly with deep-learning scores, although the correlation was positive. As suggested, many factors may influence the study style adopted by students, reducing any effect of attitude on the adoption of deep-learning strategies.

*Visual imaging ability will correlate positively with post-test and transfer test results, and pre–post gain.*

Results suggest that visual imaging ability, as measured by the VVIQ, had no influence on scores for the post-test or transfer test, or on pre–post gain. This lack of effect is counter to the original hypothesis. It might be that all individuals with normal vision and brain function have a similar ability to register the visual features of a stimulus.

Other possible reasons for the lack of effect include the nature of the questionnaire devised by Marks and the small sample size. The lack of effect is discussed more fully in Section 3.5.2.

*Students whose study style is aimed at deep learning will perform better on the transfer test, so deep-learning scores will correlate significantly and positively with transfer-test scores.*

Linear regression showed that deep learning significantly influenced overall scores for the topic-transfer test but not in the direct and applied sections. It is not surprising that deep learners were more successful at answering problems that were less obviously, or more remotely, related to the examples studied in class.

Deep learning was also found to be a significantly involved in students’ ability to develop mental models of substances shown in the animations, as examined by the post-test. This suggests that the open-ended-style questions used in this questionnaire examined understanding and not simply rote-learnt concepts.

*Conversely, those students showing a tendency to adopt surface approaches to learning will perform poorly on the transfer test, and surface learning scores will correlate significantly and negatively with transfer-test scores.*
Surface learning had a statistically significant negative effect on the topic-transfer section results, partially confirming this hypothesis. Students who solely adopt superficial learning strategies may then struggle to answer problems that are not explicitly taught in class because they tend to limit their study to what will be assessed.

Surface learning was found to have a negative impact on students’ ability to develop mental models of substances shown in animations, as examined by the post-test. Once again, this suggests that the questionnaire examined understanding.

Disembedding ability will correlate positively with post-test and pre–post gain.

Disembedding ability was found to significantly influence students’ results on the post-test and on pre–post gain. This suggests that an ability to extract details from a complex background is necessary to interpret animations or to extract information from molecular-level diagrams. This result supports the inclusion of the attention networks in the perception model and its function of “focusing attention on relevant information and processes and inhibiting irrelevant ones”.

Disembedding ability was also found to play a minor role in students’ ability to transfer information to new topics. Disembedding ability may play a role in assisting students to select appropriate ideas for transfer to new situations.

Visuospatial working-memory capacity will correlate positively with results on the post-test and with pre–post gain.

Although the sample size for this component was small, working-memory capacity still correlated significantly with post-test results (p < 0.05). This may indicate the role of the working memory in the perception of an animation, further supporting the proposed model. It is likely that the FIT also utilises the attention networks, as the questionnaire once again appears to require disembedding ability. Similarly, the GEFT would utilise the working memory, insofar as shapes need to be stored in the working memory while they are searched for. This idea is supported by the fact that the FIT and GEFT correlate significantly with each other, and is consistent with the fact that the attention networks and working memory are closely linked and work together in many cognitive activities (MacDonald et al., 2000).
Working-memory capacity also significantly influenced the results on the topic-transfer test. This may suggest that questions on this section of the transfer test exceeded some students’ working-memory capacity. Alternatively, it may indicate that working-memory capacity influences the student’s ability to relate prior knowledge to new stimuli, perhaps because working-memory space is required to search the LTM and consider the new stimulus simultaneously. The effect of visuospatial working-memory capacity on the development of mental models in chemistry warrants further investigation.

3.5.1.1. Summary

The highest post-test scores were obtained by students with high prior knowledge, high disembedding ability and high visuospatial working-memory capacity, who adopted deep-learning strategies and limited their use of surface strategies.

Greatest gains (from pre-test to post-test) were achieved by students with low prior knowledge who had high disembedding ability and used deep-learning strategies in preference to surface strategies.

Students with high prior knowledge were more able to apply their knowledge to clearly related situations. For transfer problems, where the connection between the measured prior knowledge and the questions was not clear, students with high disembedding ability, high visuospatial working-memory capacity, who preferred deep learning over surface learning, excelled.

Based on the findings of this research, it is proposed that:

- A combination of high prior knowledge and high disembedding ability allows a student to identify (or notice) the relevant features in an animation, due to the activation of the attention networks and the LTM.

- Adoption of deep-learning strategies and/or high prior knowledge allows a student to relate these features to ideas in the LTM, to enhance recall and understanding.
- High working-memory capacity ensures a student is able to effectively manage the information from complex animated displays, and construct and manipulate mental models of the phenomena.

A combination of all the above traits will result in the most sophisticated mental models.

These results, therefore, lend support to the proposed model of perception; in particular the involvement of the long-term memory, working memory and attention networks in learning from animations, as well as supporting the ideas of communication between the LTM and WM and the strong link between the WM and the attention networks. Whether there are differences in students’ ability to register visual features, which might interact with their ability to interpret animations, is uncertain. Much of the variance in students’ scores on the transfer test, in particular, is still unaccounted for. Therefore, some aspect of visual imaging ability that may be contributing, might become apparent with larger sample sizes or the use of an alternative questionnaire.

### 3.5.2. General Discussion

Useful information from this study relates to some of questionnaires used. The following section constitutes a close examination of the CSPQ, VVIQ and GEFT, analysing some of the results found, recommending improvements to the questionnaires, and suggesting future directions for this research.

**Chemistry Study Processes Questionnaire (CSPQ)**

Previous research (Harper & Kember, 1989; Richardson, 1994; Kember & Leung, 1998) supports the notion that there are two fundamental approaches to learning: a surface approach, adopted to allow the reproduction of material, and a deep approach aimed at meaningful learning of the subject matter. In this study, however, these factors did not emerge from the CSPQ, nor did the motive or strategy sub-components of deep and surface learning. The principle components analysis revealed that the data contained multiple factors. Although the internal consistencies of the surface and deep factors were good, Cronbach’s alpha reliability index is likely to be artificially high due to the large number of items in the surface and deep categories. The more items, the smaller the inter-item correlations need to be to produce a respectable-looking alpha value (Cortina, 1993). These faults may simply be the result of the
small sample size used in this study. However, examination of the questionnaire, and the literature on its construction and use, suggest a need to improve the questionnaire.

On designing the test, Biggs (1987) included different aspects of external motivation, such as the possibility of a good career and fear of failure, under the category “surface motives”. These separate factors are added together when scoring. Kember et al. (1999) showed that “fear of failure” and “career motive” appeared to be distinct factors.

Furthermore, it has since been shown (Kember et al., 1999) that studying for a career can encourage a meaningful approach to learning, and therefore, this kind of motivation should be considered positive, rather than negative, as the following quote demonstrates:

“Taken together the above discussion suggests that this career related form of extrinsic motivation should not be seen in a negative light. A course which provides a good preparation for a future career appears to motivate students to study and to study for understanding. Further, our transcripts showed no evidence of incompatibility between intrinsic interest and career motivation” (p. 329).

The problem described above is made more complicated by the fact that the double-barrelled wording of a question relating to career motive assumes that there is “a dichotomy between intrinsic interest and the job situation”, making the statement difficult to respond to by those “employing a meaning orientation, but motivated by good career preparation in a course” Kember et al. (1999).

These issues are likely to contribute to the poor factor structure of the CSPQ.

The poor factor structure of the test may also have been influenced by students’ interpretations of items in the test, some of which were double-barrelled, poorly worded, or did not fit into the intended category, as shown in Table 3.15.
### Chapter 3  
Factors Affecting Students’ Mental Models  

<table>
<thead>
<tr>
<th>Test Item</th>
<th>Perceived Problem(s)</th>
</tr>
</thead>
</table>
| 1. I am concentrating on studying chemistry largely with a view to the job situation when I graduate rather than because of how much it interests me | • Studying for a career may promote deep-learning strategies.  
• The statement is double-barrelled. Studying for a job doesn’t imply a lack of interest in the subject. |
| 6. While I realise that ideas are forever changing as knowledge is increasing, I need to discover what is meaningful for me in chemistry | • This item may have caused confusion. The connection between the first and second half of the statement is not clear.  
• The statement is double-barrelled. Realisation of knowledge as progressive doesn’t necessarily mean that a student will learn meaningfully. |
| 7. I learn **some** things by rote, going over and over them until I know them by heart | • **Some** rote learning may need to occur (*e.g.*, formulae for polyatomic ions) whether the student adopts a deep or surface approach.  
• Memorising and understanding need not be mutually exclusive (*Kember et al.*, 1999; *Sachs & Gao*, 2000). |
| 11. In studying chemistry I am focusing more on the factual content than the theoretical material | • Students may not be aware of the distinction between theory and fact. |
| 19. I learn best from chemistry lecturer(s) who work from carefully prepared notes and outline major points neatly on the board | • All students (both deep and surface learners) tend to appreciate clearly presented instruction as demonstrated by student evaluations of lecturers (*Hager, Sleet & Kaye*, 1994). |
| 25. I am prepared to work hard in chemistry because I feel it will contribute to my employment prospects | • Studying for a career may promote deep-learning strategies (*Kember et al.*, 1999). |

**Table 3.15** Perceived problems with items on the CSPQ

In this study, a high correlation was found between deep and surface learning. This might be a result of students attempting to both understand and memorise the material, a phenomenon common amongst Asian students (*Kember et al.*, 1999) and not taken into account in the SPQ. This suggests that surface and deep learning may be independent dimensions and not opposite ends of a continuum.

Problems associated with the SPQ (and modified versions of it) may be responsible for the lack of anticipated correlations in studies in which the SPQ was used. For example, in an exploration of the relationship between critical thinking skills and study strategies, *Hager, Sleet and Kaye* (1994) failed to find a significant correlation between deep or surface study strategies and critical thinking ability, but did find a relationship between critical thinking and a students’ ability to relate new material to previously learnt material to heighten understanding.
Due to the apparent flaws in the SPQ, it may be advisable to use or design an alternate measure of learning style, or to redesign the SPQ to remove some its drawbacks. A test that takes into account the different factors present in the SPQ could be used as a diagnostic instrument to indicate where problems might lie, and allows the specific difficulty to be targeted. For example, if students are anxious about their marks and this is adversely affecting their performance or their ability to learn deeply, then this issue can be addressed. This level of detail is lost in a questionnaire that sums over a number of individual factors. Kember et al. (1999) proposed the construction of a simple two-factor (surface and deep approaches) instrument for teaching evaluation and simple research, as well as a more complex instrument that takes into account some of the criticisms of the SPQ. When their paper was published, work was underway, in conjunction with Professor John Biggs, to design the two-factor version (Kember et al., 1999).

A learning style questionnaire (Inventory of Learning Styles, ILS) recently designed by Vermunt (1996) appears to overcome some of the concerns relating to the SPQ. For example, it includes a separate learning style for students who study with the intention of applying the information in a related career. Furthermore, it takes into account the multi-faceted nature of learning styles.

Vermunt (1996) categorised interview responses from university students into the following styles:

*Undirected*: Students who demonstrate this approach express concern over their inability to distinguish important details to learn. They are unsure of the best methods to study and rely on external regulation for what and how to study. They engage in little processing of the information.

*Reproduction-Directed*: This category corresponds to "surface learners". These students aim to reproduce information through memorisation and rehearsal in order to pass exams. They rely on external regulation to indicate important features to memorise. Cognitive processing is done in a stepwise fashion.

*Meaning-Directed*: This category corresponds to "deep learners". Students adopting this approach select main points based on intrinsic interest. They attempt to interrelate material. Their approach to study is regulated internally - selecting, relating and analysing are activated by the student. These students engage in deep processing of the material.
Application-Directed: These students see learning as the first step to a career and therefore pay attention to features in the instructional material that have practical relevance. They search for relations between subject matter and the reality to which it refers. They attempt to apply the content. They use concrete processing, seeing no practical use for abstract material.

Vermunt (1996) further elaborates these learning styles by examining each in relation to the nature of cognitive processing, the regulation of learning, affective processes, the mental model of learning, and learning orientation (motive for learning). Table 3.16 outlines the relationship between these components and the four learning styles.

<table>
<thead>
<tr>
<th>Components</th>
<th>Undirected</th>
<th>Reproduction-directed</th>
<th>Meaning-directed</th>
<th>Application-directed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cognitive Processing</td>
<td>Hardly any processing</td>
<td>Stepwise processing</td>
<td>Deep processing</td>
<td>Concrete processing</td>
</tr>
<tr>
<td>Regulation of Learning</td>
<td>Lack of regulation</td>
<td>Mostly external regulation</td>
<td>Mostly self-regulation</td>
<td>Both external and self-regulation</td>
</tr>
<tr>
<td>Affective Processes</td>
<td>Low self-esteem</td>
<td>Failure expectations</td>
<td>Fear of forgetting</td>
<td>Intrinsic interest</td>
</tr>
<tr>
<td>Mental Model of Learning</td>
<td>Cooperation and being stimulated</td>
<td>Intake of knowledge</td>
<td>Construction of knowledge</td>
<td>Use of knowledge</td>
</tr>
<tr>
<td>Learning Orientation</td>
<td>Ambivalent</td>
<td>Certificate- and self-test-oriented</td>
<td>Person-oriented</td>
<td>Vocation-oriented</td>
</tr>
</tbody>
</table>

Table 3.16 Learning styles and their components (Vermunt, 1996)

Vividness of Visual Imagery Questionnaire (VVIQ)

Discussion of the construct validity and reliability of the VVIQ has been extensive, examining the definition of vividness (Denis, 1995; Hishitani, 1995), gender effects (Richardson, 1995), dimensionality (Kihlstrom, Glisky, Peterson, Harvey & Rose, 1991; McKelvie, 1993) and the emotional contribution to imaging ability (McKelvie, 1993; Hishitani, 1995), for example. These issues, however, will not be considered here. The interested reader is referred to
McKelvie (1995) for a comprehensive overview of research relating to the VVIQ. More pertinent here are the concerns relating to the range of the data and the subjective nature of the questionnaire, which have a bearing on the statistical analyses conducted in this study.

Data collected with the VVIQ showed all students reporting at least moderately vivid images and many reporting extremely vivid images. This phenomenon is apparently common (Kihlstrom et al., 1991; McKelvie, 1995). It is not certain whether it is the result of response leniency, or is a physiological phenomenon. McKelvie states:

“It is also possible that the distribution of scores is not a reflection of biased or careless responding, but of the universality of imagery, and perhaps even of vivid experiencing.” (pp. 16–17)

According to this viewpoint, it would be extremely difficult to obtain subjects with poor imaging ability in order to increase the range of the data. The poor spread of responses makes the VVIQ “relatively insensitive to individual differences in imagery ability” (Kihlstrom et al., 1991) and a poor predictor of performance. As a consequence, Kihlstrom and co-workers state that “the common practice in imagery experiments of administering the tests to a small random sample of subjects, and then correlating imagery test scores with performance on some experimental task, will rarely reveal an effect of individual differences.” This is one possible cause of the lack of effect found in this study. Studies involving the VVIQ, therefore, generally adopt the method of comparing extreme groups, that is, comparing the top (“good” imager) and bottom (“poor” imager) quartiles, for example. Larger percentiles reduce the possibility of finding a relationship (McKelvie, 1995). In this study, a median split was adopted, due to the small sample size. No significant differences were found. Comparing quartiles would have reduced the sample sizes further. The study might be worth repeating with a larger sample size. However, Kihlstrom et al. (1991) point out that “even with an extremely large population of subjects to choose from, the group of ostensibly poor imagers” in their study “actually included many subjects whose ability to form at least some images may have been fairly good” (p. 140).

One possible avenue by which to increase the range of the data includes using a randomised version of the VVIQ (McKelvie, 1993). Randomising the items in the VVIQ, rather than presenting them in blocks of related images, has been shown to reduce skewing and decrease
students’ ratings of imagery vividness. Unfortunately, this may also reduce the reliability and validity of the VVIQ.

One final concern with the VVIQ is that, like all self-rating questionnaires, there is no guarantee that a high score made by one subject equates to a high score made by another subject. Comparisons can only reasonably be made between reports by the one subject. As McKelvie (1995) puts it, “similar mental experiences among subjects may be given different ratings, and different mental experiences may be given the same ratings, thereby introducing unsystematic error that may suppress between-subjects comparisons” (p. 10). Unfortunately, “critics…agree that self-reports are required to investigate visual imagery as a phenomenal event” (p. 6). Therefore, at this point in time, there does not seem to be an easy way around this dilemma. Perhaps brain-scanning techniques will help to resolve the problem in the future.

Despite the difficulties associated with measuring mental imagery, it cannot be discounted that students’ ability or tendency to construct and manipulate mental images may still be related in some way to students’ ability to learn from animations and to apply mental models in new situations. Therefore, a literature search was conducted in an attempt to locate a more objective test relating to students’ use of visual imagery. This search uncovered Riding’s Cognitive Styles Analysis (CSA).

Riding (1998) designed the CSA as a more objective test to assess imagery-related tendencies. He believes that a continuum exists between those students with strong visual preferences and those with strong verbal preferences, in relation to how they prefer to mentally represent information. Verbalisers tend to represent information as words or verbal associations. Imagers tend to experience fluent, spontaneous and frequent visual imagery (Riding, Dahraei, Grimley & Banner, 2001). This continuum represents a cognitive style designated the “verbal-imagery dimension”.

Cognitive styles are defined as "individual differences in how we perceive, think, solve problems, learn, relate to others" (Witkin et al., 1977, p. 15). They are bipolar dimensions, "considered to be a fairly fixed characteristic of an individual" (Riding & Sadler-Smith, 1992, p. 323).
In line with the idea that all subjects are capable of creating vivid mental images, Riding et al. (2001) suggest that both imagers and verbalisers can use either mode of representation if need be, but "taken overall, generally imagers prefer and learn best from pictorial presentations, while verbalisers learn best from verbal presentations" (p. 9).

The CSA can only provide an indication of a student’s preferred mode of thinking. Therefore, the score of one student cannot be compared to the score of another to make a judgement on the relative imaging abilities of these students. However, it might be that students with a preference for learning from and creating visual images are more likely to pay attention to and learn from animations. This hypothesis was tested in a follow-up study conducted in 2001 and the results are presented in Section 3.6.

Group Embedded Figures Test (GEFT)

Disembedding ability was shown to be a significant predictor for three of the dependent variables studied. This factor, therefore, appears to play a significant role in learning chemistry.

The major concern over the use of the GEFT, however, was that the scores were skewed towards greater disembedding ability, posing problems for parametric statistical analysis. This cannot be the result of response leniency because the test is objective, but instead must result from the true nature of the students. The result is somewhat expected in light of the fact that high disembedding ability represents greater analytical ability, a skill necessary for success in the sciences. Other than transforming the data, as was done in this study, little can be done about this concern. As previously mentioned, increasing the sample size is the best method of dealing with deviations from normality.

There is also some contention over what the GEFT actually measures. Does it measure a cognitive style, as suggested by its authors, or some ability or intelligence, as presumed in this study? The difference lies in whether the scale is bipolar or whether high scores represent greater ability.

The GEFT only assesses positively one end of the field-dependence/independence style. Therefore, a low score is interpreted as a sign of field-dependence. Riding and Sadler-Smith (1992) argue that low scores may be the result of low motivation, inability to follow
instructions or a visual defect. Furthermore, the test is timed and therefore requires fast processing of information, so success might be partly an indication of general intelligence (Riding & Cheema, 1991). Witkin and coworkers (1977) claim that this is not the case, and this is supported by the fact that field-dependent individuals may excel in different areas of study, as compared with field-independents. The suggestion made by Riding and Cheema (1991) that the GEFT measures spatial intelligence is more credible. Although this suggestion has been refuted by some (Howe & Doody, 1989), it is consistent with the fact that GEFT scores in this study correlated significantly with a measure of visuospatial working-memory capacity (FIT).

Riding designed the CSA to measure both ends of the wholist–analytic continuum, producing a result based on the ratio of the times taken to respond to analytic or wholist based questions. This dimension was derived, in part, from Witkin's field-dependence/-independence construct, and similarly is thought to assess whether an individual tends to process information in wholes (wholist) or parts (analytic) (Riding & Sadler-Smith, 1992). Because it is measured in a different way, however, it is seen to be slightly different.

Based on the results for disembedding ability in 2000, there is some reason to believe that analytics may outperform wholists on the post-test. This hypothesis was tested in the follow-up study, with results reported in Section 3.6, to determine if a certain ability (spatial, general intelligence) or cognitive style is responsible for the observed effect of disembedding ability on mental model development.

### 3.6. Research Hypotheses 2001

Results from Chapter 2 suggest that students’ understanding of atoms, ions and molecules may influence their ability to interpret animations. This prompted the addition of a series of questions to the pre-test to evaluate this understanding. This understanding has been labelled “basic skills” and its effect on students’ mental model development is examined in this section. Also examined is the effect of cognitive style, as discussed in Section 3.5.2.

The following hypotheses were constructed for the 2001 study:
1. The 2001 data will confirm the contribution of prior knowledge and disembedding ability to students’ development of mental models, as assessed by the post-test and pre–post gain.

2. Students who have well developed basic skills in chemistry, relating to atoms, ions and molecules, will be more successful at interpreting animations due to their greater prior understanding and will, therefore, score higher on the post-test and show greater pre–post gains.

3. Imagers will learn more effectively from animations than verbalisers and will, therefore, score more highly on the post-test and show greater pre–post gains.

4. Analysts will be more likely to focus on the details within a complex visual animation and will, therefore, perform better on the post-test and show greater pre–post gains than wholists.

3.7. Methodology 2001

A sub-group of students from the 2001 sample described in Chapter 2, Section 2.2.2.1, were administered a variety of questionnaires to evaluate various individual attributes. The group comprised 34 students (17 male, 17 female; median age 18.5). Of the 34 students, 29 had previously completed chemistry at HSC level (two-unit Chemistry, three-unit Science or equivalent), three had not studied beyond junior (Year 9/10) chemistry, one had studied Year 11 chemistry only and one was of unknown background. Questionnaires were administered at varying times throughout the year, as time allowed. Table 3.17 lists the semesters and weeks in which various questionnaires were completed, whether they were distributed in lectures, laboratories or tutorials, and the estimated time for completion (including instructions).

<table>
<thead>
<tr>
<th>Questionnaire</th>
<th>Week/Semester</th>
<th>Class distributed</th>
<th>Approximate time for completion (minutes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test</td>
<td>1/1</td>
<td>Lecture</td>
<td>50</td>
</tr>
<tr>
<td>Basic Skills</td>
<td>1/1</td>
<td>Lecture</td>
<td>10</td>
</tr>
<tr>
<td>GEFT</td>
<td>1/1</td>
<td>Laboratory</td>
<td>20</td>
</tr>
<tr>
<td>Post-test</td>
<td>11/1</td>
<td>Lecture</td>
<td>50</td>
</tr>
<tr>
<td>CSA</td>
<td>2/2</td>
<td>Laboratory</td>
<td>15</td>
</tr>
</tbody>
</table>

Table 3.17 Questionnaire distribution timetable (2001)
3.7.1. **Independent Variables**

3.7.1.1. **Prior Knowledge**

The questionnaire used to assess prior knowledge in 2001 was almost identical to that used in 2000 with a few minor modifications, as discussed in Chapter 2. (Copies of the original questionnaire and modified questions are available in Appendix A).

3.7.1.2. **Basic Skills**

Extra questions were added to the pre-test to determine if other aspects of students’ prior knowledge regarding atoms, ions and molecules influenced the results of the post-test. These questions required students to match formulae and symbols with chemical names, to discriminate between atoms, ions and molecules displayed as formulae or images, to write the physical states of various substances at room temperature, and to determine whether these same substances were made up of ions or molecules. A copy of the questions is available in Appendix A.

3.7.1.3. **GEFT**

The Group Embedded Figures test (described in Section 3.3.1.5) was once again used to measure disembedding ability (see Appendix B for sample problems).

3.7.1.4. **Cognitive Style**

A computer-delivered test of cognitive style (the Cognitive Styles Analysis or CSA), developed by Riding (1998), was administered. This test assesses two distinct dimensions of cognitive style – a verbaliser/imager dimension and an analytic/wholist dimension. The test claims to give an overall assessment of a student’s cognitive style.

The verbaliser/imager dimension is examined using a series of right/wrong statements. Some statements require the visualisation of colours and objects (imager), whereas others are more conceptual (verbaliser). Examples of each type of statement are given in Table 3.18. The program records a subject’s response time to each of the problem types, then provides the ratio of verbal response time to visual response time. This ratio places a student along the continuum of verbalisers (low ratio) to imagers (high ratio). Students scoring intermediate ratios are designated “bimodal”.

The analytic component of the analytic/wholist dimension is assessed by monitoring how quickly subjects are able to tell if a simple shape is contained somewhere within a corresponding complex figure. The wholist component is assessed by measuring the time taken to determine if two complex figures are identical. The ratio of these times gives a subjects’ position along the analytic/wholist continuum, with high ratios indicating a relatively analytical perspective and low ratios indicating a wholist perspective. Ratios falling in between are put in an “intermediate” category.

Evidence of the validity and reliability of the questionnaire is reported in the users manual (Riding, 1998).

<table>
<thead>
<tr>
<th>Verbally-related sample item</th>
<th>Table and chair are the same type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imagery-related sample item</td>
<td>Snow and chalk are the same colour</td>
</tr>
</tbody>
</table>

Table 3.18   Sample items from the Cognitive Styles Analysis

### 3.7.2. Dependent Variables

The post-test for 2001 was almost identical to that used in 2000 except for a few minor modifications, as discussed in Chapter 2 (see Appendix A for copies of the original questionnaire and the modified questions). Progress from pre-test to post-test was also examined as a dependent variable.

### 3.8. Results 2001

The effect of the independent variables, prior knowledge, basic skills and disembedding ability, on the dependent variables, post-test scores and pre–post gain, was examined using multiple linear regression. The reliability of the questionnaires and assumptions was checked prior to conducting the analysis. The effect of cognitive style on the outcomes (post-test scores and pre–post gain) was examined via the use of t-tests. Data generated using SPSS 11 are given in Appendix E.
3.8.1. **Reliability**

Cronbach’s alpha was calculated to be 0.91 for the GEFT, which is similar to the value of 0.89 quoted by Staver and Jacks (1988) and suggests high internal consistency. Spearman Brown’s split-half reliability coefficient was calculated to be 0.94, also suggesting high internal consistency.

3.8.2. **Basic Statistics**

Descriptive statistics were calculated for each of the variables to be included in regression analyses (N = 34). These are given in Table 3.19.

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
<th>Median</th>
<th>Possible</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test</td>
<td>8.71</td>
<td>3.90</td>
<td>9.00</td>
<td>0–35</td>
<td>1–16</td>
</tr>
<tr>
<td>Basic Skills</td>
<td>32.4</td>
<td>3.09</td>
<td>32.0</td>
<td>0–37</td>
<td>26–37</td>
</tr>
<tr>
<td>GEFT</td>
<td>12.0</td>
<td>5.24</td>
<td>13.0</td>
<td>0–18</td>
<td>0–18</td>
</tr>
<tr>
<td>Post-test</td>
<td>16.0</td>
<td>4.75</td>
<td>18.0</td>
<td>0–35</td>
<td>4–22</td>
</tr>
<tr>
<td>Pre–post Gain</td>
<td>7.50</td>
<td>4.60</td>
<td>7.00</td>
<td></td>
<td>–2–17</td>
</tr>
</tbody>
</table>

Table 3.19 Basic statistics for dependent and independent variables

3.8.3. **Assumptions**

3.8.3.1. **Outliers**

Box-plots were constructed to examine the incidence of outliers (see Appendix E). The post-test data contained one outlier. Examination of a histogram of the post-test data revealed that this “outlier” was part of the tail of a negatively skewed distribution. The data was transformed to improve normality (see Figure 3.15). A box-plot of the transformed data still indicated that one outlier was present but the histogram revealed that this data point was not substantially outside the normal distribution. All data points were therefore retained in the analysis.

3.8.3.2. **Normality**

Perusal of the histograms of each variable (Appendix E), in conjunction with calculation of Shapiro-Wilks statistics (Table 3.20), suggested that the data from both the post-test and
GEFT were negatively skewed. The post-test data underwent \textit{reflect} and \textit{log10} transformations to create a normal distribution. The GEFT data was transformed with \textit{reflect} and \textit{sqrt} to produce a more normal distribution. Transformed data was used in the regression analyses (Section 3.8.4).

<table>
<thead>
<tr>
<th>Test</th>
<th>Shapiro-Wilks Statistic</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRE-TEST</td>
<td>0.968</td>
<td>0.419</td>
</tr>
<tr>
<td>BASIC SKILLS</td>
<td>0.956</td>
<td>0.184</td>
</tr>
<tr>
<td>GEFT</td>
<td>0.898</td>
<td>0.004</td>
</tr>
<tr>
<td>POST-TEST</td>
<td>0.869</td>
<td>0.001</td>
</tr>
<tr>
<td>PRE–POST GAIN</td>
<td>0.984</td>
<td>0.877</td>
</tr>
</tbody>
</table>

Tranformations

<table>
<thead>
<tr>
<th></th>
<th>Shapiro-Wilks Statistic</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reflect and Sqrt GEFT</td>
<td>0.938</td>
<td>0.054</td>
</tr>
<tr>
<td>Reflect and Log10 POST-TEST</td>
<td>0.971</td>
<td>0.504</td>
</tr>
</tbody>
</table>

Table 3.20  Shapiro-Wilks test of normality
3.8.3.3. Multicollinearity

The assumption of multicollinearity was checked by calculating Pearson correlation coefficients between independent variables (Table 3.21) and tolerance levels (Table 3.22). A statistically significant correlation between disembedding ability (GEFT) and prior knowledge (pre-test) was not high enough to cause multicollinearity according to tolerance levels.
Pre-test Basic Skills GEFT
Pre-test 1
Basic Skills 0.315 1
GEFT 0.486** –0.150

** Correlation significant at 0.01 level (2-tailed)

Table 3.21 Pearson correlation coefficients between independent variables

<table>
<thead>
<tr>
<th>Test</th>
<th>Tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test</td>
<td>0.703</td>
</tr>
<tr>
<td>Basic Skills</td>
<td>0.901</td>
</tr>
<tr>
<td>GEFT</td>
<td>0.763</td>
</tr>
</tbody>
</table>

Table 3.22 Tolerance levels with post-test as the dependent variable

3.8.3.4. Linearity

Scattergrams of independent versus dependent variables were plotted to examine the assumption of linearity. Most correlations appeared linear (see Appendix E), although the plot of basic skills versus pre–post gain appeared to have some curvature (see Figure 3.16).

![Figure 3.16 Non-linear relationship between basic skills and pre–post gain](image)

13 Correlations were calculated with the transformed data for the GEFT. Reflecting the scores reverses their order hence the signs of correlation coefficients have been changed to reflect the true directionality of the relationship between the variables.
3.8.4. Multiple Regression Analysis

Multiple linear regression employing the backward elimination method was used to examine the effect of the independent variables on the post-test and pre–post gain. Factors with a probability of greater than 0.1 were removed from the equation, to yield “best models” for predicting outcome on the dependent variables. Analyses were performed using SPSS 11. Once again, assumptions were checked in relation to the variate, by examining normal probability plots and scatterplots of the standard residuals.

3.8.4.1. Post-test

Regression analyses using the post-test as the dependent variable yielded the statistics shown in Table 3.23. Prior knowledge (+)\(^{14}\) was the only significant variable, accounting for 19% of the variance in the post-test scores.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standardised coefficient (Beta)</th>
<th>Significance (p)</th>
<th>Adjusted R(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Post-test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prior knowledge</td>
<td>(−) 0.467</td>
<td>0.005</td>
<td>0.193</td>
</tr>
</tbody>
</table>

Table 3.23 Linear regression model – post-test scores as a function of prior knowledge

Examination of the normality plot and scatterplot of the residuals revealed no substantial deviations from assumptions (Appendix E).

3.8.4.2. Pre–post Gain

The regression analysis performed with pre–post gain as the dependent variable yielded prior knowledge (−) and basic skills (+) as the most significant factors affecting pre–post change. These variables accounted for 21% of the variance, with prior knowledge having a negative impact on the outcome and basic skills having a positive effect.

\(^{14}\) Regressions were performed with the transformed data for the post-test. Reflecting the scores reverses their order hence the sign of the coefficient in the regression equation shown in Table 3.23 does not reflect the true directionality of the relationship between the variables.
### Table 3.24  Linear regression model – pre–post gain scores as a function of prior knowledge and basic skills

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standardised coefficient (Beta)</th>
<th>Significance (p)</th>
<th>Adjusted R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior Knowledge</td>
<td>-0.499</td>
<td>0.004</td>
<td>0.212</td>
</tr>
<tr>
<td>Basic Skills</td>
<td>0.343</td>
<td>0.043</td>
<td></td>
</tr>
</tbody>
</table>

The normal probability plot of the residuals revealed some slight deviation from normality (Appendix E). The scatterplot of the standardised residuals (Appendix E) showed slight spreading out of points at positive predicted values, suggesting some heteroscedasticity. This may be a result of the non-linear relationship between basic skills and pre–post gain (see Figure 3.16) and may indicate that the given R² value is an underestimation of the actual (non-linear) relationship. Violation of these assumptions suggests an interaction between these variables and a third, unidentified, variable.

### 3.8.4.3. **Further Analysis**

GEFT data were examined for possible reasons explaining why disembedding ability did not emerge as a significant factor. Two students had unusually low scores of one and zero. This is unexpected and unusual for a group of science students, in particular, and it is likely that a lack of motivation, inability to follow instructions, or a visual defect may have contributed to such a low score, as suggested by Riding and Sadler-Smith (1992). Exclusion of these cases improved the correlation between GEFT scores and post-test scores.
The analysis was therefore repeated after excluding these cases (N = 32). Assumptions were checked and transformations performed on data as described in Section 3.8.3.2 (see Appendix E).

Multiple linear regression, using the backward elimination method, once again yielded prior knowledge (+) as the only variable significantly affecting the post-test scores. Inclusion of all three independent variables, however, increased $R^2$ by a substantial amount. These models are shown in Table 3.24. Pearson correlation coefficients were calculated between dependent and independent variables to examine the relationships (signs of the correlations have been changed to represent the true direction of the relationship). The correlations were all found to be statistically significant at $p < 0.05$ (see Table 3.26). The alternative model and correlation coefficients show that the expected relationships are present in the data, when the two anomalous cases are eliminated.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standardised coefficient (Beta)</th>
<th>Significance (p)</th>
<th>Adjusted $R^2$ (sig)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Post-test: Model 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prior Knowledge</td>
<td>(-) 0.526</td>
<td>0.001</td>
<td>0.252</td>
</tr>
<tr>
<td><strong>Post-test: Model 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prior Knowledge</td>
<td>(-) 0.354</td>
<td>0.048</td>
<td>0.313</td>
</tr>
<tr>
<td>Basic Skills</td>
<td>(-) 0.270</td>
<td>0.095</td>
<td></td>
</tr>
<tr>
<td>GEFT</td>
<td>0.218</td>
<td>0.196</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.25 Comparison of linear regression models with post-test as the dependent variable

** Correlation significant at 0.01 level (2-tailed)
* Correlation significant at 0.05 level (2-tailed)

The analysis was also repeated with pre–post gain as the dependent variable. In this case, all three independent variables were found to be significant (see Table 3.27), accounting for 26% of the variance in pre–post gain.
Table 3.27  Linear regression model – pre–post gain scores as a function of prior knowledge, basic skills and disembedding ability

<table>
<thead>
<tr>
<th>Variable</th>
<th>Standardised coefficient (Beta)</th>
<th>Significance (p)</th>
<th>Adjusted R² (sig)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prior Knowledge</td>
<td>–0.584</td>
<td>0.003</td>
<td></td>
</tr>
<tr>
<td>Basic Skills</td>
<td>0.382</td>
<td>0.025</td>
<td>0.261</td>
</tr>
<tr>
<td>Disembedding Ability</td>
<td>(–) 0.346</td>
<td>0.052</td>
<td></td>
</tr>
</tbody>
</table>

The variate for the post-test (model 1) did not appear to substantially violate any assumptions. Model 2, however, showed deviation from normality but did not appear to substantially violate the assumptions of linearity and homoscedasticity. Residual plots for pre–post gain did not reveal any substantial deviations from normality, linearity or homoscedasticity. Normal probability plots and scatterplots of standardised residuals can be found in Appendix E.

3.8.5.  t-Tests

Unpaired two-tailed t-tests (equal variances not assumed) were performed to examine any differences between wholists and analysts, and imagers and verbalisers, on the post-test and with regard to pre–post gain. Tests were also performed to determine whether any differences existed prior to instruction.

Table 3.27 gives the averages and standard deviations of each group on the pre-test, post-test and with regard to pre–post gain.
Table 3.28 Averages and standard deviations (SD) on the pre-test, post-test and with regard to pre–post gain, for each cognitive style

<table>
<thead>
<tr>
<th>Style</th>
<th>Pre-test</th>
<th>Post-test</th>
<th>Pre–post gain</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Wholist</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>9.90</td>
<td>15.9</td>
<td>6.00</td>
</tr>
<tr>
<td>N</td>
<td>10</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>SD</td>
<td>3.45</td>
<td>3.45</td>
<td>3.27</td>
</tr>
<tr>
<td><strong>Analyst</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>9.33</td>
<td>16.1</td>
<td>6.89</td>
</tr>
<tr>
<td>N</td>
<td>9</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>SD</td>
<td>3.57</td>
<td>5.88</td>
<td>4.94</td>
</tr>
<tr>
<td><strong>Verbaliser</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10.8</td>
<td>17.4</td>
<td>6.63</td>
</tr>
<tr>
<td>N</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>SD</td>
<td>2.71</td>
<td>5.90</td>
<td>4.03</td>
</tr>
<tr>
<td><strong>Imager</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>8.06</td>
<td>16.0</td>
<td>8.00</td>
</tr>
<tr>
<td>N</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
<tr>
<td>SD</td>
<td>3.83</td>
<td>4.76</td>
<td>4.44</td>
</tr>
</tbody>
</table>

3.8.5.1. The Wholist/Analyst Cognitive Style

No significant differences were found between wholists and analysts on the pre-test, post-test or in regard to pre–post gain (see Appendix E for t-tests).

3.8.5.2. The Imager/Verbaliser Cognitive Style

No significant differences were found between imagers and verbalisers on either of the dependent variables (post-test, pre–post gain). However, there appeared to be a significant difference between imagers and verbalisers on the pre-test at p < 0.1 (two-tailed unpaired t-test), with verbalisers outperforming imagers (see Appendix E for t-tests). The lack of difference between the two groups on the post-test suggests that the instruction may have helped narrow the gap between verbalisers and imagers.

3.8.5.3. Comments

The above calculations assume that the populations from which the samples were drawn have normal distributions. This is a reasonable assumption for the pre-test and pre–post gain data,
considering that normality tests performed on larger sample sizes revealed normal distributions (see Table 3.17). It may not, however, be reasonable to assume the same for the post-test data, which showed a negative skew. The small sample sizes and violation of the normality assumption for the post-test data most certainly limited the detection of significant differences between students with different cognitive styles. Once again, the study should be repeated with larger sample sizes to validate the results.

3.9. Discussion 2001

The results of this study are used to substantiate and extend some of the claims made from the 2000 data. Replication of results is a reliable indicator of their validity. Once again, the sample used for this study was relatively small and some assumptions for the statistical analyses were violated, so the results should be treated with caution.

3.9.1. Hypotheses

The 2001 data will confirm the contribution of prior knowledge and disembedding ability to students’ development of mental models, as assessed by the post-test and pre–post gain.

The 2001 data confirm the contribution of prior knowledge to outcome on the post-test and the negative contribution of prior knowledge to pre–post gain.

The effect of disembedding ability did not appear quite as strong as for the 2000 data, but there is evidence to support the relationship of this trait to students’ mental model development. This suggests that the influence of this variable within the 2000 data is likely to be a true effect, but it is difficult to estimate the extent of this effect in the population because the sample sizes was small in both studies. Further research is required to substantiate this claim.

Students who have well developed basic skills in chemistry, relating to atoms, ions and molecules, will be more successful at interpreting animations due to their greater prior understanding will, therefore, score higher on the post-test and show greater pre–post gains.

In general, the results support the influence of a basic knowledge of chemistry on the development of students’ mental models. “Basic skills” was found to be a significant
predictor of pre–post gain and also correlated positively with post-test scores, suggesting that fundamental knowledge of atoms, ions and molecules may have enabled students to learn successfully from animations. This reinforces the influence of relevant prior knowledge on the development of students’ mental models.

*Imagers will learn more effectively from animations than verbalisers and will, therefore, score more highly on the post-test and show greater pre–post gains.*

No differences were found between imagers and verbalisers on the post-test or with pre–post again. However, verbalisers outperformed imagers on the pre-test. This may reflect the way chemistry is “traditionally” taught in high schools, *i.e.*, without the use of extensive visualisation. The difference between imagers and verbalisers was no longer present at the post-test, suggesting that instruction using animations may have been beneficial for imagers, allowing them visual access to material that they may have previously struggled to learn from written or verbal descriptions. These results are tentative, because the samples compared in this study were extremely small. Larger sample sizes might also reveal an effect of this cognitive style on the post-test or pre–post gain. The influence of this cognitive style on students’ learning from animations warrants further investigation.

*Analysts will be more likely to focus on the details within a complex visual animation and will, therefore, perform better on the post-test and show greater pre–post gains than wholists.*

No differences were found between analysts and wholists in the post-test or with pre–post gain. This suggests that an individual’s preferred mode of analysing material does not affect their learning from animations. It is therefore likely that ability within these preferred modes, that is how well someone performs analytically or wholistically compared with others, influences a student’s ability to learn from animations. The effect of analytical ability is demonstrated by the influence of disembedding ability on students’ mental model development.

Once again, these conclusions are only tentative because the sample size is small. Further investigation using larger samples may reveal significant effects of the wholist/analyst styles.
3.9.1.1. **Summary**

The results of this follow-up study can be summarised as follows:

- Highest post-test scores were obtained by students with high prior knowledge of ionic and molecular substances, a solid general knowledge of atoms, ions and molecules, and high disembedding ability.

- Greatest gains (from pre-test to post-test) were achieved by students with low prior knowledge who had well developed basic skills in chemistry, as well as high disembedding ability.

- Students who have a preference for learning visually may benefit from the use of animations in teaching.

These results, once again, support the model of processes involved in the perception of animations; in particular the influence of the LTM on learning, (prior knowledge, basic skills) and the involvement of the working memory and the attention networks (disembedding ability).

The relationship between preferred mode of learning (visual or verbal) and the model is not clear. A preference for visual learning may lead to activation of the attention networks when visual stimuli are shown. Alternatively or additionally, visual learners may have a greater propensity than verbal learners to register visual features mentally, supporting block 2 of the model (auto-registration of visual features).

3.9.2. **General Discussion**

R-squared values for the regression equations in this study were small compared with those in the 2000 study. This is likely to be at least partly due to the fact that deep and surface learning were not included as variables. There may also be some fundamental differences between the 2000 and 2001 samples that account for the reduced effects of prior knowledge and disembedding ability in the 2001 analysis.
The results show little effect of cognitive style on the measured outcomes. As mentioned, this may be a result of the small sample sizes. There are, however, some other comments that can be made about the CSA that might explain the lack of effect.

Firstly, the CSA does not provide absolute measures of ability that can be compared from one student to the next. It only provides an indication of a student’s preferred mode of thinking. A student who is labelled a “wholist” because they are more able to think wholistically than analytically may, in fact, be a better analytical thinker than someone labelled an “analyst”. Therefore, it may be useful for an individual to know their own cognitive style to reach individual goals in learning, but cognitive style may not be useful as a predictor of relative success at a particular task.

Secondly, students’ responses to the questionnaire may be very sensitive to environmental and personal factors other than those it is claiming to measure, thereby reducing the reliability of the results. For example, the test provides a measure of cognitive style based on the time taken to respond to questions. Short pauses or lapses in concentration might, therefore, interfere with results. The language used in some items might have also caused an increase in response time while the student processed the meanings of certain words. This is highly likely in a multi-cultural sample like the one used in this study. Furthermore, some of the terminology was not really suitable for Australian students. The word “pavement”, for example, is rarely used in Australia.

Finally, Riding’s cognitive style dimensions, although independent, are found to interact with each other (Riding and Sadler-Smith, 1992). Styles may either complement or duplicate one another. Complementary styles include: wholist-verbaliser and analyst-imager. Students with complementary styles have access to both global and specific features of the material. For example, the analyst style allows the individual to discern the details and structure, whereas the imager style might allow the construction of an integrating image, providing an overall perspective. The "duplicate" situation does not have this advantage. It may be that particular combinations of styles are more conducive to learning from animations. Due to the small sample size in this study, combinations of cognitive styles could not be analysed. This is an area worthy of further research.
3.10. Conclusions

The overall conclusions of the studies presented in this chapter are as follows:

- Greatest improvements in mental models were found in novices with high disembedding ability and a basic understanding of chemical symbolism, who adopted deep learning approaches rather than surface ones. Based on the model, these students notice details in animations (attention networks) and relate this information to existing knowledge (LTM, encoding).

- Students with high prior knowledge, high disembedding ability and high visuospatial working-memory capacity, who adopted deep approaches to learning and limited surface approaches, showed superior mental models of chemical phenomena and superior ability to apply these mental models to new situations. Based on the model, these students interpret the details of animations (attention networks) using their existing knowledge (LTM, encoding), and are able to successfully hold and manipulate detailed percepts and images from animations in their minds (working memory). They are able to recall their images of animations (LTM, retrieval) and apply them to relevant transfer problems.

- Animations may provide imagers with easier access to chemical information, narrowing the gap between the mental models of imagers and verbalisers. This may indicate the involvement of the “auto-registration of visual features” component of the model and/or the activation of the attention networks.
Chapter 4

An In-Depth Examination of Students’ Mental Model Development

4.1. Introduction

This chapter presents four detailed case studies of first-year university chemistry students, tracking the development of their mental models of molecular and ionic substances and their ability to apply these models to the interpretation of symbolic, macroscopic and molecular representations.

4.1.1. Scientific Models

Consensus suggests that models "stand for something else which they 'represent' in some way" (Duit & Glynn, 1996). This "something else" is commonly referred to as the "target" (Bhushan & Rosenfeld, 1995; Duit & Glynn, 1996; Gilbert, Boulter & Rutherford, 1998a; Oversby, 1998) and may be an idea, object, an event, system or process (Gilbert et al., 1998a). The model is not a replica of the "target" but instead exhibits some characteristics that correspond to the target - "correspondences" (or shared attributes), and some that don't - "non-correspondences" (or unshared attributes) (Harrison & Treagust, 1996; Oversby, 1998). Gilbert et al. (1998a) describe the four most common modes of representation for models in science.

- **Material**, where a physical object is used.  
  *Example: 3D models of molecules and structures.*

- **Visual**, where a diagram or animation is used.  
  *Example: a diagram showing the polarity of a molecule or an animation depicting the dissolving of salt in water at the molecular/ionic level.*
• **Verbal**, where an oral description is used.

*Example:* analogies describing chemical equilibrium.

• **Symbolic**, where mathematical conventions are utilised.

*Example:* mathematical formulae (e.g., \( p = \frac{m}{v} \)) and symbolic representations such as chemical formulae and equations.

### 4.1.2. Mental Models

A mental model is a high-level cognitive representation automatically constructed from one’s perception or conception of the world. In other words, it is essentially a personal, and hence not necessarily accurate, interpretation of what we perceive or conceive (Gilbert *et al.*, 1998a). Mental models are necessary for us to understand and interact with the world around us. They are incomplete (Johnson-Laird, 1983) and flexible and updated as new information is acquired (Johnson-Laird, 1983; Franco, Lins de Barros, Henrique, Colinvaux, Krapas, Queiroz & Alves, 1999). In science, a mental model refers to one’s personal understanding of a particular scientific phenomenon. All scientific models begin as mental models in the minds of scientists. Scientific models can then be used to help students and other scientists construct their own mental models.

Johnson-Laird sums up his concept of a mental model:

"It is now plausible to suppose that mental models play a central and unifying role in representing objects, states of affairs, sequences of events, the way the world is, and the social and psychological actions of everyday life. They enable individuals to make inferences and predictions, to understand phenomena, to decide what action to take and to control its execution, and above all to experience events in proxy." (p. 397)

According to this framework, mental images are said to “correspond to views of models” and "the significance of an image depends on the processes that construct and interpret it" (Johnson-Laird, 1983). Our ability to manipulate images to solve problems is a result of the mental model that the image is incorporated in. "In imaging, say, a rotating object, the underlying mental model of the object is used to recover a representation of its surfaces,
Chapter 4  Examination of Students’ Mental Model Development  253


A mental model must be functional to the person who constructs it (Johnson-Laird, 1983). This point is adapted in the science education literature insofar as mental models serve as means by which students can explain and predict physical or chemical situations (Anderson, Howe, & Tolmie, 1996; Greca & Moreira, 1997, 2000; Treagust, Chittleborough & Mamiala, 2000). In this chapter, the term “mental model” will refer to the ideas and images students use to describe and explain chemical phenomena and associated chemical symbolism. Students’ mental models of substances and reactions in chemistry are explored using discussion, drawing and description, critical analysis, prediction and explanation.

4.1.3.  Effects of Prior Knowledge on Learning from Models

In science teaching, modelling is often used to help students develop appropriate mental models. This is necessary because much of the phenomena discussed cannot be experienced first-hand. The success of modelling will in part depend upon the level of understanding a student brings to the classroom.

To learn from models, students need to have relevant prior knowledge to be able to interpret them properly (Justi & Gilbert, 2002). For example, "a student cannot learn from space-filling models of molecules without at least rudimentary concepts of atom, molecule, carbon, oxygen, and so on" (Jones et al., 2001). Similarly, without some understanding of bonding, a student might inappropriately assume that "sticks" hold ions together in a sodium chloride lattice. Therefore, the usefulness of a model will be related to students' knowledge of the concepts "embedded" in that model (Jones et al., 2001). Students will extract from models the features and ideas they consider relevant and may attempt to relate these ideas to what they already know (Greca & Moreira, 2000). Inability to discriminate the important aspects of models can lead to an increase in the number of misconceptions (Dyche et al., 1993) and can result in inappropriate mental models. Harrison and Treagust (1996) identified problems that arose when grade 8–10 students partly or wholly interpreted models literally. For example, they discussed misconceptions relating to the terms "shells" and "clouds" in atoms. Griffiths and Preston (1992) suggested that exposure of year 12 students to ball-and-stick models or three-dimensional diagrams may have caused the misconception that water molecules are
composed of two or more solid spheres. Students may also need to be aware of the conventions used when diagrams and models are constructed (Lowe, 1988; Wheeler & Hill, 1990; Pinto & Ametller, 2002) or chances of misinterpretation are high.

Greca and Moreira (2000) point out that novice students do not have the necessary prior knowledge to interpret models. Research conducted by Keig and Rubba (1993) supports this view. Students from years 10–12 exhibited limited ability to translate between electron configurations, formulae and ball-and-stick representations and this ability was related to a student’s prior knowledge regarding the representations.

Students’ pre-existing mental models of scientific phenomena ("children's science" or "alternative conceptions") that contradict scientifically-acceptable ideas might also inhibit a student’s ability to learn science, as suggested by Duit and Glynn (1996):

"Many learning difficulties in science instruction are caused by the fact that students' mental models and the conceptual models to be learned are grounded in significantly different general frameworks and are often contradictory” (Duit & Glynn, 1996, p. 170).

They suggest that “learning science then means to develop students' pre-instructional mental models towards post-instructional models that share at least certain key facets with the conceptual model taught." In this chapter, the development of students’ mental models towards more scientifically-acceptable models is studied, and the effects of both relevant and non-scientific prior understanding is examined.

4.1.4. Modelling Ability

In 1991, Grosslight and co-workers undertook a study with 7th grade and 11th grade students and a selection of "experts", looking at the differences in their ideas regarding the "nature of scientific knowledge and how it is acquired". Participants were asked general questions relating to their understanding of the term "model", purposes of designing models, possibilities for changing models and multiple models of the same entity. Grosslight found that participants' responses became increasingly more sophisticated with educational experience, and that there were distinct differences in the ways novices and experts viewed
the nature of models. Responses generally fell into three categories, which were used to assign the "modelling ability" of each student.

Level 1 modellers view models as simple copies of reality. Multiple models are considered to show different views of the same entity. The majority of 7th graders and some 11th graders fell into this category.

Level 2 modellers also concentrate on components of reality portrayed by models but realise there need not be a one-to-one correspondence between the model and the reality. The model is a tool used to show certain features of the "reality" through, for example, highlighting, simplifying and omitting certain features. Level 2 modellers emphasise the use of models as a communication tool. They believe that multiple models are used to highlight different features of the "reality". A small percentage of 7th graders fell into this category. Most 11th graders demonstrated either level 2 ideas or a mixture of level 1 and level 2 ideas.

A level 3 modeller understands the use of models for developing and testing often abstract ideas, rather than the depiction of reality. They concentrate on the explanatory and predictive power of models. Multiple models are used to test rival hypotheses or to address different issues regarding a particular phenomenon. Harrison and Treagust (1996) suggest that a level 3 modeller would "construct and manipulate diverse multiple models without being perturbed by their differences". Only experts fall into the level 3 category.

Grosslight et al. (1991) relied on students’ understanding of the term "model" to determine his levels of modelling ability. Part of the study outlined in this chapter aims to discover whether students demonstrate aspects of Grosslight's levels when probed about modelling with reference to particular models, without direct questioning on "models" and "modelling" per se. This is similar to the method used by Harrison and Treagust (1996).

Believing that there is a one-to-one correspondence between the model and target is likely to result in literal interpretations of models and the development of misconceptions regarding the molecular level of matter (Dyche et al., 1993; Bhushan & Rosenfeld, 1995). For example, Keig and Rubba (1993) reported a correlation between students' use of electron-dot notation and the static-electron misconception, demonstrating that students may take literally the depiction of electrons in this representation.
Allowing students to keep this naïve perspective introduces other problems relating to students' perception of science, as Gilbert, Boulter and Rutherford (1998b) point out:

"Students may well see an explanation as definitive, i.e. as corresponding precisely to nature, as being nature. Where this happens, and where the students are later introduced to other explanations of the same phenomena, then there is a risk that they come to see science as untrustworthy, on the criteria that they have constructed."

In science, multiple models are often required to explain different aspects of one phenomenon. Teachers construct additional models to help students understand, and still more models are used as simplifications to aid in the drawing process. Not surprisingly, students are often overwhelmed by all the representations presented to them and this may obstruct learning (Jones et al., 2001). Level 1 modellers will find it difficult to understand why so many models exist and will most likely seek the one correct model among the many. They may choose this model based on the extent to which it is used in the classroom or on how concrete and simplistic the model is. This idea is supported by the fact that most students from a sample of grade 8–10 students preferred models of atoms and molecules that depicted them as "discrete, concrete structures" (Harrison & Treagust, 1996).

Science educators now commonly purport that modelling should be explicitly taught to students (Andersson, 1990; Renstrom, Andersson & Marton, 1990; Davies, 1991; Harrison & Treagust, 1996, 2000; Oversby, 1999; Justi & Gilbert, 2002). The purpose of each type of representation should be discussed with students (Jones et al., 2001) and special effort made to help students identify the correspondences and non-correspondences between the model and the target (Davies, 1991; Bhushan & Rosenfeld, 1995; Harrison and Tregustag, 1996; Oversby, 1999). Furthermore, models should be used in a classroom in a manner that mimics their use in the scientific world; that is, for testing, predicting and solving problems (Grosslight et al., 1991; Bhushan & Rosenfeld, 1995; Tregust et al., 2000; Tregust, Chittleborough & Mamiala, 2002).

Harrison (2000) suggests that students might see certain depictions of the molecular level, such as animations, as real due to their vivid, realistic appearance. This assertion is also made by Large (1996):
"An animated representation of a chemical reaction may produce a mental image in the viewer, but the viewer must then appreciate that the image is stylised rather than actually representational" (p. 14).

Realistic animations might therefore have a deleterious effect on the development of students’ modelling abilities.

In the following research, we extend Grosslight’s definition of modelling ability to include other aspects of modelling believed to be important. The working definition utilised in this research incorporates the following points:

- **Interpretation**: the ability to note some correspondences and non-correspondences between the source (model used in explanation) and target (that which is being explained) (Bhushan & Rosenfeld, 1995; Oversby, 1998);
- **Multiple Modelling**: ability to accept multiple models and discuss reasons for multiple models of the same thing (Grosslight, 1991; Harrison & Treagust, 1996, 2000);
- **Development**: ability to understand the nature of scientific modelling (Grosslight, 1991; Duit, 1996; Bhushan and Rosenfeld, 1995).

Students’ responses relating to these points are used to allocate modelling abilities. A student competently displaying all of the above abilities would be rated a level 3 modeller. Within each of the above categories, it is possible to discriminate different modelling levels, based on students’ comments relating to each category. For the purposes of this study, modelling abilities are allocated on the basis of students’ comments regarding interpretation of material and visual models only. It is assumed that these are the models most likely to be construed as realistic depictions of the molecular level, and hence pose the most danger in obstructing the development of students’ understanding of scientific modelling. This has implications for the use of vivid computer animations in teaching chemistry.

### 4.1.5. Aims and Hypotheses

This study explores learning in chemistry by examining the changes in students’ mental models of certain substances over one year of study, the factors perceived to have influenced
these changes, and the use of these mental models in explanations of molecular, symbolic and macroscopic representations. Specifically, it aims to examine more closely the effects of disembedding ability and prior knowledge on students’ mental-image development, their ability to apply concepts, their use and interpretation of VisChem animations, and their modelling ability.

These aims are explored in case studies of four students, selected on the basis of their results on the pre-test and GEFT (see Chapter 3). Each student represents a combination of high or low prior knowledge and high or low disembedding ability.

Table 4.1 summarises the hypotheses proposed for the outcomes of the four students based on the conclusions of Chapter 3.

<table>
<thead>
<tr>
<th>High prior knowledge</th>
<th>High disembedding ability</th>
<th>Low disembedding ability</th>
</tr>
</thead>
<tbody>
<tr>
<td>(HH)</td>
<td>• Excellent mental models of substances shown in animations, with little room for progress</td>
<td>• Reasonable mental models of substances shown in animations, but little progress through the year</td>
</tr>
<tr>
<td></td>
<td>• Excellent ability to apply the above knowledge</td>
<td>• Excellent ability to apply the above knowledge</td>
</tr>
<tr>
<td></td>
<td>• Ability to point out and explain relevant details in animations</td>
<td>• Ability to explain animations and point out global features (rather than details)</td>
</tr>
<tr>
<td></td>
<td>• Level 3 modelling ability</td>
<td>• Level 3 modelling ability</td>
</tr>
<tr>
<td>(HL)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Low prior knowledge</th>
<th>(LH)</th>
<th>(LL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Reasonable mental models of substances shown in animations due to significant progress through the year</td>
<td>• Limited ability to apply the above knowledge</td>
<td>• Some problems with mental models of substances shown in animations but some progress through the year</td>
</tr>
<tr>
<td>• Limited ability to apply the above knowledge</td>
<td>• Ability to point out details in animations but some difficulty in explaining details</td>
<td>• Limited ability to apply the above knowledge</td>
</tr>
<tr>
<td>• Ability to point out global features (rather than details) but some difficulty explaining animations</td>
<td></td>
<td>• Ability to point out global features (rather than details) but some difficulty explaining animations</td>
</tr>
<tr>
<td>• Level 1 or 2 modelling ability</td>
<td></td>
<td>• Level 1 or 2 modelling ability</td>
</tr>
</tbody>
</table>

Table 4.1 Predicted outcomes of prior knowledge and disembedding ability combinations after instruction
4.2. Methodology

Detailed case studies examining student learning in chemistry are rare. Notable examples are the studies by Harrison and Treagust (2000) that examine students’ mental models of atoms, molecules and the chemical bond; by Taber (2000) that explore a student’s use of the multiple mental models of chemical bonding; and by Hinton and Nakhleh (1999) that look at students’ representations of molecular, macroscopic and symbolic levels of chemistry thinking.

Case studies offer a rich source of information on how individuals learn and allow the exploration of changes in student thinking that occur over time, including changes in their mental models. The emphasis is on depth rather than breadth (Hinton & Nakhleh, 1999). Instructional effectiveness can be examined at a more intimate level than is allowed by questionnaires. Hinton and Nakhleh (1999) argue that in-depth interviews with a small sample of students is the most appropriate method available for answering how and why questions.

4.2.1. Sampling

On completion of the pre-test distributed in 2001 (described in Chapter 21), students were given the opportunity to volunteer to participate in a series of one-to-one interviews. The volunteers’ results on the pre-test and the GEFT were examined and students with various combinations of scores were selected and approached. Students scoring in the top 35% in the pre-test or GEFT were designated “high” scorers; those scoring in the bottom 35% designated “low” scorers. Due to a lack of volunteers in a couple of the combination categories, individual students who had not previously volunteered were approached. Complete data were obtained from four students whose case studies are presented in this chapter. Each student represents a unique combination of prior knowledge and disembedding ability.

4.2.2. Case Studies

As well as completing the pre-test and post-test, students participated in four one-to-one semi-structured interviews throughout their first year of university chemistry. Table 4.1 shows the

\[\text{1 Version of the pre-test included an additional question on precipitation of lead iodide from aqueous solutions of potassium iodide and lead nitrate.}\]
semesters and weeks in which data were collected, in relation to the topics covered in their chemistry lectures.

<table>
<thead>
<tr>
<th>Week</th>
<th>Topics</th>
<th>Data Collection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>SEMESTER 1</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Types of Substances</td>
<td>Pre-test</td>
</tr>
<tr>
<td>2</td>
<td>Chemical Reactions</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Working with Substances in the Lab</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Working with Reactions in the Lab</td>
<td>Interview 1: HH, HL</td>
</tr>
<tr>
<td>5</td>
<td>Working with Solutions in the Lab</td>
<td>Interview 1: LH</td>
</tr>
<tr>
<td>6</td>
<td>Atomic Structure</td>
<td>Interview 1: LL</td>
</tr>
<tr>
<td></td>
<td><em>Mid-semester Exam</em></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Atomic Structure and the Periodic Table</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Chemical Bonding, Structure and Properties</td>
<td>Interview 2: HH, HL, LL</td>
</tr>
<tr>
<td>10</td>
<td>of Substances</td>
<td>Interview 2: LH</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td></td>
<td>Post-test</td>
</tr>
<tr>
<td></td>
<td><em>End of Semester Exam</em></td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>SEMESTER 2</strong></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>Redox Reactions and Electrochemistry</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Thermochemistry</td>
<td>Interview 3: HH, LL</td>
</tr>
<tr>
<td>4</td>
<td>Kinetics</td>
<td>Interview 3: HL, LH</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td><em>Mid-semester Exam</em></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Equilibrium</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Acid-base Equilibria</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Organic Chemistry</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td></td>
<td>Interview 4: HH, HL, LH</td>
</tr>
<tr>
<td>11</td>
<td></td>
<td>Interview 4: LL</td>
</tr>
<tr>
<td>12</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Table 4.2*  Timetable of data collection
Questions discussed during all the interviews related to one of the following four categories:

- Imagery Development
- Interpretation of Chemical Symbolism
- Interpretation of Macroscopic phenomena
- Interpretation of Molecular Representations

Explanations of these categories are given below.

**Imagery Development**
This aspect of the case studies tracked changes in students’ basic images that were initially assessed by the pre-test. It therefore looked at any changes in students’ ideas and images of molecular substances: water (solid, liquid, gas) and ionic substances (solid sodium chloride, aqueous solution of sodium chloride, precipitation of lead iodide). Students were also asked to identify factors that had influenced the development of their images.

**Interpretation of Chemical Symbolism**
This aspect looked at students’ ability to represent formulae and equations at a molecular level. The equations covered a range of different topics including gas-phase reactions, acid/base solutions and reactions, precipitation, complexation and equilibrium. Often, more than one type of equation (for example, “molecular” and ionic equations) was presented for the same reaction. This was done to probe the depth of students’ understanding of processes at the molecular level and their ability to link this to different symbolic representations. Table 4.3 gives a summary of the symbolic notation students were required to interpret.

**Interpretation of Macroscopic Phenomena**
This aspect was included to test students’ ability to use mental models of molecular, ionic and metallic substances to explain macroscopic phenomena. Table 4.4 gives a detailed summary of the content of the questions in this category.

**Interpretation of Molecular Representations**
This aspect examined students’ ability to interpret and critically evaluate various molecular-level representations, including models, diagrams, animations and analogies. Questions relating to modelling allowed the determination of each student’s modelling ability. Critical analysis and interpretation of diagrams, animations and analogies allowed further exploration
of students’ mental models of molecular and ionic substances, and equilibrium and redox reactions. A comparison of students’ interpretation of VisChem animations allowed the examination of the possible effects of prior knowledge and disembedding ability. Table 4.5 gives a detailed summary of the content of the questions in this category.

<table>
<thead>
<tr>
<th>Interpretation of Chemical Symbolism</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
</tr>
<tr>
<td><strong>Interview conducted</strong></td>
</tr>
<tr>
<td><strong>Formulae and Equations</strong></td>
</tr>
<tr>
<td><strong>Application of Mental Models of Molecular Substances</strong></td>
</tr>
</tbody>
</table>
| Molecular representations            | 1, 3 (pre-post test) | 2 NO₂  
Formula for a representation of N₂O₄.² |
| Gas-Phase reaction                   | 1                  | 4 NH₃ + 5 O₂ → 4 NO + 6H₂O (1) |
|                                      |                    | 4 NH₃(g) + 5 O₂(g) → 4 NO(g) + 6H₂O(g) (2) |
| **Application of Mental Models of Ionic Substances** |
| Strong Acid Solution                 | 2                  | 0.050 M H₂SO₄ |
| Acid/Base Reaction                   | 2                  | NaOH(aq) + H₂SO₄(aq) → Na₂SO₄(aq) + H₂O(l) |
| Precipitation                        | 2                  | 2KCl + Pb(NO₃)₂ → PbCl₂ + 2KNO₃ (1) |
|                                      |                    | 2KCl(aq) + Pb(NO₃)₂(aq) → PbCl₂(s) + 2KNO₃(aq) (2) |
|                                      |                    | 2K⁺(aq) + 2Cl⁻(aq) + Pb²⁺(aq) + 2NO₃⁻(aq) → PbCl₂(s) + 2K⁺(aq) + 2NO₃⁻(aq) (3) |
| Complexation                         | 2                  | Set 1: |
|                                      |                    | Cu²⁺(aq) + 2OH⁻(aq) → Cu(OH)₂(s) |
|                                      |                    | Cu(OH)₂(s) + 4NH₃(aq) → Cu(NH₃)₄²⁺(aq) + 2OH⁻(aq) |
|                                      |                    | Set 2: |
|                                      |                    | Cu(H₂O)₆²⁺(aq) + 2OH⁻(aq) → Cu(OH)₂(s) + 6H₂O(l) |
|                                      |                    | Cu(OH)₂(s) + 4NH₃(aq) + 2 H₂O(l) → Cu(NH₃)₄(H₂O)₂²⁺(aq) + 2OH⁻(aq) |
| **Advanced Topics**                  |
| Gas-Phase Equilibrium                | 4                  | CINO₄(g) + NO(g) ⇌ CINO(g) + NO₂(g) |
| Weak Acids Equilibria                | 4                  | H₃BO₃(aq) ⇌ H₂BO₃(aq) + H⁺(aq)..(1) |
|                                      |                    | H₃BO₃(aq) + H₂O(l) ⇌ H₂BO₃(aq) + H₃O⁺(aq) (2) |

Table 4.3  Content of interview questions involving interpretation of chemical symbolism

²Questions derived from study by Garnett & Hackling (2000).
<table>
<thead>
<tr>
<th>Interpretation of Macroscopic Phenomena</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
<td><strong>Interview conducted</strong></td>
</tr>
<tr>
<td>Application of Mental Models of Molecular Substances</td>
<td></td>
</tr>
<tr>
<td>Nail-Polish Remover</td>
<td>3</td>
</tr>
<tr>
<td>Application of Mental Models of Ionic Substances</td>
<td></td>
</tr>
<tr>
<td>Precipitation Reaction</td>
<td>3</td>
</tr>
<tr>
<td>Advanced Topics</td>
<td></td>
</tr>
<tr>
<td>Redox Reaction</td>
<td>4</td>
</tr>
</tbody>
</table>

Table 4.4  Content of interview questions involving interpretation of macroscopic phenomena

<table>
<thead>
<tr>
<th>Interpretation of Molecular Representations</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Section</strong></td>
<td><strong>Interview conducted</strong></td>
</tr>
<tr>
<td>Modelling Ability</td>
<td></td>
</tr>
</tbody>
</table>
| Modelling                                  | 1, 3 | **Interpretation**: Discussion of multiple models of a water molecule and solid sodium chloride\(^3\). See Appendix C for the models shown.  
**Multiple Modelling**: Explanation of why there are many models to represent the same substance.  
**Development**: Questions relating to the reality of models, development of models and reasons for modelling. |
| Application of Mental Models of Molecular and Ionic Substances |  |
| Criticism of Molecular Diagrams and Animations | 3 | Criticism of four diagrams and an animation that might mislead novice students. See Appendix C for diagrams and Appendix G (attached CD) for the animation. |
| Advanced Topics                            |  |
| Application of Mental Models of Molecular and Ionic Substances, Advanced Topics |  |
| Interpretation of Molecular-Level Animations | 4 | Interpretation of VisChem animations seen in lectures (ice melting, evaporation of water, sodium chloride dissolving, aqueous solution of sodium chloride and silver chloride precipitation) and one unfamiliar animation (redox reaction of copper with silver nitrate). |

Table 4.5  Content of interview questions involving interpretation of molecular representations

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\[^3\] Question derived from study by Harrison and Treagust (1996)
The categories examined in each interview along with sample interview questions are given in Table 4.5. Full copies of interview schedules are available in Appendix C.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Sample Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Imagery Development</strong></td>
<td>Discuss whether this idea has changed at all, and how it has changed [and] identify and describe factors which have influenced any changes</td>
</tr>
<tr>
<td>- Changes since completion of pre-test</td>
<td></td>
</tr>
<tr>
<td>- Causes of any changes</td>
<td></td>
</tr>
<tr>
<td><strong>Interpretation of Molecular Representations</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Modelling</strong></td>
<td></td>
</tr>
<tr>
<td>- Models of the water molecule</td>
<td>Here are some more models of water molecules. What do you think of these models?</td>
</tr>
<tr>
<td>- Nature of scientific modelling: interpretation of computer-animated space-filling model of a water molecule</td>
<td>How close do you think this animation is to what a water molecule would actually look like?</td>
</tr>
<tr>
<td><strong>Imagery Development</strong></td>
<td></td>
</tr>
<tr>
<td>- Any further developments</td>
<td>Individualised questioning</td>
</tr>
<tr>
<td>- Causes of any changes</td>
<td>What do you think has helped you to further develop this idea since I last talked to you?</td>
</tr>
<tr>
<td><strong>Interpretation of Chemical Symbolism</strong></td>
<td>I want to show you another equation. Tell me what it means to you. Are you able to draw me a representation of the reactants and products from this equation?</td>
</tr>
<tr>
<td>- Acid solution</td>
<td></td>
</tr>
<tr>
<td>- Acid/base</td>
<td></td>
</tr>
<tr>
<td>- Precipitation</td>
<td></td>
</tr>
<tr>
<td>- Complexation</td>
<td></td>
</tr>
<tr>
<td><strong>Imagery Development</strong></td>
<td>Individualised questioning</td>
</tr>
<tr>
<td>- Any changes between Interview 2 and Post-test</td>
<td></td>
</tr>
<tr>
<td><strong>Interpretation of Macroscopic Phenomena</strong></td>
<td>Why do you think some liquids smell? Can you explain it at a molecular level?</td>
</tr>
<tr>
<td>- Nail-Polish remover</td>
<td></td>
</tr>
<tr>
<td>- Precipitation Reaction</td>
<td></td>
</tr>
<tr>
<td><strong>Interpretation of Molecular Representations</strong></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td><strong>Modelling</strong></td>
<td>Which do you think is the best representation? Why? What do you think of some of these other models?</td>
</tr>
<tr>
<td>- Models of solid sodium chloride</td>
<td></td>
</tr>
<tr>
<td>- Nature of scientific modelling: interpretation of computer-animated model of aqueous potassium fluoride</td>
<td>How close do you think this animation is to what the molecular world of an aqueous solution of potassium fluoride would actually look like?</td>
</tr>
<tr>
<td><strong>Criticisms of Molecular Diagrams and Animations</strong></td>
<td>Do you think students might develop any misleading/incorrect ideas from them?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Interview 4</strong></th>
<th><strong>Interpretation of Chemical Symbolism</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>- Equilibrium</td>
<td>Imagine you are able to zoom down to the molecular level and watch this reaction at equilibrium. What would you see?</td>
</tr>
<tr>
<td></td>
<td>- Strong and weak acids</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Interpretation of Macroscopic Phenomena</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>- Redox experiment</td>
<td>I’m going to show you a reaction between this piece of copper metal and this solution of silver nitrate. Can you explain, using drawings to help, what is happening at the molecular/ionic level?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong>Interpretation of Molecular Representations</strong></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Analogical Modelling of Equilibrium</strong></td>
<td>For each analogy, I want you to describe the advantages (what’s right with it) and limitations (what’s wrong with it).</td>
</tr>
<tr>
<td><strong>Interpretation of Molecular-Level Animations</strong></td>
<td>I want you to point out all the important features that the animation is trying to show.</td>
</tr>
</tbody>
</table>

| **Table 4.6** Categories examined in each interview with sample interview questions |

Interviews with students were designed to be completed within an hour, and in most cases this was a reasonable estimation. All interviews were recorded on both video and cassette and transcribed verbatim. Quotes used in this chapter have been edited to aid readability, by replacing hesitations, repetitions, long pauses, *etc.*, with “...”, replacing ambiguous wording with statements in square brackets and including actions in italics with square brackets.
4.3. Quantitative Data

Tables 4.7 and 4.8 show the scores obtained by each student on substance categories on the pre-test and post-test.

<table>
<thead>
<tr>
<th>Section</th>
<th>HH</th>
<th>HL</th>
<th>LH</th>
<th>LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Substances: General Features (out of 14)</td>
<td>8</td>
<td>6</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Specific Features Regarding Water (out of 6)</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ionic Solid (out of 6)</td>
<td>3</td>
<td>3</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Ionic Solution (out of 9)</td>
<td>2</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td><strong>Test Total</strong></td>
<td>15</td>
<td>12</td>
<td>5</td>
<td>6</td>
</tr>
</tbody>
</table>

Table 4.7 Students’ scores on the pre-test

<table>
<thead>
<tr>
<th>Section</th>
<th>HH</th>
<th>HL</th>
<th>LH</th>
<th>LL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular Substances: General Features (out of 14)</td>
<td>9</td>
<td>10</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Specific Features Regarding Water (out of 6)</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Ionic Solid (out of 6)</td>
<td>4</td>
<td>5</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Ionic Solution (out of 9)</td>
<td>5</td>
<td>4</td>
<td>8</td>
<td>7</td>
</tr>
<tr>
<td><strong>Test Total</strong></td>
<td>19</td>
<td>21</td>
<td>20</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 4.8 Students’ scores on the post-test

Table 4.11 gives a comparison of students’ pre-test scores, GEFT scores and post-test scores.

<table>
<thead>
<tr>
<th>Student</th>
<th>Pre-test Score</th>
<th>GEFT Score</th>
<th>Post-test Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH</td>
<td>15</td>
<td>17</td>
<td>19</td>
</tr>
<tr>
<td>HL</td>
<td>12</td>
<td>10</td>
<td>21</td>
</tr>
<tr>
<td>LH</td>
<td>5</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>LL</td>
<td>6</td>
<td>8</td>
<td>18</td>
</tr>
</tbody>
</table>

Table 4.9 Comparison of pre-test scores, GEFT scores and post-test results

The data do not show the expected trends based on the statistical analysis described in Chapter 3, largely due the fact that HH scored lower than was expected for a student with high prior knowledge and disembedding ability.

The following case studies (Sections 4.4–4.7) provide detailed accounts of students’ responses in interviews, with supporting quotes. They do not include analyses of these data.
The reader may therefore wish to proceed directly to the discussion section (Section 4.8, page 414) for interpretive summaries of the data, with page references to the relevant sections in the case studies.
4.4. Case Study 1 (HH)

HH represents a student with high prior knowledge (pre-test score: 15) with high
disembedding ability (GEFT score: 17).

4.4.1. Imagery Development

This section documents the development of HH’s images of substances, assessed by the
questionnaire, through the year. These data were collected from the pre-test, interviews 1–3
and the post-test.

4.4.1.1. Molecular Substances

General Features
HH’s knowledge of the general features of molecular substances was thorough and consistent
throughout the year.

Liquid Water
HH’s original representation of liquid water showed water molecules represented using a ball-
and-stick model, “floating around” with some hydroxide and hydrogen ions. In interview 1,
he suggested that he would probably omit the hydrogen and hydroxide ions from his
representation.

HH: Probably just the H₂Os floating around…If I could have done it again I probably wouldn’t have
put the H’s and the OHs in. I don’t think. I think I would just have H₂Os going around, I think.

He also realised that he didn’t really use a mental image to construct his representations but
rather just worked from concepts.

HH: I don’t think I bring up an image I just do it.

Interviewer: You don’t picture something?

HH: No.

Interviewer: So you are just aware that there are lots of water molecules in there and they’re…free
moving?

HH: Mm, yeah.
His representation and description in the post-test contained little information. He represented water molecules using a space-filling model and mentioned that they had no fixed structure. He failed to mention movement, and consistent with his above comments, he did not mention the auto-ionisation of water molecules. In interview 3, he was probed about the movement of the molecules in liquid water. After some questioning, he demonstrated knowledge of this idea.

Interviewer: So they're moving in the gas?
HH: Yeah, that's right. Oh well they're moving more than in the liquid.
Interviewer: Right, so they're moving in the liquid as well?
HH: Yeah.
Interviewer: Okay. …Is there any reason why you didn't write down that they were moving?
HH: Oops! No.
Interviewer: If you picture liquid water in your head, if you can picture it. You don't picture it?
HH: Yeah I can. I can picture it…
Interviewer: Is it moving?
HH: Yeah, but not very fast...

**Gaseous Water**

At the beginning of the year, HH described gaseous water as widely spaced molecules floating around, using a ball-and-stick model.

By interview 1, his ideas had not changed, but he felt that the animations shown in lectures had confirmed his image, although he could not visualise the one relating to gaseous water.

In the post-test, HH used a space-filling representation to illustrate gaseous water. He once again mentioned the large spacing between water molecules. He described the molecules as being “highly excited”, but did not mention the movement associated with this excitement. In interview 3, he discussed the energy and movement of the particles in the gaseous state as compared with the liquid.
HH: …From a liquid to a gas…energy of the molecules changes, the spacing changes…I don’t know what else. Energy, space.

Interviewer: How does the spacing change?

HH: The spacing between the molecules changes. It's bigger.

Interviewer: And how does it get bigger?

HH: Because they’ve got more energy and they move around a lot more.

Solid Water

HH’s initial representation of ice in the post-test simply showed closely packed water molecules represented using a space-filling model. By interview 1, his understanding had developed. He described a structured array of water molecules, held by hydrogen bonding.

HH: If I’d done it now I probably would have had, it would have been a bit more orderly. That probably would have been like Os and the 2 Hs kind of near each other because of the polarity of the molecule.

He was asked about his image of ice again in interview 2 to see if he had developed the idea of vibrations at a molecular level. He represented ice as a three-dimensional lattice of water molecules. When asked what you might see happen if you zoomed down to the molecular level he suggested “you’d see electrons moving around and stuff but that’s it.” He believed that, besides the movement of electrons, the molecules “in the ice form…were stationary.”

In interview 2, he was also asked to explain why water expands on freezing. Although he knew ice to be less dense than water, he could not come up with an explanation as he realised that his mental model of closely packed water molecules contradicted this fact.

HH: I don’t know because with my little theory here, it should be more…like more densely packed which doesn’t make sense because it’s supposed to be less dense so…

His image had not developed further by the post-test. He described solid water as a “fixed, rigid structure” with “polar attractions”, represented using a space-filling model. Therefore, during interview 3, he was once again probed about vibrations. After initially suggesting that movement at a molecular level only occurred once heat was applied, he realised that this was not quite the case.
Interviewer: Okay so at what point does the movement start then?

HH: As soon as heating occurs.

Interviewer: Okay, so any movement before heating occurs?

HH: Ahh…yes there is but…walking contradiction. Yeah, cause isn’t like, absolute zero’s where all the movement stops or something? …So I guess there is. I’m guessing there’s some movement but not much. Like the movement is more pronounced when heating occurs.

Interviewer: Okay, when you picture ice in your head, do you see…some sort of slight movement?

HH: Yeah, actually, yeah just like little vibrations, nothing huge just little [hand movements] shaking and stuff, shivering.

In interview 3, he was once again asked about the expansion of water on freezing. He made the tentative suggestion that there might be “air getting trapped in there or…but that doesn’t sound very feasible…”

4.4.1.2. Ionic Substances

Solid Sodium Chloride

HH initially chose the correct representation of solid sodium chloride, based on the fact that it featured ions in a structured array. He appeared to understand that there are no molecules in the structure. He expanded on reasons for his selection in interview 1. Animations in lectures seemed to confirm some of his ideas regarding the structure of this ionic solid.

HH: That’s got no ions. It should be ionic.

Interviewer: Alright. Ions rather than atoms.

HH: …This one just shows individual pairs of sodium chloride and that one shows that they’re random.

Interviewer: Okay, so what’s wrong with the individual pairs?

HH: …They’re a kind of crystal lattice…a positive doesn’t share with just one negative ion. They share with the all the surrounding ones as well. I remember that, I remember that from the little ball, the ball, video thing, the animation, because I remember I like the 3D bits. It was good. It was good.

Consistent with his original ideas on ice, he felt that solid sodium chloride only started to vibrate once heated. He had this same misconception in interview 2. The post-test did not reveal any significant changes in this student’s idea of solid sodium chloride. He was once again questioned about movement during interview 3. Finally he proposed that there may some movement prior to heating.
HH: Well I guess it's probably still the same as I said before. There's probably some...movement but when the heat occurs the movements are bigger until...the movements are just so great that they actually tear away from the intermolecular bonding.

**Aqueous Solution of Sodium Chloride**

In the pre-test, HH showed knowledge of the fact that ions of sodium chloride separate in aqueous solution and are attracted to water molecules via polar attractions. However, he was not aware of how many water molecules would bond to each ion. By interview 1, his image had evolved. He mentioned that there would be many water molecules relative to ions, water molecules would be attracted to ions, the ratio of sodium to chloride would be one-to-one and that ions would be separate in solution. He could picture water molecules tearing the ions from the solid crystal lattice to dissolve it, an image taken from a VisChem animation shown in the lectures. He claimed to have total confidence in his understanding of this idea. The post-test revealed similar understanding, though he failed to mention the ratio of chloride to sodium and the movement of the particles. In interview 3, he mentioned movement of the particles and tried to explain why he may not have thought to mention it in the post-test.

HH: ...ions floating around with water attached to them...water attracted to, polar attractions...the whole thing and stuff

Interviewer: The whole thing and stuff?

HH: ...You know the whole movement stuff, floating around in the water...

Interviewer: Now for this question here when I asked you to...compare your mental representation to the representation written here, you mentioned that it would be 3D but you didn't mention movement there. Any idea why you didn't mention movement there?

HH: ...I probably just didn't think it was necessary. I probably just assumed...that movement would be there and probably wouldn't think to write it. Yeah. Either that or I probably didn't think of it. I don't know. But I'm sure I would've thought of it, the movement. Cause...when I think of it, I don't just think of it like just a fixed picture. I think of it as like movement and stuff as well.

**Precipitation of Lead(II) Iodide**

HH began university with a fairly sophisticated image of a precipitation reaction (see Figure 4.1). He produced an equation with slight errors, correctly identifying lead(II) iodide as a precipitate. He represented each of the reactants as separate ions in solution, illustrating the presence of water with a surface line. He represented the spectator ions as being separate in the resulting solution. The structure of lead(II) iodide was not represented, but simply depicted as a rectangle labelled PbI₂.
During interview 1, he suggested some slight changes to his representation – he noticed incorrect stoichiometry and felt that water molecules should have been represented attracted to the ions. He was asked about the structure of the lead(II) nitrate and suggested it would be a crystal structure similar to sodium chloride, but slightly different due to the fact that the ratio of cations to anions would be 1:2. He felt that drawing molecular-level representations in laboratory classes had helped to improve his ability to visualise precipitation reactions.

The representation produced by HH in the post-test strongly resembled his representation in the pre-test. The only differences were that he had corrected the equation for the reaction and represented the appropriate stoichiometric ratios in the diagram.

### 4.4.2. Interpretation of Chemical Symbolism

This section looks at HH’s ability to represent symbolic notation at a molecular level. These data were collected from the pre-test, interviews 1, 2 and 4 and the post-test. Molecular representations were probed in interview 1 (Sections 4.3.2.1 – 4.3.2.2), ionic representations in interview 2 (Sections 4.3.2.3 – 4.3.2.6) and equilibrium in interview 4 (Section 4.3.2.7). For further information regarding the content of the interview questions, see Table 4.3 (page 262) or Appendix C.
### 4.4.2.1. Symbolic Representation

HH’s understanding of the formula $2\text{NO}_2$ did not change over the year. In both the pre-test and post-test, he stated that it referred to 2 moles of the molecule, nitrogen dioxide. He represented this by drawing two molecules of NO$_2$. In interview 1, the link between moles and molecules was approached. The student knew that moles and molecules were different but became confused about what the coefficient 2 in the formula represented. He felt that the number had most meaning when included in an equation.

HH: Oh well, it's a ratio. That's what it is. It's like in a chemical formula. It'd be a ratio of like, a mole ratio.

The student had no trouble in either the pre-test or the post-test naming the molecular representation N$_2$O$_4$.

### 4.4.2.2. Gas-Phase Reaction

The concept of coefficients arose again during discussion of the given equation (gas-phase reaction, no states specified). Even though he conceptualised the numbers in terms of moles, HH realised the ratios would be the same for individual molecules.

HH: Well mole ratios are four to five to four to six which means…well what I've learnt… that four moles of…ammonia and five moles of oxygen gas react to form four moles of NO…and six moles of water.

Interviewer: Okay, so what would you have in your representation?

HH: Um, reactants, I'd put…Yeah, I'm still tossing up whether it's four…oh I guess it doesn't really matter too much.

Interviewer: Okay, why do you say…?

HH: It's still a ratio so it doesn't matter. It'll still break down to this.

He began drawing ammonia molecules, then started to wonder what states the species were in.

HH: [draws] What is that? That's a liquid or something. NH$_3$ is…it's not a solid.

Interviewer: So in order to represent this equation you feel as if you need the states?

HH: Yeah, I would…Cause I can’t just leave it like that. I’d have to know whether they're going to be spaced apart or if they're going to be a definite structure which they're not going to be, cause I don't think it's a solid.
He was therefore shown a second equation with the states included and proceeded to draw a representation showing correct stoichiometric ratios of reactants and products. He drew molecules of oxygen and ammonia interspersed and widely spaced to represent the reactants and mentioned that the particles would be moving. The products were represented similarly.

HH: …They're gaseous so they don't have a fixed structure like in a solid…They've got that much energy that they're just moving around.

Interviewer: And they're all mixed in together then?

HH: …Well that's them mixed…If I could've done it differently, probably I could've put like a little beaker or something or a jar of NH₃ gas and O₂ gas before they'd been mixed…

4.4.2.3. Strong Acid Solution

HH understood what the label “0.050 M H₂SO₄” meant in terms of number of solute particles per litre of water.

HH: Ah, that means there's…0.05 times 6.022 times 10 to the 22, 23 particles per litre of water…

Interviewer: Particles of what?

HH: H₂SO₄

He was able to produce a reasonable representation of the molecular level of sulfuric acid (see Figure 4.2) and pointed out that more water would be present. His main fault was to represent hydrogen ions rather than hydronium ions in solution. He drew the correct ratio of ions and showed ions appropriately hydrated.

He was also able to predict the effect of doubling the concentration, at a molecular level.

HH: …There'd be too many to draw…but there would be less waters because there'd be more hydrogen and sulphate ions.

Interviewer: Mm, how many more?

HH: A lot?

Interviewer: …Say that's what you see if you zoom down to a .05 molar solution. How would that compare to a point one molar solution?

HH: …I guess it should be double. I guess…Yeah, so there should be like, I guess there should be eight, eight hydrogen ions and four sulphate ions floating around, I guess…That's in my theory.
HH knew that nothing would visibly happen when (equal molar) solutions of sulfuric acid and sodium hydroxide were added together without an indicator. However, he thought that on mixing the two solutions, you were simply mixing the two sets of ions, without any reaction occurring. Contradicting this, he suggested correctly that if you evaporated the water from the resulting solution you would obtain sodium sulphate salt.

HH: Well, what happened was… Nothing really happened. …All that happened was they got mixed cause they’re still in an ionic solution so all that's really happened, unless you like distilled the water like, took the water out of it and…dehydrated it. It'd form a salt, which would be sodium sulphate, yes, but…just by adding ‘em all you're doing really is adding the ions to the ions and just more water and more water.

When shown the “molecular” equation for the reaction, he realised that the hydroxide and hydrogen ions would react together to form water molecules.

HH: These have been added and these are in…ionic form at the moment surrounded by their waters… When they get added together…the hydrogen ions and the hydroxide ions form water molecules and these are floating around in their ionic states, floating.

He then produced a suitable representation of the resulting solution showing a two to one ratio of hydrated sodium and sulphate ions amongst other water molecules.
4.4.2.5. Precipitation

HH was unprepared to draw a molecular-level representation of the reaction between an aqueous solution of potassium chloride and an aqueous solution of lead(II) nitrate without being given the states of each substance. He did, however, give a verbal description of the information given by the equation.

HH: …Well 2 moles of potassium chloride added to 1 mole of lead nitrate…reacts to form…lead chloride and 2 moles of potassium nitrate.

When given the equation with the states included, he drew the representation shown in Figure 4.3. Initially, he represented the presence water by drawing the surface level of the solution. He drew separate ions in each of the reactant solutions and for the products, separate spectator ions and a box labelled PbCl₂. He demonstrated the action of water molecules on the ions in the solutions by including a couple of examples. He was then questioned about the structure of PbCl₂ and produced the representation shown in Figure 4.3. He stated that there would be a one to two ratio of lead to chloride ions in a structured three-dimensional lattice.

Figure 4.3 HH’s representation of the “molecular” equation (with states given) showing the precipitation of lead(II) chloride

HH was then shown the full ionic equation, and used it as evidence that he had correctly interpreted the “molecular” equation. He also identified this third equation as being the best representation of what occurs at the molecular level because “It shows that…when in solution they're floating around like ions”. 
4.4.2.6. Complexation

HH was able to give a brief description of what you would observe when reacting copper ions with hydroxide ions, and then the copper hydroxide with ammonia: the formation of a precipitate in the first, then dissolution of the precipitate in the second.

HH: That plus that forms a precipitate...

Interviewer: So you'd see a precipitate?

HH: Yeah

Interviewer: Yep and what happens when you add excess ammonia to that?

HH: When the ammonia's added to that, the precipitate would dissolve to form the complex ion copper tetra amino…it'd dissolve because…it forms that complex ion and that the hydroxides are free to go away.

He reluctantly produced a representation of the copper(II) hydroxide precipitate and claimed it would be an ionic lattice with two hydroxides for each copper ion.

HH: The structure? I can't draw the structure of this.

Interviewer: …It doesn't have to be an exact structure but give me some of the main ideas.

HH: I can't do it, cause I've never drawn a structure in a different ratio from…one to one so I don't know.

Interviewer: So tell me what the main ideas would be.

HH: Well the main ideas are that there's two…hydroxide ions for every one copper ion.

Interviewer: Okay, well just stick a couple of hydroxides in there.

HH: I liked this one, I liked it how I did it. It was great…[refers to representation of lead chloride drawn earlier in the interview].

Interviewer: What are each of those bonds you're joining them with?

HH: Oh, ionic bonds, I guess.

HH was asked to describe what he thought happened at a molecular level when ammonia was added to solid copper(II) hydroxide. He used his understanding of an ionic solid dissolving in water to produce the following sophisticated argument.
HH: …This is my theory. I don't know if I'm right or not but if ammonia was a polar molecule similar to water then it'd attack the structure in a similar fashion to water…break the ionic bonds and replace it with itself and the OHs would be all on their own… So these would get broken, right there and the NH₃s would join on there somehow…

Interviewer: How did you get the idea of the water molecules coming down? …You compared this to water molecules coming down.

HH: Because I know that, I think that's kind of the structure of ammonia [draws structural formula]… I know there's lots of hydrogens down the bottom and then there's the nitrogen up the top…The hydrogens are all the positive bits and up here's your negative bit…So, kind of polar molecule like the water. Similar to water, not the same but similar but anyway, that's just my crazy theory…

He then attempted to produce a representation of the products of the above reaction. He drew the complex ion with four ammonias in a tetrahedral arrangement around the central copper ion and specified that the overall ion would have a two plus charge. Two hydroxide ions were drawn separately. He stated that water would also be present.

On being shown the modified equations, and after drawing a representation of the hydrated copper ion, he redrew the representation of the complex ion in an octahedral arrangement with four ammonia molecules in one plane and water molecules attached above and below the plane. He drew a parallel between the hydrated copper ion and the copper tetraamine complex ion.

HH: See the NH₃s are in the same plane and then you've got the waters…

Interviewer: …So you think that this would be an octahedral shape? …

HH: Yeah, I reckon that's right actually…Because, I reckon the NH₃s do act like a water, slightly polar but neutral charge. The NH₃s just take place of the other water molecules somehow. That's what I think… Kind of a substitution reaction.

### 4.4.2.7. Equilibrium Reactions

**Equilibrium**

HH seemed to have a sound understanding of the concept of equilibrium, as shown by the following excerpt. He did not mention the fact that concentrations of reactants and products remain constant but are not necessarily equivalent to each other.
Interviewer: What is an equilibrium reaction?

HH: …When the forward and reverse processes, the rate, the reaction rates are equal…the reaction rates are equal for the forward and reverse reactions.

Interviewer: …Can you explain how the forward and reverse reactions can both occur?

HH: They just occur simultaneously. In some parts of the solution or whatever it is there’s say dissociation of ions or something and then in other parts there’s reforming of the ions.

**Gas-Phase Equilibrium**

HH produced a molecular-level representation of the gas-phase equilibrium showing all four species present in stoichiometric ratios. He was asked about the stoichiometric ratios. Although he was aware of the equilibrium constant, he was unsure how this related to the relative numbers of species present.

Interviewer: …You’ve got here one each of each of these.

HH: Yeah

Interviewer: So in an equilibrium, would you have those in stoichiometric ratios?

HH: …No, no, hang on.

Interviewer: What makes you say no?

HH: Cause I’m thinking of the, cause I know what the equation for it is. I know like the equation for the equilibrium constant is like the products over the reactants with the powers of the coefficients of stoichiometry, or whatever it is. I just can’t think if they’d be stoichiometrically thingomobob. Anyway, no, I’ll say no.

Interviewer: Because?

HH: I don’t know.

He conceived of the process as involving the transfer of an oxygen atom *via* the collision of the appropriate species.

HH: Well these two bump together to form these two… They react to form these two and then these two, well not form those two exactly, to form NO₂ and CINO and these two would react together to form CINO₂ and NO.

Interviewer: Okay, how do they…did you say bump together?

HH: That was my…Yeah

Interviewer: So they need to hit each other?

HH: I don’t know…if they have to hit each other. Probably, or something like that. Yeah because they’d have to transfer the oxygen there…something like that.
The student was then asked to predict the effect of adding more NO\(_{(g)}\) to the reaction mixture. He suggested the reaction would move to the right to form more products. He explained this by suggesting that the increase in the number of NO molecules would increase the probability of a reaction with ClNO\(_2\).

HH: Because you’re raising the concentration of the NO so I guess that means there’s more NO to be used up and that way there would be more NO to react with ClNO\(_2\)…

**Weak Acid Equilibria**

HH’s discussion of the dissociation of boric acid revealed an understanding of both the process of equilibrium and the action of water on the dissociation of weak acids. He first mentioned the simultaneous dissociation of the boric acid molecules and reforming of the ions into boric acid molecules. He stated that water joins up with the hydrogen ions to produce hydronium ions and that water uses its polarity to pull apart the molecules of boric acid.

HH: …The \(\text{H}_3\text{BO}_3\)... boric acid, you would see the boric acid molecules. You’d see some of them floating around in the solution and then you’d see ions floating around, and…you’d see ions reforming to form the acid, and then you’d see the acid dissociating into the ions.

Interviewer: Okay, now take a snapshot… and draw what you see.

HH: You’d just see the same thing I guess. Well maybe not exactly the same… That’s the thing splitting apart… together like that, reforming… and of course there’d be water doing its little jig as it does, hooking up with the \(\text{H}^+\) to form hydronium…

Interviewer: So you’ve got water molecules coming in there again, have you, and attaching to form hydronium ions?

HH: I guess.

Interviewer: … Does the water take part in the reaction at all other than that, or does it just come in later?

HH: Oh no, I think it does. Yeah, it actually does the separating. It pulls it apart using its polarity and stuff to tear the ions apart…

Although he knew, in theory, that hydronium ions form, he visualised the species as hydrogen ions.
Interviewer: ...Okay, if you just took a snapshot of the solution and you didn’t worry about what was happening in there, like these sort of reactions, what species would you see in there?

HH: H⁺, H₂BO₃⁻ and H₃BO₃…

Interviewer: ...Would you have just H⁺ ions floating around?

HH: No, H₂O⁺…

Interviewer: ...Do you picture it as H⁺ ions or as H₂O⁺?

HH: I always picture it as H⁺. I probably should picture it as H₂O⁺…

Interviewer: But you know that it’s H₃O⁺?

HH: Yeah. I know, that’s just the way I’ve always thought of it. I just think of it as H⁺ but I know, I still know that it’s H₂O⁺.

On being shown a second equation including water in the dissociation of boric acid, HH suggested that he would add water to his original representation and draw hydronium instead of hydrogen ions.

4.4.3. Interpretation of Macroscopic Phenomena

This section looks at HH’s ability to explain macroscopic phenomena. These data were collected from interviews 3 (Sections 4.3.3.1–4.3.3.2) and 4 (Section 4.3.3.3). Information regarding the content of the interview questions is given in Table 4.4 (page 263) or Appendix C.

4.4.3.1. Nail-Polish Remover

HH appeared capable of producing a description of what was occurring at the molecular level when a bottle of nail-polish remover was opened. However, he spontaneously sought an explanation of why it occurred, in terms of energy and pressure rather than simply discussing what the molecules were doing. He seemed to differentiate between the molecules coming from the liquid and the actual smell.
Interviewer: Why do you think that some liquids smell?

HH: Because they're volatile.

Interviewer: What does that mean?

HH: They evaporate quickly. Vapour press...yeah there's something like vapour pressure or something ...I know petrol's volatile... It's like that... You pour a bit of petrol on the ground it just evaporates. Oh well it disperses really quickly. I don't know why, it just turns...gaseous really quickly.

Interviewer: Okay, can you describe what's happening at a molecular level?

HH: No. I can try. Is it something to do with like those, all that, it's something to do with pressure and...the amount of pressure on it isn't enough to keep the molecules in a liquid state so it changes to a gas and disperses.

Interviewer: Okay, but can you describe what's happening to the molecules?

HH: ...According to my other stuff that I said, they must be getting more energy somehow and but I can't see that happening cause it's not like the temperature's changing or anything. It's just the pressure and now I'm confused…

Interviewer: Why does it take so long for the smell to reach your nose?

HH: Because it's mixed in with all the other air particles and stuff and so it just depends on how...concentrated it is...when it comes out. Like at first just a little bit comes out and then as it gets more concentrated in the air it kind of saturates the air and with its own particles and smell...I don't know. That's what I think anyway.

Interviewer: Okay, what do you think actually reaches your nose when you can smell it?

HH: The smell? No idea. Is it…

Interviewer: The substance is ethyl acetate...that's it there.

HH: Okay, I see.

Interviewer: The structure there… So what do you think reaches your nose?

HH: One of those, or maybe not one of those but a lot of those.

Interviewer: Okay, the whole molecule?

HH: Yeah...in the gaseous state, floating around and stuff.

Interviewer: And what would be in the liquid?

HH: Liquefied molecules of that, lots of them.

4.4.3.2. Precipitation Reaction

HH was able to provide an accurate prediction of what would occur if lead(II) iodide and potassium nitrate were added as solids to either end of a container holding water.
HH: They'll dissolve...soluble, all nitrates are soluble...and I guess that'll just dissolve because I think it's just a salt or something. A salt of some sort... So that should just...dissolve and after that I don't know. Lead iodide and potassium nitrate might form... It’ll form a precipitate or something...of lead iodide...

When his prediction was confirmed he was able to describe what occurred as the solids were added and gave a detailed representation of the resulting products (Figure 4.4).

HH: Well as soon as they hit the water, water uses its polarity...to tear the ionic bonding, the ions apart from each other and then they're floating around and stuff and when they float around the insoluble pairs come together, they rebond to form that yellow [substance] there.

His initial representation of the products showed the spectator ions, K⁺ and NO₃⁻, appropriately hydrated, with lead iodide represented by a circle with the label PbI₂. He was asked about the structure of the lead iodide. He stated that the lead iodide would, in fact, be an ionic lattice and subsequently drew the representation shown in Figure 4.4.

HH: ...I don't know how to draw these... It's like a crystal structure of some kind and it's three dimensional...but there's like two for every, two iodines for every one lead...I don't know how to draw it but yeah it's a crystal structure.

Interviewer: Yep and are there lead iodide molecules in there?
HH: ...No, there's, well it's like ionic so there's ionic bonds in between the ions.
4.4.3.3. Redox Reaction

HH provided adequate descriptions of solid copper and aqueous silver nitrate at a molecular level (see Figure 4.5). He represented solid copper as a lattice structure of Cu$^{2+}$ ions in a sea of electrons. He represented aqueous silver nitrate with separate silver and nitrate ions, with water molecules electrostatically attracted. He stated that water molecules would surround the ions.

HH: …solid copper…like electrons move around and stuff. So it’s just like a, it’s not really an electron sea but it’s like the electrons are free to move throughout the lattice structure… Are they Cu$^+$ or 2+ or something and then there’s the electrons floating around…Okay aqueous solution of silver nitrate…waters, can’t be bothered drawing them all, but water all around…

The student was unable to predict the outcome of the reaction. On seeing the experiment, he suggested that it might be an oxidation–reduction reaction. He was able to identify the grey substance as silver and understood that copper must have been present in the resulting solution due to the blue colour produced.

HH: Look at that. What happened? What’s that? …Corrosion or something, oxidation and reduction…

Interviewer: …Describe to me what you think is happening at a molecular level and draw diagrams to assist your explanation…What do you think that grey/black stuff is?

HH: Silver. Silver ions coating the copper…

Interviewer: [shows an experiment conducted earlier] What do you notice in that one?

HH: Its blue so there must be copper ions in there…in the water. So that would happen over time with this one as well? Is there like a replacement going on or something. Is like the Ag swapping with the coppers or something like that or is it just like, oh no, the coppers are getting…oxidised or reduced. It’s got something to do with the reduction potentials or something, doesn’t it? …What I would have thought is that the surface of the copper is being oxidised or something by the…water, no… I don’t know, its just leaving a layer of silver on there though …

After some assistance, he was able to produce an equation for the reaction. He knew that the reaction would involve some sort of electron transfer but could not visualise the process. He was, however, able to construct acceptable diagrams of the products (see Figure 4.5), intentionally leaving out the water molecules.
4.4.4. Interpretation of Molecular Representations

This section looks at this student’s ability to interpret and critically analyse molecular representations. These data were collected from interviews 1 (Section 4.3.4.1), 3 (Section 4.3.4.1–4.3.4.2) and 4 (Sections 4.3.4.3–4.3.4.4). The structure of this section and the content of the interview questions are elaborated in Table 4.5 (page 263).

4.4.4.1. Modelling

4.4.4.1.1. Interpretation

Models of Water

HH initially chose a space-filling representation as the one most closely resembling an actual water molecule, because the representation showed three-dimensionality. In the interview, he suggested that it was a better representation because the other correct representations were more symbolic, whereas the space-filling model was more realistic. In addition to it being
three-dimensional and bent, he liked the fact that the model showed the differently sized hydrogen and oxygen atoms.

HH: I chose two because it's like...in real life that's what I would have pictured it as if I could be shrunk down to a little person have a look... That's what I think I would have seen. It just seems the most realistic. These are all kind of chemical structure but that's like representative like.

Interviewer: More symbolic.

HH: Yeah, they're more symbolic. This is more...the actual structure.

Interviewer: Well what else about number two besides the fact that it's three dimensional and bent, is there anything else about that structure that makes you feel it looks more realistic?

HH: Probably the sizes as well.

Interviewer: Sizes of the atoms?

HH: Yeah, because...hydrogens are smaller, oxygen is bigger.

HH was then shown a collection of correct representations of water molecules (see Appendix C). He once again chose the space-filling model (B) as the one closest to the actual structure. Because model C also showed three-dimensionality, the bent shape and the differently sized atoms, he was asked why he preferred the space-filling model to this representation. HH was able to point out the falsity of using sticks to represent bonds.

Interviewer: B again...you told me you liked it the best because of the different sizes and because it’s a three-dimensional structure and because of the bent shape. So why do you choose this one over this one?

HH: ‘Cause I don’t like the sticks.

Interviewer: Why don’t you like the sticks?

HH: …Because it, I know that there’s, well there’s obviously not sticks in between molecules in real life.

Interviewer: Okay.

HH: I don’t know. They can kind of, I guess they are trying to represent the properties but I think there’s the force, like it doesn’t represent the forces of attraction in between the different atoms...there’d be like forces of attraction between...

In terms of the other models, he was unable to interpret model A and he commented that model E described the electrons involved in bonding. He felt that the more structural representations, such as model D, would be most useful when there is a need to show double and triple bonds.
When discussing a three-dimensional VisChem animated representation of a water molecule, HH was easily able to point out non-correspondences between the model and target, even though he thought that the model was a good way of representing what an actual water molecule looked like. He commented on the colours; was aware of the presence of a tiny nucleus within each atom, electrons in shells moving around and the reasons for the use of the “hard shell” appearance. He proposed that these additions had been made to the model for clarification and simplification purposes; for example, to allow for a comparison of size, to show the angle clearly, and to reduce the amount of information that must be absorbed.

Interviewer: Okay, well are there any features of that you think are not realistic?
HH: Probably the colours.

Interviewer: Okay, so why do we colour them like that?
HH: Oh, just to fill space, I guess and show the different atoms making it up. It wouldn’t fill the space like that either because they’re only ions or atoms…if you blew it up, it’d be that like that, with all the electrons in their funny shapes, orbits and stuff.

Interviewer: What do you mean, there’d be “that like that”?
HH: Oh well, tiny little nucleus… Cause I remember something, reading something…about…if the nucleus was a football in the centre of a football field then it’d take up the entire stadium, cause like that’s how big the shells with the electrons would be…

Interviewer: So, you’ve described like an atom with electrons and that, a tiny nucleus in the middle. So how does this outer shell like thing here fit in with that picture? Like what does that hard casing there represent?
HH: Probably the valence shell or the outer shell.

Interviewer: And would you expect it to be hard?
HH: No, no, no cause there’s…space between the electrons and stuff.

Interviewer: So why do we draw it sort of spherical and hard looking like that, do you think?
HH: Just to, I don’t know, just to show the main concept, …the angles that the hydrogens are at and the probably the size comparison maybe. Like size differences between the hydrogen and the oxygen…just make it easier…it’s just to make it easier on your mind I guess.

Interviewer: Simplify it down…
HH: Easy to see, take in and all that sort of stuff. It’s just easier. That’d be easier to look at than electrons and stuff going, flying…everywhere.

Models of Solid Sodium Chloride

HH was able to recognise some of the non-correspondences and correspondences between different models of solid sodium chloride and the “actual” substance. He appreciated the
three-dimensional nature of matter and criticised diagrams A and B for not representing this feature. He felt that diagram E probably best represented what the substance would actually look like at the molecular level, because it showed a 3D lattice with closely packed ions. He felt that model C and the physical ball-and-stick model were similar and useful in showing the lattice structure, but he felt that the portrayal of the distance between ions and the colours were unrealistic and misleading. However, he liked the fact that the physical model showed the differences in ionic sizes. He disliked model D because it contained no detail about the structure. He did not feel it was misleading, however, because although the substance is made up of ions, “when they are together…it's a neutral substance.” He acknowledged that model B was useful to show the vibrations of ions.

4.4.4.1.2. Multiple Modelling

When discussing multiple models of water molecules in interview 1, HH was asked about the purpose of having many models to represent the one thing.

HH: …Because different ways of representing it. Different. Used for different purposes.

He went on to describe some of the different uses of each model, as described in Section 4.3.4.1.1; for example, representing electrons involved in bonding, or representing double or triple bonds.

In interview 3, he was asked about multiple models of sodium chloride. He stated that different models were used for “different applications” and that models would be developed “as we progress more by technology”. He felt that a simple formula (NaCl\(_{(s)}\)) would be suitable for a starting student and as their knowledge progressed, they could eventually be introduced to more “realistic” 3D models like C and E.

HH: This is salt. This is sodium chloride. Its formula is [NaCl] and then you break it down to like ions and then…you could do like these more basic molecular-level representations showing movement and stuff and then show the three-dimensions and the lattice structure.

4.4.4.1.3. Development

HH felt that the 3D space-filling representation of a water molecule was probably the best representation scientists had come up with, based on the experimental evidence. This seemed
to contradict further comments he made regarding the features of atoms and molecules that were excluded from this representation (described in Section 4.3.4.1). He seemed aware of electron scanning microscopes, but was not sure whether anyone had actually seen a molecule.

HH felt that the VisChem animation of aqueous potassium fluoride was a reasonable representation of what the solution would actually look like. He based this response on the fact that the animation was close to his mental model of a solution, although there were less ions than he imagined.

HH: Pretty good. Probably having only one ion of each potassium and fluoride is probably a bit unrealistic. I'm sure there'd be more floating around so I'm sure that'd happen a bit more often. Things like that but having lots of water and stuff's good as well so that there is lots of water going around…polarity etc etc.

HH struggled to come up with an answer to how these representations might have been developed. He suggested that there might be just “people with good imaginations doing it”. After further questioning, he suggested that the image might have been constructed based on ideas that people already knew about charges on ions and water molecules, for example. Eventually, he mentioned the idea of experimentation.

HH: So people just sit around and think about it?
Interviewer: No, obviously they research it a lot. It's probably what they devote their lives to.
HH: How do they research it?
Interviewer: I don't know how they do that. They're crazy.
HH: What do they do in order to find out these ideas?
Interviewer: Electron microscopes and stuff like that…Lots of things…Lots of experimentation with different substances…

He felt that these images were developed “to make it easier for people to understand…how the molecular world works” and that animations make “it even easier cause then…it's right in front of you, it's like you're looking at what might actually be happening at the molecular world and like with movement and three-dimensions”. In line with these comments, he felt that representations of aqueous solutions were designed to teach students the ideas. He felt that the lecturer deemed this important as it enabled them to interpret experimental data in terms of molecular-level processes.
HH: So when we do experiments we can think about the molecular level, like what's happening at the molecular level not just like what's happening at the macroscopic level. Not what we can see, what is actually happening.

He believed that the animations were useful to him in some further ways, as described by the following quote.

HH: It...makes it easier for me to understand...probably just easier to listen... If he was just standing up there saying, oh yeah, there's lots of water going around with all these things and stuff...I'd go huh? Huh? And I'd probably have to write it like draw it down and...have a look at it to see what it actually looked like to understand it but when he actually puts something up there and says oh, as you can see all the waters around the thing [etc], you go ey cool. I'll remember that...

He felt that the animations helped him interpret the information the lecturer was trying to present.

He thought the animation would form a good basis for what all aqueous solutions look like, but would have to be modified slightly for different substances, like polyatomic ions, for example. He was not comfortable with the idea that this model may not be accurate, but accepted that he may be introduced to more complex models as his tuition progressed.

HH: Cause you spend all your...time learning something and then they go ooh, it's not right...I guess, when you think about it it's like a progressive thing or something. It's like taking one step at a time or something. You can't just like jump in...oh yeah there's...sub-shells...

Interviewer: Okay, so you think the teacher's...building up to it?

HH: Yeah...as long as he didn't come in and say well that's all wrong...

Interviewer: You're sort of are more comfortable with the idea of being given correct information?

HH: Yeah...I don't like being misled. It's not good at all.

He was also willing to accept that scientists’ ideas about solutions may have developed further or changed since this representation was proposed, because “there's always research and stuff going on so it's probably just progress...” He therefore suggested that scientists may not agree that this is a good model of an aqueous solution, but that it is relevant for his level of knowledge and understanding. He conceded there might be other models of aqueous solutions out there but to him, this was what aqueous solutions looked like.
Interviewer: Do you think that scientists would agree that this was a good representation of an…ionic aqueous solution?

HH: Probably not…They probably have something to say about it because they'd probably know a lot more but…they'd probably think the same thing that I do…oh yeah it's pretty good for a basic…but then they'd go but…I'm a scientist so I'd say yada, yada, yada…

Interviewer: Okay so you think there are probably other models of aqueous ionic solutions that scientists use?

HH: Yep, probably, but that's right to me.

4.4.4.2. Criticism of Molecular Diagrams and Animations

Diagram 1: Dry Ice

HH pointed out two relevant features of this diagram that he believed to be misleading. Firstly, the fact that the molecules appeared randomly distributed and secondly, the use of the magnifying glass.

Quote 1:

HH: They should be like…a fixed structure. They're all like random and stuff.

Quote 2:

HH: Magnifying glass! …Yeah you might be able to see atoms! Der!

He suggested that instead of the magnifying glass, which gave a false impression of the size of the molecules, you could “probably just have a circle and have like…another enlarged picture showing the molecular…like stating molecular-level representation”.

Diagram 2: Saturated Solution

HH made several relevant criticisms of this diagram. He commented that it should show water molecules, although felt that this extra detail might confuse a less educated student, and hence would need to be restricted for perhaps university students.
HH: Yeah well, there's no water, there's no waters going around…

Interviewer: So you'd put water molecules in there?

HH: Yeah, you need 'em, you really do.

Interviewer: Okay

HH: For a more detailed drawing that is. That's a pretty basic drawing but to have more detail if you wanted more detail but if it was for just like year 9 students or something it'd probably confuse…them. What’s all these waters doing? …

Interviewer: Alright, so you’d keep it simple for a younger student.

HH: Yeah, that's right…for a uni student then for sure wack in some water.

He also realised that the sizes of the ions were misrepresented but felt there was nothing that could be done about that. He mentioned that size differences between sodium and chloride ions should be shown. Finally, he suggested that the three-dimensional structure of the sodium chloride be depicted.

**Diagram 3: Electron Transfer**

The student only expressed one criticism of this diagram: that the atoms were simplified such that they did not show details like the nucleus or sub-shells.

HH: Oh yeah. I get it. I see. It's pretty basic, yeah. It's like just, not much detail. That's obviously representing the outer shell, the valence shell of each…each of the atoms and that's just representing an electron, electron transfer from the sodium to the chlorine…but it doesn't like show a nucleus or anything. It doesn't show the sub-shells and stuff like that.

He felt it was a reasonable basic representation but required a caption along the lines of “representation only shows outer shell of atom…should be nucleus…not detailed, not to scale”.

He did not seem certain whether electron transfer would occur in such a manner, resulting in the formation of ions.

Interviewer: Would that actually happen?

HH: Well not quite like that. Not like that but, yeah…an electron is transferred…Yeah it would happen something like that.
Diagram 4: Precipitation

HH made the significant comment that this diagram failed to show water molecules. Otherwise he felt that the diagram was almost perfect.

Interviewer: What do you think of this diagram?

HH: You need water. Water is important when representing ions in solutions…But yeah it's alright. It got size differences…shows charges etc then over here it shows…a 3D representation of the crystal structure…I think the only thing missing there, with the real life pictures it's good as well, yeah.

Interviewer: Just the lack of water molecules?

HH: Yeah, that's probably the only thing there …if it does say it in there then it's probably almost perfect. It says mole ratios and stuff, good explanation. I'd give it a 9 out of 10, I'd say.

Animation: Dissolving

This animation seemed to appeal to HH but even so, he proceeded to point out many areas where it was misleading or inadequate. He suggested that there was not enough water included and there was too much space between the water molecules present. He disliked the use of the ball-and-stick representation for solid sodium chloride because “it doesn't have big sticks in between the ions” and he commented that the sodium chloride lattice should be vibrating.

HH: I like all the water. I think that there's probably not enough water…But yeah it does show the basic…dissolving but I think. I feel there's too much space between the water…I think it's good how it shows the polarity and

Interviewer: Do you think there are any other ideas that might mislead new students?

HH: Yeah, the crystal, the lattice of sodium chloride…it's not like that. It doesn't have big sticks in between the ions… That's one thing that would detract from the whole greatness of the animation.

Interviewer: Okay, do you recall being shown a similar animation?

HH: Yeah, I do.

Interviewer: And how was it different from this one?

HH: …It was similar to that except the sodium chloride was represented better, I think. If I remember correctly and yeah the sodium chloride was represented without…the sticks. It was just the…space-filling model or something. Sodium chloride isn't moving. It should be moving cause it's not at zero K which is when all movement stops.
4.4.4.3.  Analogical Modelling of Equilibrium

**Analogy 1: Soccer Game**

Although HH seemed to have some difficulty in interpreting this analogy, he was able to see that players on the bench and players on the field represented the reactants and products.

HH: Like the bench might represent the products or reactants and the players on the field represent whatever the other is.

Interviewer: Okay, so lets pick one, say the bench is the

HH: Products

Interviewer: Okay, and the field is the reactants…

HH: Yep

He showed confusion over the statement “There is no change in the number of players on the field, even though their identities are different”, equating this to the idea of an equilibrium as a closed system in which the number of particles remains constant.

Interviewer: Okay

HH: Yeah so [reads] It’s a bit weird because like its talking about the players on the bench and then its talking about there’s no change in the number of players on the field. Which is like, I don’t know, maybe they’re going crazy.

Interviewer: So what they’re saying is when you take one person off the soccer field you’ve got to put one person back on.

HH: Yeah something like that.

Interviewer: So there’s always the same number on the field.

HH: Yeah, yeah

Interviewer: So how does that correspond to the equilibrium situation?

HH: Well, is it like a closed system or something like that. Like nothing really escapes it, it just reacts within itself kind of…

He misinterpreted the statement “identities are different” suggesting that it referred to the fact that reactants change into products, forming new substances, with new “identities”.

HH: The changes in the molecular structures and stuff like ClNO$_2$ going to ClNO and NO to NO$_2$…

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5 Analogies can be found in Interview 4 Protocol (2001) in Appendix C.
He correctly interpreted the sentence “there is no requirement that the number of players on the field and on the bench be equal.”

HH: Like the differences in the concentrations of the products and the reactants, they don’t have to be equal…

HH seemed to feel that this analogy might be misleading to other students because he found it confusing. He wasn’t able to articulate exactly what he thought was misleading about it.

Interviewer: Do you think that students might develop any misleading ideas from this analogy?

HH: I thought it was a little bit confusing, oh well not real confusing, but it might be a bit misleading the first time you read it or something.

Interviewer: What features of it, do you think?

HH: There are just a couple…Not sure…I was going to say cause here it says there is no change in the number of players on the field. Oh I’ve already said that. No, it should be alright. It’ll do.

**Analogy 2: Juggling**

HH was able to see the connection between juggling and an equilibrium system suggesting that “the balls in the air might be like the products, and the balls in the hand are like the reactants and it’s just the change between the balls in the air and the balls in the hands, like the change between products and reactants or the reactants to the products”.

When discussing the last statement in the analogy, this student revealed a misconception relating to equilibrium, that the number of reactants and products may not remain constant.

Interviewer: What about “such that the number of balls in the air or in the hands always remains the same.”

HH: That’s not…that’s like saying that…

Interviewer: Say there are always four balls in the air and always two balls in the hands.

HH: No, that’s not right. No because, I don’t think it’s right anyway…because they’re constantly reacting there’s going to be different numbers of, different numbers of the products and different numbers of the reactants every now and then.
**Analogy 3: Dancing**

HH appreciated this analogy and was able to point out how it corresponded to an equilibrium system.

Interviewer: So what do the males and the females represent?

HH: …Well, males might be one reactant and females another…

Interviewer: And what are the products?

HH: The products would be the pairs. Every time a couple begins dancing together…

Interviewer: What bit does that correspond to?

HH: The actual equilibrium…there’s always like one splitting…apart. Just say there’s a molecule and it splits up into ions or something and then there’s ions reforming to molecules or couples in this case, I guess.

He thought, however, that the last sentence, “A male must find a female partner and persuade her to dance before they can dance together”, was superfluous and did not relate to equilibrium.

HH: Oh I’ve heard this one before I think…Yeah I get that. I just don’t like that last sentence – “a male must find a female partner and persuade her to dance before they can dance together.” That’s, that’s a bit…

Interviewer: It’s what? What don’t you like about it?

HH: It just doesn’t, it doesn’t really relate to chemistry at all…

Interviewer: You think that you could just leave out that sentence?

HH: Yeah, they could have left that out, I think, that was just pretty pointless saying that, but the rest of it…makes sense…

HH felt this was the best analogy, as he believed it to be easier to understand than the other two.

**4.4.4.4. Interpretation of Molecular-Level Animations**

**Ice Melting**

HH was a little unsure about what this first animation represented, even though he initially identified it correctly. Despite this uncertainty, he was able to point out many significant ideas
Chapter 4  Examination of Students’ Mental Model Development

represented by the animation of ice melting, including the structured lattice, movement, energy changes and intermolecular bonding.

HH: It’s heating of ice I think. Well it’s ice at the moment, its not any more, melting, …its not ice is it? It’s something else, or is it, I don’t know…

Interviewer: OK, so what features would you point out?

HH: The movement I guess. I don’t know, what do you mean, what features?

Interviewer: Say you were showing the animation in a lecture and were describing it to students and you were pointing out every relevant idea in there, what would you point out?

HH: The structure, the lattice structure… This is heating isn’t it, this is like melting? As the heat increases, the energy of the molecules increases and they move more until the actual intermolecular forces are overcome by the energy of the molecules and they just break apart.

Interviewer: Okay. Are there any other details in there you would like to point out?

HH: …The polarity of the molecules, I guess, maybe. You can see the positive’s going to the negative ends…and its still doing it there.

Interviewer: Still doing it there? …So you can still see the polarity having an effect once it’s liquid.

After viewing the animation, he was able to construct an explanation for why ice is less dense than water, based on the structure of each. However, he interpreted the difference in spacing to be due to an increase in attraction in the liquid state.

Interviewer: Can you explain using that animation why ice is less dense than water?

HH: …Because when it becomes a liquid the molecules, they’re not held in a fixed structure… When they’re fixed structure there’s like fixed spaces between them, but when they’re a liquid they go like that and they’re closer together and…they’re like more attracted to each other due to their like polarity rather than held in, held in one place by their

Interviewer: They’re more attracted in the liquid?

HH: Kind of. I don’t know. Like they’re held by intermolecular forces there…in a fixed position, but then you can see like when they break away from that, they kind of like move closer together, they become more dense, kind of.

**Water Evaporating**

Viewing this animation prompted HH to recall many significant ideas, although he did not recall the animation and hence was not certain what it represented. He mentioned the terms evaporation, vapour pressure, equilibrium and surface tension when trying to make sense of the animation. He suggested that some water molecules may have been returning to the liquid surface because they had lost energy or because of an attraction to other water molecules.
HH: Oh hang on, what’s going on here? Oh this is... What is that, I don’t remember... Is that like evaporation... or something like that? Something to do with vapour pressure and stuff. It looks like it because you can see the molecules floating away from the liquid like but then they’re coming back... Is that like an equilibrium between the gas and the liquid or something, or is it? Oh, I don’t know.

Interviewer: Are there any other details there that you notice? Why do you think some of them might come back?

HH: Because they lose their energy somehow. I don’t know how. Loss of energy, that’s what I would have thought.

Interviewer: Okay, watch that one there... What do you think happened to that one?

HH: Surface tension

Interviewer: Okay, what does that mean?

HH: See that’s what we’re doing in physics now... What happened to it? I don’t know what happened to it.

Interviewer: Why did it come back down again?

HH: ... looks like he was attracted to that other one...

Sodium Chloride Dissolving

Although HH never specifically stated what process this animation represented, he seemed to understand what was occurring. He identified the sodium chloride and the water molecules. He commented on the water molecules tearing the ions from the lattice, the relative sizes of the ions, the lattice structure of sodium chloride, the electrostatic attractions between water molecules and ions, and the movement and hydration of the ions.

HH: What are we doing here?... Sodium chloride... Oh here we go, get into it... tear him off. That’s it, good form, well done...

Interviewer: ... What finer details would you like to point out?

HH: The lattice structure of the sodium chloride... The size differences between the chlorine and the sodium ions... Different polarities of the different ends of the water molecule.

Interviewer: Be a bit more specific. What do you mean by that?

HH: What, the polarity? How... the positive hydrogen end or the positive dipole of the water molecule is attracted to the negative chloride ion and... the negative dipole... is attracted to the sodium...

Interviewer: ... Any other details?

HH: Yes. The movement of the molecules... They don’t cease movement until absolute zero... Water molecules completely surround ions when they’re torn apart like that...
Aqueous Solution of Sodium Chloride

HH was able to identify the animation of aqueous sodium chloride. He noticed the coming together of a cation and an anion and attributed this to an attraction between their opposite charges. He also mentioned polarity effects and commented on the ratio of water molecules to ions.

Interviewer: …What’s that one showing?

HH: Sodium chloride in solution and then they reformed for a split second and then got torn apart again... I guess that’s kind of like an equilibrium kind of thing or something.

Interviewer: Why do you think they come together? Do you actually think they form any sort of new substance there?

HH: No not really, just positive/negative attraction I guess.

Interviewer: …What other features would you point out?

HH: …Polarity of the water again, as usual.

Interviewer: What do you notice about, say, that screen or that screen? …What’s a really obvious detail?

HH: Not many sodiums and chlorines. The waters out number the sodium and chlorines vastly.

Precipitation of Silver Chloride

HH did not recall this animation but after much deliberation was able to correctly determine what it was representing.

HH: …Oh hang on. Oh this is, is this the forming of the precipitate or something? Precipitation? The nitrate is just floating round because nitrates are soluble…and silver chloride forms a precipitate so it would have been silver nitrate and something chloride mixed together and when they mix together the silver and the chlorine form the precipitate and well, there’s the nitrate there and whatever else. I don’t know what the other one is. I might have missed it but there is something else there, stay in the solution.

Interviewer: Yep, okay. Are there any other smaller details, now that you’ve got the overall picture, that you wanted to point out?

HH: Not really. Just the usual I guess, polarity, lattice, nitrate…

Redox Reaction of Copper with Silver Nitrate

HH immediately identified this animation as the reaction between copper and silver nitrate conducted earlier in the interview. Although he noticed the main ideas in the animation, his discussion remained fairly brief.
HH: This is this… That’s the copper, that’s the nitrate going around again, that’s the copper solid there. What happens? It just deposits…a layer of silver on top or something. I guess…

Interviewer: …Can you see what happens as the silver is deposited?

HH: As the silver is deposited, the electrons surround it like that and then they take a, water takes a copper, so it’s yeah, like a substitution kind of thing I guess…They substitute…a copper ion for a silver ion or something. Because of the charge would that mean there’d be like twice as many silvers for the same amount of coppers?
4.5. Case Study 2 (HL)

HL represents a student with high prior knowledge (pre-test score: 12) and with low disembedding ability (GEFT score: 10).

4.5.1. Imagery Development

The following section documents the development of HL’s images of substances, assessed by questionnaire through the year. These data were collected from the pre-test, interviews 1–3 and the post-test.

4.5.1.1. Molecular Substances

General Features

In the pre-test, HL suggested that molecules get larger from solid to liquid to gas. He reasoned that gases are “on the right-hand side of the periodic table (more electrons in shell, therefore larger atomic radius)”. It is obvious that he misinterpreted the question. He was asked about this question in interview 1 and agreed with the response he provided in the pre-test. When questioned about one substance in three different states, he was unsure about the relative sizes of the molecules.

In interview 2, he was once again asked if there was any change in the size of the molecule when water changes from solid to liquid to gas. He replied that he “wouldn’t imagine so”. In the post-test, he chose the response that showed the solid, liquid and gas molecules the same size, but showed fairly low confidence in his answer.

Liquid Water

Using a ball-and-stick model, HL initially represented liquid water as discrete water molecules. By interview 1 he had developed a mental image that featured the space-filling model of a water molecule, because this was how it had been represented in lectures. He also added the feature of hydrogen bonding to his image.
HL: I’d have ‘em so the oxygen’s always facing the hydrogen atom.

Interviewer: Okay, so you’re showing the hydrogen bonding.

HL: Yeah…and that’d be the oxygen’s negative and the hydrogen’s slightly positive.

By interview 2, HL’s image seemed to have deteriorated, although it is unclear what contributed to this change. He represented liquid water as separate atoms of oxygen and hydrogen. Later in the interview, when discussing solutions, his attention was directed by the interviewer to the depiction of discrete water molecules. This led him to change his mind regarding liquid water at a molecular level.

Interviewer: So is the structure of water…in a solution different to what it is in just liquid water?

HL: Hm, I guess not. That’d be wrong.

Interviewer: You think your first representation’s wrong?

HL: Yes it’s wrong.

Interviewer: What changes might you make to it?

HL: I would, it’s H2O so two hydrogen and bonded to an oxygen atom. So that’s the molecule… Just lots of molecules floating around…

During this interview, he mentioned, for the first time, the motion of the water molecules in the liquid state.

HL: Yep, just not held as tightly. They can vibrate more and move a little bit…but as a solid you can’t move as much as the liquid.

In the post-test HL, used a space-filling representation to depict discrete water molecules and commented that they were able to move about randomly. In interview 3, he simply mentioned the movement of the molecules in water, and produced a diagram similar to the one he drew for the post-test. He could not identify any specific occurrences that had helped him to revert back to the correct notion of liquid water as containing discrete water molecules. The changes in HL’s representations of water throughout the year are shown in Figure 4.6.

Gaseous Water

As described above, this student used a ball-and-stick model to represent the discrete water molecules in gaseous water, in the pre-test. He did not provide a written explanation of his drawing. In interview 1, he expanded on his idea of gaseous water by mentioning that there
are fewer molecules in a given space than in liquid water, that there is still some hydrogen bonding, and that there is movement.

Interviewer: How about gaseous water? Do you want to explain to me how you perceive that? How you did and how you do now?

HL: Okay, I’d have less molecules in there than what I had for liquid because it’s a gas…less molecules. That would be the same still, they still bond, still sort of bonding between, hydrogen bonding is happening between them.

Interviewer: Between the molecules?

HL: Between the molecules… Not as great extent than the liquid.

Interviewer: Okay, is there anything else happening in there?

HL: …They’re supposed to be moving around a lot.

Strangely, in interview 2, this student represented gaseous water as separate oxygen and hydrogen atoms, moving freely (see Figure 4.6).

HL: Liquid to gas…the atoms separate a lot more…in a gas the atoms pretty much aren’t joined at all. They’re free to move about wherever they want.

However, as with liquid water, by the post-test, the student had the correct idea, representing discrete water molecules using the space-filling model. He also mentioned movement and collisions.

In interview 3, HL was a little less descriptive regarding his image of gaseous water than in the post-test, mentioning spacing and movement but not collisions.

HL: The gas, they’re free to move around wherever they want, random, random motion…so it’s not as closely packed as a liquid is.

When shown his answer to the post-test, he simply commented in relation to collisions “Yeah, that happens too”. When asked how he developed the idea of gaseous collisions, he suggested it was something he learnt in high-school chemistry. This is peculiar, considering he did not mention the idea until the post-test. He could not identify what caused the changes in his images between interview 2 and the post-test.
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#### Figure 4.6 Changes in HL’s representations of solid, liquid and gaseous water through the year

<table>
<thead>
<tr>
<th>Solid water</th>
<th>Liquid water</th>
<th>Gaseous water</th>
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<tbody>
<tr>
<td><strong>Pre-test</strong></td>
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<td><strong>Interview 2</strong></td>
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<td><strong>Post-test</strong></td>
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<td><strong>Interview 3</strong></td>
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Solid Water

In the pre-test, HL represented ice as interlinked hydrogen and oxygen atoms, in a lattice structure, using a ball-and-stick model (see Figure 4.6). He admitted that the representation was an uninformed guess. It is interesting and perhaps concerning that he agreed with his depiction when questioned in interview 1, even though VisChem animations had been used in lectures to teach the correct image. He could not identify anything from lectures that had confirmed or influenced his idea.

Interviewer: How about the solid water?
HL: …Water molecules in the lattice. I just didn’t know how to represent them.

Interviewer: Okay so when you say the water molecules are in the lattice, do you have like discrete single water molecules or do you have some sort of interlinking of hydrogen and oxygen like this?
HL: …the interlinking

Interviewer: like that, so you still think similar to that?
HL: Yes

Interviewer: …So you don’t have like single water molecules any more?
HL: No

Interviewer: …Okay, so nothing in lectures has confirmed or
HL: No, nothing in lectures.

In interview 2, he was asked to produce a representation of solid water. His representation was similar to that described above but he used a space-filling model (see Figure 4.6). He described his representation as “A lattice…hydrogen and oxygen atoms bonded together as a solid,” and later suggested that there was some slight movement. The student was asked to explain why water expands when frozen. He was unable to provide an explanation.

By the post-test, he had developed a more scientifically-acceptable mental model of solid water, showing discrete, vibrating water molecules in a structured lattice (see Figure 4.6). He reported having reasonable confidence in his answer. He produced a similar diagram in interview 3, describing it as closely packed water molecules. When shown his answer to the post-test, he noticed that he had forgotten to mention vibrations of the water molecules. When asked how he had developed the idea of vibrations, he once again attributed his knowledge to high-school chemistry. This is curious considering that his image of solid water in the post-
test was nothing more than a guess. HL still could not offer an explanation for why water expands when frozen. He was also unable to identify learning strategies that had enabled him to correct his original image.

4.5.1.2. Ionic Substances

Solid Sodium Chloride

In the pre-test, HL was able to identify the more scientifically acceptable representation of solid sodium chloride, citing as his reasons its closely packed nature and its structure. In interview 1, he still agreed with this choice. He was questioned about his understanding of the bonding present. HL appeared to harbour the misconception that ionic bonds occur only between ions that have exchanged electrons and that electrostatic forces attract the ionically bonded ion-pairs together.

Interviewer: What sort of bonding is in sodium chloride?

HL: Ionic.

Interviewer: …Can you describe to me what your idea of ionic bonding is?

HL: Yep, it’s just where two ions, sodium…and chloride, sodium has one electron more and wants to get rid of it or it needs the one electron…and so they’ll swap electrons and…chloride has 8 electrons now and that’s just the way that the lattice is set out. Chlorine, sodium, chloride, sodium.

Interviewer: Okay, is there going to be a different bond between the two that exchanged electrons compared to say this chloride ion and the other sodium ions around it?

HL: …I guess so…

Interviewer: Which would be…the ionic bonds?

HL: [connects pairs of ions on diagram]

Interviewer: Okay, and what sort of bonds do you think would occur between [the pairs]?

HL: …sodium ions attracted to chloride ions. That’s what brought them together.

Interviewer: Okay, so there’s still an attraction here between positive and negative?

HL: Yep, yep.

He was aware that there would be some vibration in the solid.
Interviewer: And before you start heating are they…?
HL: They’re still tightly packed. They’re still connected together.
Interviewer: Are they moving at all?
HL: …A little. Not very much though.

In interview 2, HL was asked to produce a representation of solid sodium chloride. He drew closely packed, alternating sodium and chloride atoms (see Figure 4.7).

HL: That’s a sodium atom, that’s a chlorine atom bonded together and they’re all bonded together to form a lattice.

Because he had failed to represent the ions in the lattice, he was once again questioned about the bonding in the lattice. The following interview excerpt shows that he understood the lattice to be made up of ions. He had, however, retained his misconception regarding electron exchange in ionic solids.

Interviewer: Describe what type of bonding occurs in sodium chloride?
HL: Ionic.
Interviewer: Okay, now describe to me what you understand ionic bonding to be.
HL: Where the positive…ion gives away its…no, when an atom has less than four electrons in it’s valence shell it’ll give away its electrons to the non-metal but [tape muffled] has more than four electrons in its shell, so that has 8, so the non-metal has 8 and the metal doesn’t have any.
Interviewer: Okay so you end up with a sodium ion and a chloride ion…so does that mean that there’s only an ionic bond between those two that swap the electron or is there an ionic bond between that sodium and every chloride around it?
HL: There’d be an ionic bond between the ones that swapped the electrons as far as I know.
Interviewer: So how would you describe the bonds between the other…like that sodium has six chlorides around it. How would you describe the bonding between that sodium and all the other…chlorides?
HL: …Because the sodium has one less electron it’d be positively charged and the chlorine has one more electron so it’s negatively charged, so it gets an electrical attraction between the two.

He was still aware that the particles in the solid vibrate.

Interviewer: What might you see happening that’s not represented by that diagram there?
HL: …a little bit of movement I guess…just a bit of movement, the atoms shaking.
HL’s image of solid sodium chloride in the post-test seems consistent with his earlier descriptions. He chose the correct representation and commented on the closely packed, structured lattice and the presence of sodium and chloride ions. He did not criticise diagram 2 (in the post-test) for showing ion-pairs, but only suggested that they be moved closer together. This may have suggested that he still harboured the misconception regarding ionic pairs in the solid. His discussion in interview 3, however, suggested that he correctly believed there to be distinct ions in the lattice, electrostatically attracted. He could not, however, see the problem in simply moving the ion-pairs in diagram 2 closer together. He seemed concerned only with the appearance of the diagram and not the underlying concepts.
Interviewer: …For representation 2 here you've written that the ions are…not close enough together and that's the only comment you've made as a criticism for this, so is there anything about that diagram that might conflict with your idea of an ionic solid?

HL: …Not really.

Interviewer: So if you just moved those closer together that would be adequate?

HL: Yeah, that one's touching that one, that one's touching that one.

Interviewer: Okay, now in the representation that you've chosen here you have a sodium ion surrounded by four chloride ions. Can you describe the bonding between that sodium ion and the surrounding four chloride ions?

HL: Just electrostatic attraction I guess…the ion would be positive and so the negative chloride ions would be attracted to it…holds it together, I suppose.

Interviewer: Okay and is there the same electrostatic attraction between the one sodium ion and all the chlorides surrounding it?

HL: Yeah.

Interviewer: …Based on that fact, is there anything else about number 2 which might sort of disagree with that idea or conflict with it in some way?

HL: …No.

Interviewer: Do you see there being pairs of ions in this structure?

HL: No, it's single ions…single ions not paired up just single.

Interviewer: Okay, but that doesn't strike you as maybe a criticism of this diagram?

HL: …I suppose so. It’s close to that diagram, it’s like that diagram.

Interviewer: What do you mean?

HL: It's right except…they're paired up and that one's not…the ions are paired up with each of the other ions.

Interviewer: Okay, but you think if you push them closer together that they wouldn't be paired up anymore?

HL: …They'd look the same.

**Aqueous Solution of Sodium Chloride**

HL’s initial concept of an aqueous solution of sodium chloride was of separate sodium and chloride ions in water. He did not appear aware of the interactions between the ions and water molecules. He chose diagram 5 as the most scientifically acceptable representation, not noticing the incorrect ratio of ions. By interview 1, he had added to his image the idea of ion-dipole forces, and decided that diagram 1 was a better representation. He attributed this development to drawing in the lab.
HL: …Oxygen goes slightly negative and it’s a positive sodium ion so there’ll be an electric charge there…attraction.

Interviewer: Okay, so there’s an attraction between the oxygen of the water molecule and the sodium ion…You obviously didn’t think that to start with. How have you developed that idea?

HL: [The lecturer] showed us. He was…drawing stuff during one of the pracs, I think it was. Yeah, just teaching us how to draw the hydrated NaCl…and stuff like that. You’ll have water molecules in between…you’ll have the ions broken up completely then water molecules around it, surrounding it then make sure you’ve got the oxygen next to the…

Although he felt diagram 1 was the best representation, he thought adding some more water, as well as having a couple of water molecules around each ion, could improve it.

HL: I’d just have more water molecules going round there.

Interviewer: Just separate floating around or…?

HL: Yeah I’d have a couple floating around and maybe a couple like that, surrounding it…

Interviewer: …Okay, how many do you think would be around each ion?

HL: Just a couple…about two, one or two around these ones.

In interview 2, HL produced a diagram of aqueous sodium chloride similar to that described above (see Figure 4.7). He showed separate sodium and chloride ions with single water molecules electrostatically attracted to the ions. However, he inadvertently represented water molecules as $\text{O}_2\text{H}$. He noticed this later in the interview. He put in the correct ratio of ions only after his attention was directed to the idea. He stated that there would be two or three water molecules surrounding each ion.
HL: As you pour water down…you’d split up…the sodium chloride lattice…so you’d have sodium ions and chloride ions floating around in the water.

Interviewer: Okay, are you going to have two sodiums for every one chloride?

HL: No, of course not [fixes diagram].

Interviewer: Okay, so what have you done with those water molecules there?

HL: …The negative ends of the water molecules are attracted to the…sodium ion because it’s positive…and the hydrogen end which is the positive end of the water molecule is attracted to the negative end of the sodium…Oh, chlorine.

Interviewer: And is there only one water molecule for each of those ions?

HL: No there’d be more surrounding it.

Interviewer: How many do you think?

HL: Lots, two or three I guess.

He felt that an animation of sodium chloride dissolving had helped him develop this image.

Interviewer: How do you think you formed that idea?

HL: I probably got it from [the lecturer].

Interviewer: Do you remember anything specific from the lectures that may have helped you learn those ideas?

HL: The stuff…on the CDs in the back of the textbook…he shows us during the lectures and stuff…

Interviewer: …What can you remember from them?

HL: The sodium chloride, the salts…all bonded together and as you pour water down it splits, it pulls the sodium chloride apart so…as the sodium chloride comes apart, comes up into the water, water molecules surround the ions.

In the post-test, HL still believed that diagram 1 was the best representation, suggesting again that water molecules could be added, though not as many as in diagram 3. He made clear the key features of electrostatic attraction, separate ions and the one-to-one ratio of sodium to chloride ions. In interview 3, he was once again asked to construct a diagram of aqueous sodium chloride (see Figure 4.8) and was asked to describe his representation. When doing so, he noticed that he had oriented his water molecules incorrectly. It is interesting to note that the number of water molecules he believed to be surrounding each ion increased in each subsequent interview, up to four in this interview. HL realised that the particles in the solution would be moving. He underestimated the overall ratio of ions to water molecules in solution.
HL: …The lattice breaks up so just the sodium ion and the chloride ion floating in the water molecules.

Interviewer: Okay. Now you've directed your water molecules deliberately there. Can you describe why you've done that?

HL: The…slight attraction…electric attraction between the water molecules. The oxygen end…I've drawn it the wrong way round. The oxygen end should be slightly attracted to the…positive sodium…I've drawn them so that the hydrogen's actually attracted to the sodium but it's not.

Interviewer: So you've drawn the water molecules the wrong way round?

HL: Yeah… There's an attraction between the ions and the water molecules.

Interviewer: Okay, and how many water molecules would you expect to see surrounding each ion?

HL: …Just a few. Would be a few, three or four maybe.

Interviewer: …Are they the only water molecules in the solution?

HL: No, it'd be more than that.

Interviewer: Okay, so for every pair of ions about how many water molecules would you expect to see?

HL: Ah, say maybe seven or eight or nine.

Interviewer: Okay so that includes the ones surrounding and the ones in between? Okay, now if you imagine that in your head and you can picture it, is there anything else happening?

Interviewer: …They're moving round a bit.
Precipitation of Lead(II) Iodide

This student showed some understanding of precipitation reactions in the pre-test, suggesting that a precipitate of lead(II) iodide resulted from the reaction of potassium iodide and lead nitrate. In interview 1, he attempted to provide an explanation for what happens at the molecular level. He expressed the alternative conception that molecules of lead nitrate and potassium iodide break up when you pour them in together and “swap partners”, resulting in molecules of lead(II) iodide and potassium nitrate. In the post-test, he presented an equation for the reaction explaining the reaction by the statement: “when PbNO$_3$ mixes with KI, a precipitate of PbI$_2$ forms (the solid) and K$_2$NO$_3$ is the spectator ion which takes no part in the reaction”. In interview 3, he was asked to produce a molecular-level drawing of this process but he lacked confidence in doing so. He constantly entertained alternative ideas and wasn’t sure which were correct. These mostly related to whether ions were grouped in pairs or separate. His representation is shown in Figure 4.9. He represented the reactants as separate ions in solutions, and the products as molecules. The water molecules were added later. He correctly oriented the water molecules in the lead nitrate solution but not in the potassium iodide solution. The dubious nature of his ideas is demonstrated in the following excerpt.

Interviewer: How about you draw a representation of each of the reactants first?

HL: I guess this is how they look. I'm not sure…I really don't know now.

Interviewer: …What are you unsure about?

HL: Whether the lead and the nitrate ions join together or whether…they're separate ions floating around in the solution.

Interviewer: Okay.

HL: Got the…sodium chloride there…just floating around in the waters, in the water. I was wondering if it's supposed to be like that or if it's supposed to be joined together.

The confusion continued with his representation of the products, after he was probed about whether or not you could tell which was the solid just by looking at the molecular-level representation. He suggested that maybe the potassium nitrate would separate.

Interviewer: Okay, are there any differences at the particle level between the lead iodide and the potassium nitrate that would tell you it was a solid?

HL: …I don't think. I don't know. The potassium and nitrate ions might not be joined together. I don't know.
He was then encouraged to compare his concept of a solid with the representation he had produced of a solid in a solution. He eventually came to a scientifically acceptable concept, suggesting that the lead(II) iodide would be a structured ionic lattice and the potassium and nitrate would be present separately as spectator ions.

Interviewer: Does that fit with your other conceptions of solids?

HL: It'd be, lead iodide, lead iodide forms on the bottom of the beaker… and the molecules or the ions'll be closely packed together I guess. Yeah, so it would be a solid.

Interviewer: The molecules or the ions?

HL: The ions will pack together to form a lattice on the bottom of the beaker.

Interviewer: Okay, so are you thinking now you'll get more of a lattice like sodium chloride?

HL: Yeah.

Interviewer: or like water, like ice?

HL: No, like sodium chloride on the bottom of the beaker…

Interviewer: …Okay and what are the potassium and nitrate doing?

HL: Just floating around. I guess it'd be, they'd be separate ions, floating around in the solution with the water molecules.

Reactants

Products

Figure 4.9  HL’s representation of the precipitation of lead(II) nitrate from interview 3
4.5.2. Interpretation of Chemical Symbolism

This section looks at HL’s ability to represent symbolic notation at the molecular level. These data were collected from the pre-test, interviews 1, 2 and 4 and the post-test. Molecular representations were probed in interviews 1 (Sections 4.4.2.1–4.4.2.2), ionic representations in interview 2 (Sections 4.4.2.3–4.4.2.6) and equilibrium in interview 4 (Section 4.4.2.7). For further information regarding content of the interview questions, see Table 4.3 (page 262) or Appendix C.

4.5.2.1. Symbolic Representations

In the pre-test, HL gave a correct written description of the formula $2\text{NO}_2$ but drew a single molecule containing two nitrogen and four oxygen atoms. He was asked about his representation in interview 1. He once again gave a correct molecular-level description and soon realised he had made a mistake in the pre-test, with his representation. He insisted, however, that he’d just made a silly mistake and that this was not something he had learnt since starting university chemistry.

Interviewer: Okay, according to…your definitions, how would you describe this symbolic representation?

HL: …So there’s one nitrogen bonded to two oxygen atoms and there’s two of those. I drew it wrong!

HL gave both a correct formula ($\text{N}_2\text{O}_4$) and an incorrect one ($2\text{ NO}_2$) for the molecular-level representation in the pre-test. On seeing his response during interview 1, he commented that the second answer was wrong.

Interviewer: …How about question number 7? How did you come up with your formula for that and do you still think it’s right?

HL: Two nitrogens plus four oxygens, so it’s N2, which means there’s two nitrogens and 4, O4 means four oxygens, so yeah.

Interviewer: So the second representation written there, is that incorrect?

HL: That’s incorrect, the first one’s right but the second one’s not right.

He gave correct responses to both these questions in the post-test, so they were not discussed further in interview 3.
4.5.2.2. Gas-Phase Reaction

When given the equation for the gas-phase reaction between ammonia and oxygen, with no states included, HL produced a representation of the reaction that showed the correct stoichiometric ratios of each of the reactants and products. Introduction of the same equation with states prompted HL to draw a mixture of the reactants rather than drawing them separately. He proposed the same change for the products.

4.5.2.3. Strong Acid Solution

HL understood the concentration label on the sulfuric acid container, as demonstrated by the following quote, but was unable to appropriately represent a strong acid at the molecular/ionic level. His representation featured molecules of \( \text{H}_2\text{SO}_4 \) (see Figure 4.10).

HL: It's .05 molar...sulfuric acid, so concentration is .05 moles per litre, so that you'd have .05 moles of sulfuric acid atoms per litre per liquid.

Interviewer: What liquid?

HL: Water.

Interviewer: Okay.

HL: It's a bit dilated.

Interviewer: Okay, so there's water in there?

HL: Yep.

Figure 4.10  HL’s representation of 0.050 M sulfuric acid
He further demonstrated his understanding of concentration by correctly identifying changes at the molecular level on halving the concentration.

Interviewer: Okay, what would happen if I halved the concentration? Made it .025 instead?

HL: You'd have…half the number of moles of sulfuric acid…so you'd…more water molecules…in here than the sulfuric acid.

Interviewer: Okay so your ratio of sulfuric acid to water is?

HL: Less.

4.5.2.4. Acid/Base Reaction

HL correctly predicted that you would not observe the reaction between sulfuric acid and sodium hydroxide. He was also able to correctly identify the products that form as a result of the reaction. His concept of what occurs at the molecular level was, however, not scientifically acceptable. His ideas were similar to the ones he used in his original explanation for the precipitation reaction above. He believed that molecules of sulfuric acid and sodium hydroxide would split into ions on mixing and swap partners to produce sodium sulphate and water. His representation of the products, therefore, showed Na₂SO₄ molecules dispersed among water molecules, correctly oriented towards the ions in the Na₂SO₄ molecule. His description of the reaction and products is given in the following quote.
HL: The hydrogen atoms from the sulfuric acid...they split up and they become ions and...so does the sodium hydroxide so it becomes...sodium ions and the hydroxide ions. So we would...get water and you'd have...sodium sulphate.

Interviewer: Okay, at what point...do they split in half?

HL: ...When you mix them.

Interviewer: And why does that happen?

HL: Oh, I don't know why that happens. It just does. It's a freak of nature.

Interviewer: Okay, there's an equation for the reaction you just described to me. Can you draw me...a representation of the products? ...

HL: ...sodium sulphate...the water molecule’s liquid and you'd have twice as many water molecules as you'd have sodium sulphate.

Interviewer: Okay and you've scribbled off these hydrogens here and put them on the other side. Why did you so that?

HL: Because...the sodium would be slightly positively charged and...the oxygen atom...slightly negative so it'd be attracted to the positive end of the sodium.

Interviewer: Okay, would there be any more water in there other than those two water molecules?

HL: Yeah...there'd be more.

4.5.2.5. Precipitation

On being shown a “molecular” equation for a precipitation reaction without states, HL produced the first representation shown in Figure 4.11. He represented reactants and products as molecules, in the correct stoichiometric ratios. He was then shown the same equation with states (see Equation 2, Figure 4.11). This prompted him to add water to his representation to account for the “aqueous” solutions in the equation. He also moved the lead chloride molecules to the bottom of the container to represent the solid. After realising that the bonding in lead(II) chloride would be ionic, he decided that the PbCl₂ molecules should have been drawn closer together. Once again he suggested that the reaction occurs via a splitting of molecules into ions, then a swapping of partners.

HL: ...Mix the lead nitrate in with the potassium chloride...the two molecules would split up into its ions and when it's in ions it'll...bond with other things.

Finally, HL was shown the full ionic equation of the precipitation reaction. This threw him into a state of confusion similar to that he experienced for the precipitation reaction, discussed above (page 314). He suggested that the ionic equation might represent the separate ions, once
the reactants are mixed, but also considered the possibility that the reactants were present as separate ions before mixing. He considered leaving the lead chloride in his representation as it was, but splitting the potassium nitrate. When asked which equation he thought best represented the process, he was unsure. He settled on the complete ionic equation and then gave one further description of the molecular level.

HL: … I'd just have the atoms floating around in the solution I guess.

Interviewer: Separated?

HL: Yeah, separated. K plus, Cl minus…So that for every lead atom that is in the reactants you'd get…two potassiums and two chlorine, two chlorines and two nitrates…as the products…you'd still get the…lead chloride solid but you'd have…the potassium and the nitrate…split up…

Interviewer: Yep and would you have water in there?

HL: Yep.

His final description was closer to being scientifically acceptable. He drew an example of one of the ions in solution (see Equation 3, Figure 4.11). He showed a couple of water molecules correctly oriented towards the ion.
4.5.2.6. Complexation

This student was able to provide a convincing statement about what the two equations associated with complexation were showing. He did not seem to view the reaction as being interactive but rather as a splitting of reactants followed by the formation of new substances.

HL: Copper and hydroxide, so you'd get copper hydroxide which is a solid, you're mixing two liquids to give a solid as product...the copper hydroxide formed mixes with the ammonia to give...the complex ion and the hydroxide ions...the copper hydroxide, they'll split to form ions and the ions will react with the ammonia, so the copper, so you form the copper thing, the complex ion with the ammonia...

Interviewer: Okay, so you no longer see any solid in the solution?

HL: No, it splits, the solid, the atoms that make up the solid split, so there'll be no more.
He produced a molecular-level representation of the product of the first reaction, solid copper(II) hydroxide. The solid was represented as molecules of Cu(OH)$_2$ amongst water molecules, consistent with many of his other representations but not scientifically acceptable. The student refused to attempt a depiction of the copper ammonia complex. He instead described it as follows.

HL: Copper bonded to the ammonia. I think it's like a one copper there, one copper atom bonded to four ammonia molecules.

He could not describe how these were geometrically arranged round the copper. He suggested that the hydroxide ions were “just floating around” separately in the solution.

He was then shown the modified version of the equations. HL confused hydration of the ions with hydration of a salt, represented by “.xH$_2$O” after the formula. He therefore did not interpret the inclusion of the six water molecules with the copper as hydration of the ion.

He felt that the second set of equations just showed that there were water molecules present, and he did not see the need to reconsider his image of the molecular level, except for the fact that there would be water “bonded directly to the copper and the ammonia.” It is difficult to know exactly what he meant by this because he would not draw the products.

HL selected the final set of equations as best representing the molecular level, simply because “there's water there”.

### 4.5.2.7. Equilibrium Reactions

**Equilibrium**

HL seemed able to conceptualise equilibrium as a process where reactants are forming into products at the same rate as products are forming back into reactants, as shown by the following quote. He expressed the misconception, however, that the reverse reaction only started once the product had formed as much as it could.
HL: A reaction that has gone as forward as it can...reactants to products. At the product stage, it starts reacting again and goes backwards, goes back to the products and at equilibrium the...amount of reactants going to products is the same as the amount of...products going to reactants.

Interviewer: ...Can you explain how those forward and reverse reactions can both occur?

HL: ...The forward one would occur first and when it gets to...products, the products, the products just go back to the reactants.

Interviewer: Okay, so do you see it sort of like as a pendulum swapping back and forth?

HL: Those going back at the same time, going backwards and forwards at the same time. There’s some going forward some going backwards.

Gas-Phase Equilibrium

In his initial representation of this equilibrium reaction, HL separated the reactants and products by an equilibrium sign (see Figure 4.12). After being questioned about this, he produced the second diagram shown in Figure 4.12 and suggested that all species would be present together in the reaction vessel. He believed these to exist in stoichiometric ratios and was unsure what the equilibrium constant meant.

Interviewer: Okay, now here you’ve represented two each of each of these. Can you explain to me why you’ve...done them in those ratios?

HL: Cause there’s only one, in the equation there’s only one mole of each, there’s ratios and it’s one mole so it’s in a ratio.

When asked to predict what would happen if extra NO\(_{(g)}\) was added to the equilibrium, HL offered an explanation in terms of Le Chatelier’s principle.

HL: If I added more NO, the system’s going to try and decrease the amount of NO there, so it’s going to go forward I’d imagine. Yeah, cause you’re adding more to it the system’s not, the system’s at equilibrium, it’s happy where it is so if you add more stuff to it it’s got to try and counteract that, so it’s going to [go] forward again I think.

He was also able to offer an explanation for why the shift occurs, at the molecular level.

HL: There’d be more NOs there to react with the ClNO\(_2\) so...the ClNO\(_2\) that hasn’t reacted with the NO yet can...it’s got more of a chance to react...

Interviewer: ...And so that would cause what?

HL: A shift to the, the equilibrium to the right, I think to the products.
Figure 4.12  HL’s representations of a gas-phase equilibrium

**Weak Acid Equilibrium**

HL produced a similar diagram for the dissociation of boric acid at equilibrium, showing stoichiometric ratios of each species. However, when asked about the $K_a$ value, he suggested that it was a weak acid and hence would only dissociate to a small degree. This prompted him to add extra boric acid molecules to his representation, conflicting with his idea of stoichiometric ratios. He also added water molecules after some questioning.

Interviewer: Okay, and that equilibrium constant doesn’t mean anything to you there? The $K_a$ value?

HL: Oh the $K$, the $K_a$ value, the $K_b$. It’s, I know this. It’s how strong the acid is I think…the larger the $K_a$ value, the stronger the acid, the more likely it’s going to break up into the $H^+$ and its conjugate base.

Interviewer: Okay, what would that $K_a$ value tell you?

HL: It’s pretty small so it’d be a pretty weak acid.

Interviewer: Right, so how would your representation change, or would it change at all in that case?

HL: Maybe there’d be more… There’d be more boric acid there, I think. Cause it wouldn’t break up…as much.

Interviewer: Mm hmm. Okay, so what’s happened there now? You no longer have stoichiometric ratios.

HL: I don’t know

Interviewer: Does it matter?

HL: It should but I don’t know. I don’t know what’s going on. You’ve lost me.
He was then shown a modified equation of the same reaction showing hydronium ions rather than hydrogen ions. He produced another diagram, showing each species in the equation in stoichiometric ratios. He seemed to understand that the first equation was just an abbreviated version of the same reaction. He thought that his second representation was more correct, in terms of what you would see at a molecular level, but thought that there might be a few hydrogen ions floating round in the solution.

Interviewer: Which representation is right?

HL: This one would be more right.

Interviewer: So you don’t have hydrogen ions just floating round in solution?

HL: I guess you would. Not many of them though, I don’t think. There would be a couple, not many so you can leave them out.

Interviewer: …Can you describe how the reaction from reactants to products occurs there then?

HL: …boric acid’s reacting with the hydrogen in the water...and the boric acid loses its hydrogen to the water.

Interviewer: Okay, so you think the water directly, is directly involved in the reaction?

HL: Yeah, I’d say so.

4.5.3. Interpretation of Macroscopic Phenomena

This section looks at HL’s ability to explain macroscopic phenomena. These data were collected from interviews 3 (Sections 4.4.3.1–4.4.3.2) and 4 (Section 4.4.3.3). Information regarding the content of the interview questions is given in Table 4.4 (page 263).

4.5.3.1. Nail-Polish Remover

HL had little confidence in his ability to explain what happens at the molecular level when we open a bottle of nail-polish remover. With questioning, he proposed some ideas. He suggested that the nail-polish remover might be boiling and hence converting from liquid to gas; in which case the molecules of ethyl acetate in the bottle would be identically structured to the molecules that are given off in the gas that reaches the nose.
Interviewer: What do you think it is that's coming out of that jar and getting to your nose?

HL: I really don't know… the molecules, breaking up in the, I don't know, they're coming out of the liquid…

Interviewer: …Can you construct some sort of mental image of how…that might occur?

HL: …Might be because it has a low melting point or something, boiling point or something… it's just turning into gas when it breaks away.

Interviewer: Okay.

HL: Can you describe that at a particle or a molecular level?

Interviewer: …You'd see that [referring to structure of ethyl acetate molecule] in the solution and there's, it's boiling… some of those molecules are breaking away from your… liquid up into the air…

HL: …So the molecules in the liquid are the same as the ones that are coming up into the gas?

Interviewer: Yeah, I suppose so.

4.5.3.2. Precipitation Reaction

HL predicted that each of the solids (lead(II) nitrate and potassium iodide), when added to water, would dissolve, breaking up into their individual ions. He did not realise that a reaction would occur in the resulting solution. After observing the formation of a precipitate, he was able to give an explanation for what had occurred, correctly describing the products.

Interviewer: What do you see happening?

HL: Ah, a precipitate forming.

Interviewer: Okay, so how would you explain that?

HL: When the lead nitrate and potassium iodide were added to the water… the solid broke up… the ions came together… the lead and the iodide formed the yellow stuff.

Interviewer: …And how would you describe the structure of that yellow stuff at a particle level?

HL: It'd be just… ionic solid as salt, I guess.

Interviewer: Okay, yep and is there anything in the clear area?

HL: Yeah… the potassium and the nitrate ions.

Interviewer: …And would they separate or together?

HL: … Separate I guess.

He could not describe the role of water in dissolving the solids.
4.5.3.3. **Redox Reaction**

HL produced a representation of copper showing “a lattice of copper atoms joined together” (see Figure 4.13). His representation of aqueous silver nitrate featured molecules of silver nitrate among water molecules (see Figure 4.13). He was unable to predict the reaction between these substances.

After seeing the reaction, he concluded that the copper had corroded and he interpreted the blue solution as meaning there was copper present in the solution. He was unsure whether the grey coating was nitrate or silver. He was therefore given the products of the reaction in the form of an equation. As a result, he provided the following explanation of what had occurred.

HL: Oh okay, so it swaps, oh so it swaps…the silver and the copper swap around.

Interviewer: So how do you think that might happen at a molecular level?

HL: …That reacts with that. [The nitrate ion would] leave behind its silver and gain the copper.
His representation of the products was similar to the one he produced for the reactants, but with a lattice of silver atoms coated on the copper and a solution containing copper nitrate molecules and water molecules (see Figure 4.13).

### 4.5.4. Interpretation of Molecular Representations

This section looks at HL’s ability to interpret and critically analyse molecular representations. These data were collected from interviews 1 (Section 4.4.4.1), 3 (Section 4.4.4.1–4.4.4.2) and 4 (Sections 4.4.4.3–4.4.4.4). The structure of this section and the content of the interview questions are elaborated in Table 4.5 (page 263).

#### 4.5.4.1. Modelling

##### 4.5.4.1.1. Interpretation

**Models of Water**

HL favoured the symbolic representation of a water molecule in the pre-test due to its familiarity and the extent of its use in high-school or university chemistry. He claimed in interview 1, however, that the space-filling representation would more closely resemble the actual structure, because the bonds weren’t represented as lines.

HL: In number 1, you’ve got the lines there that represent the bonds. In number 2, you don’t have that.

When shown multiple representations of water molecules, he claimed that he couldn’t select a model that best represented the actual structure because all the models were correct. He did not have a preference for any one model. He mentioned little about correspondences and non-correspondences between the model and target. He simply mentioned that model E showed electrons whereas model B just showed “how they’re bonded”.

When shown the animated 3D model of a water molecule, HL demonstrated awareness of some of the non-correspondences between the model and target.
Interviewer: Okay, now would a molecule look exactly like that?

HL: No it wouldn’t be red and white…

Interviewer: …Why would they put it red and white on an animation like this?

HL: So you know that the white one’s hydrogen and the red one’s the oxygen.

Interviewer: Okay, so you can distinguish between the two types of atoms…What about that sort of hard sphere? …Is that what atoms and molecules are actually like?

HL: …I wouldn’t think so.

HL was also aware that protons, neutrons and electrons are constituents of the atoms making up the water molecule, even though they were not visible in this model.

**Models of Solid Sodium Chloride**

In interview 3, HL was shown some models of solid sodium chloride. Once again, he did not have a preference for any particular model because he felt that they all showed solid sodium chloride. He went on to volunteer information about the different features of each model.

Interviewer: Do you think that any one of these representations is better than the others?

HL: I can't say any of them are better…They all show sodium chloride…as a solid. "A" shows it as a solid, just the way the molecules together in a single…face of the lattice…and "B" shows the sodium chloride ions together but there's a little bit of movement. It's shaking…"C" still shows the same ions bonded together…"D" still shows sodium chloride solid…they all show the same thing.

Interviewer: Yeah, you just see them all as sodium chloride?

HL: Yeah

Interviewer: You don't have a preference for any one of them?

HL: Not really

Further probing prompted him to identify a non-correspondence relating to the portrayal of bonds as sticks.

Interviewer: Do you think there's anything wrong with imagining bonds as sticks between ions?

HL: …I don't think they'd be sticks.

Interviewer: You don't think they'd be sticks.

HL: No. It’d just be an attraction between the…ions.
4.5.4.1.2. Multiple Modelling

In interview 1, HL felt that different models were used to demonstrate different features.

Interviewer: Okay, so what might be a reason for there being so many different models?
HL: To show different things I guess, yeah. See, you’ve got the electrons there…

In interview 3, he concentrated on the use of different representations for explanatory purposes.

Interviewer: Why do you think then that we have so many different representations?
HL: It makes it easier to explain…what's going on at the, say, particle, molecular level or
Interviewer: How would having different representations help that?
HL: If you were trying to explain why the…sodium chloride is bonded or something you know you'd have "E", "C" show that.
Interviewer: "E" and "C" show how it's bonded?
HL: Yeah, I guess so… "A" does too. Makes it easier to explain things I guess.
Interviewer: Okay, do you think there are any aspects of sodium chloride…at a molecular level, that might be better explained by certain representations?
HL: Yeah.
Interviewer: And what sort of features would they be?
HL: With "B", you can see the molecules just vibrating…ions vibrating…"C" see how the ions are bonded together.

4.5.4.1.3. Development

HL mentioned the use of an electron microscope as a way to view atoms and molecules. However, as discussed above, he did not believe that the VisChem animation of a water molecule was completely realistic. He was able to point out some non-correspondences. His comment “like that” below seems to suggest that he believes that the VisChem animation models reality.
Interviewer: What is it?

HL: A water molecule.

Interviewer: Okay, do you think that anyone has actually ever seen atoms or molecules?

HL: Yeah

Interviewer: …How would they see them?

HL: Like that.

Interviewer: …What sort of instruments would they use to see something like that?

HL: An electron microscope, I guess.

He believed that models of water molecules were designed by scientists to explain ideas to other people.

Interviewer: Why do you think scientists…make up these sort of models…and animations of water molecules…?

HL: It’s just easier to explain to people.

In interview 3, HL was shown an animation of aqueous potassium fluoride and asked questions relating to scientific modelling. He seemed to feel that the animation was quite realistic, in that it would closely resemble what you might see if you were able to zoom down to the molecular level and observe your surroundings. He seemed to make this judgement by comparing the animation to his own mental model of an aqueous ionic solution, because he believed that the animation showed too few ions in solution.

Interviewer: How close do you think this animation would be to what the molecular world of potassium fluoride in water might actually look like?

HL: Might be more potassium and fluorine molecules, ions in the solution, I guess.

Interviewer: Alright, so there’s more water molecules there than you sort of imagine there to be?

HL: Yeah, there’s only one of each ion that I can see. Yeah.

Interviewer: Is there anything else that you think…it if you were actually able to zoom down and see what was going on, any other differences there might be?

HL: No. I’m pretty happy with that.

Interviewer: Okay. So if you put more…potassium fluorides in there…that’s what you’d see if you zoomed down?

HL: Yeah. I’d say so.
HL’s discussions of the reasons for modelling and the development of models once again seemed to focus mainly on the use of models in explanations. He initially suggested that models might be developed through simple speculation about what’s going on when you observe an experiment or phenomenon. Therefore, they were designed to explain macroscopic phenomena.

Interviewer: Okay, how do you think representations of solutions or aqueous ionic solutions were first developed? Not just this type but any sort of representations of aqueous ionic solutions.

HL: …If you add…salt, like sodium chloride or potassium fluoride into the water, the salt breaks up, so when it breaks up you’d think that…the ions are breaking up from each other in the water.

Interviewer: Okay. How do we know that there are ions?

HL: …I don’t know.

Interviewer: You don’t know where these ideas might have come from?

HL: I have no idea.

Interviewer: Why do you think representations of the molecular world of aqueous solutions were developed?

HL: To explain, to explain why when you add the salt to the water it…seems to break up, it breaks up.

Interviewer: So to explain observations?

HL: Yeah

Whereas models were developed to help explain phenomena, he felt that animations were designed to help explain the ideas to students.

Interviewer: Okay. What do you think is the purpose of producing animations like this to represent these ideas?

HL: To explain what’s going on. To explain your observations and…to explain what’s going on.

Interviewer: …And why would we represent it in an animation?

HL: …We can actually see what’s going on and stuff… I guess it makes it easier to explain cause you can see what’s happening in the…solution.

Interviewer: …And who would you be explaining it to?

HL: …Anyone that wants to know.

He seemed to feel that the only reason his lecturer was teaching this was because it is part of chemistry.
Interviewer: Why do you think your lecturer wants you to learn this?

HL: Cause I’m doing chemistry and this is chemistry. I don’t know.

He felt that the image of an aqueous ionic solution might be useful if he wanted to explain it to someone else.

Interviewer: Well, do you think that these images are of any use to you?

HL: Yeah, maybe if I want to explain to someone that asked me for my help or something I could explain it to them or show it to them.

HL was happy with his mental image of an aqueous solution and the animation of it. He felt that it was applicable to other aqueous solutions and it would be difficult to convince him otherwise. He felt that other scientists would agree that it was a good representation.

He wasn’t sure whether scientists had developed the idea further or constructed new models of aqueous solutions. When probed, he suggested that new models might be developed as a result of scientists finding out something new through experimentation or simply revising their conception of what occurs. He believed that different models “might make it easier to explain things or might be just how one, like one scientist, sees it different, a different scientist might see it differently.”

4.5.4.2. Criticism of Molecular Diagrams and Animations

Diagram 1: Dry Ice

HL felt that this diagram was suitable for “explaining the carbon dioxide molecule and what dry ice looks like at a…molecular level.” He realised, however, that the magnifying glass may be somewhat misleading to a novice student.

Interviewer: Do you think that a novice student might develop any misleading or incorrect ideas from that diagram?

HL: I don't think so… Oh, except that you can't see the molecules with a magnifying glass… They're smaller than that.
Diagram 2: Saturated Solution

HL had a sufficient grasp of what this diagram represented. Therefore, he thought that the representation of the process was adequate.

HL: …Sodium and the chloride ions move around…some of them come together to form the solid, the sodium chloride, and they all go to the bottom and as that's happening more of it is coming, more sodium and more chloride ions are coming together and as that's happening the…going down the bottom as solid.

Interviewer: Yeah, so you've got sodium chloride forming and sodium chloride dissolving.

HL: Yeah, sort of at the same time.

Interviewer: Yep and do you think that diagram represents that process well?

HL: Um, yeah.

He made one criticism, relating to the exaggerated size of the ions in the beaker.

Interviewer: Do you think…that students might develop any misleading or incorrect ideas from that diagram?

HL: Ah…not really cause I know what it is… Maybe the size of the…ions… The beaker…would have more sodium and chloride ions in there… Just the size of the ions, I guess.

To address this, he suggested writing “something down to the side of it saying ‘not actual sizes’”.

Diagram 3: Electron Transfer

For this diagram, HL offered the criticism that electrons are, in actual fact, not situated around each atom in pairs, but rather moving randomly about, so that you cannot determine where they are at any given moment. He suggested that a caption for the diagram could state this idea.

Interviewer: Do you think that there might be any misleading or incorrect ideas in there for novice students?

HL: Just that…that's not the way the electrons are situated. I don't think, I don't think they pair up.

Interviewer: Okay. What's your conception of how the electrons are?

HL: 'They're randomly, in random movement, always moving around. You can't really, they don't really stop.
He was under the misapprehension, however, that this electron transfer was necessary for the formation of an ionic solid.

Interviewer: Does this type of electron transfer between sodium and chlorine atoms ever occur, do you think?
HL: Yeah, I guess.
Interviewer: When would that occur?
HL: When sodium and the chloride ions come together to form…the sodium chloride solid.
Interviewer: You think there's a transfer of electrons when the solid's forming?
HL: Yeah.
Interviewer: When does that, when would that occur?
HL: As it forms…when the sodium and the chloride ions come together.

Diagram 4: Precipitation

HL initially did not see the need to change this representation. When told that he had drawn water molecules in an earlier representation of the same reaction, he conceded “It's an aqueous solution, so there'd have to be water molecules in there”.

Animation: Dissolving

HL was successful at interpreting this animation but did not feel that any changes needed to be made or that any features might mislead novice students.

4.5.4.3. Analogical Modelling of Equilibrium

Analogy 1: Soccer Game

HL was able to link this analogy with his concept of equilibrium.

HL: The players on the field would be the reactants and the players off the field, on the bench, would be the products, I guess and they’re just interchanging between them.

However, he initially misinterpreted the statement “there is no change in the number of players on the field” and once again revealed his misconception about the relative amounts of reactants and products present at equilibrium. He then corrected this, suggesting that the statement indicated that the amounts of reactants and products remain constant.
Interviewer: “There is no change in the number of players on the field”. What does that correspond to?

HL: …At equilibrium… the number of reactants equals the number of products I guess… Yeah the number of reactants doesn’t change. The amount of reactants and products don’t change.

Initially, he proposed that the “identities are different” referred to the different species that were present in the reaction vessel.

HL: …means you’ve got sort of players having different identities. You’ve got different types of molecules and atoms and stuff in the… vessel.

After prompting, he seemed to understand the intended correspondence with an equilibrium system.

Interviewer: …But what about when you substitute an old player for one off the bench… there’s different people there then.

HL: Then you’d be doing the same with the… molecules. One’d go… from the reactants to the products side and vice versa so

HL rejected the final statement, “there is no requirement that the number of players on the field and the bench be equal”, because it did not correspond to his conception that the amount of reactants and products at equilibrium are equal.

Interviewer: “There is no requirement that the number of players on the field and the bench be equal”.

HL: …In an equilibrium they are equal.

Interviewer: So you’re not sure about that then.

HL: I think it is equal in equilibrium but I’m not sure about that.

Interviewer: … Where do you think that analogy breaks down then?

HL: There is no change in the number of players on the field… maybe the number of players on the field and the bench are equal or not equal. Usually they are not equal. I think at equilibrium they are equal.

Analogy 2: Juggling

HL’s discussion of this analogy revealed similar understanding and misconceptions. He was able to make sense of the analogy but interpreted the statement “the number of balls in the air
or in the hands always remains the same” to mean that the amounts of reactants and products remained equal.

HL: Balls go up or the reaction goes forward and at the same time the balls return… Yeah at the same time the balls are returning back… goes from reactants to products and products back to reactants…

Interviewer: What does that mean? [referring to the last sentence]

HL: So the number of, the amount of products is the same as the number of reactants, the number of balls in the air is the number of products, equals the number of balls that are in the hands, in other words reactants.

**Analogy 3: Dancing**

HL liked this analogy but incorrectly suggested that males and females, as the reactants, were sitting down whereas the pairs, or products, were dancing. Although he appropriately identified the singles as the reactants and the couples as products, the analogy suggests that all people are dancing. This misinterpretation may have been the result of wanting to separate the reactants and products.

HL: Sounds okay… So the males and females are sitting down by themselves…the reactants… and the ones pairing up dancing are…the products… As the products split up…yeah…it’s a good analogy.

He was able to relate the analogy to the forward and reverse reactions in equilibrium systems.

HL: When the couple splits…the products, the molecules are breaking up and they begin dancing separately…they go back to being reactants…and another couple begins dancing together, the reactants go back to, are going to products so

He made some sense of the final sentence in the analogy, “a male must find a female partner…” suggesting that “atoms must…react together before they can go into products…before they can become products”.

This student also felt that this analogy was better than the others.

**4.5.4.4. Interpretation of Molecular-Level Animations**

**Ice Melting**

HL was able to give a description of what was happening in the animation of ice melting and noticed some of the details in the animation.
HL: You’ve got solid water, ice, the water molecules are held together and it’s being heated…starting to heat up, the molecules start to wriggle around a bit. It gets heated up more, the molecules vibrate more violently, when it’s reached melting point the molecules start to break up…

Interviewer: …Okay, are there any finer details you’d like to point out? …

HL: I guess the way that the…water’s structured.

Interviewer: How is it structured?

HL: In rows…and how they shake when it gets heated up.

Interviewer: Do they shake before it gets heated up?

HL: Oh they shake a little bit, not as violent though… When it’s really heated up they shake that violently that it breaks. The whole thing breaks up.

In light of some of his earlier images of water, it is interesting to note that he mentioned that the water molecules stay intact on melting.

Interviewer: Is there anything else you notice about this once it’s melted?

HL: The water molecules staying together sort of in the, like individual molecules…

Having seen the animation, HL eventually came up with an explanation, albeit vague, for why water expands when frozen.

HL: It’s neatly packed in rows…there’s a lot of space in between the…rows.

Interviewer: Okay, so we’re looking through this tunnel of space here?

HL: Yeah…

Interviewer: So how does that explain it?

HL: When you freeze it…lots of space…I’m trying to put it together…

Interviewer: …We’ll start with it the same way round as this animation’s showing, so you’ve got it frozen and it’s already a greater volume, it’s expanded and then once it melts again the volume shrinks…

HL: Yeah, there’s not as much space between the molecules in the liquid form as in the solid so, yeah so the more space… If you freeze it then it’s going to expand…because you’ve got space between the…rows.

**Water Evaporating**

HL provided an interpretation of the animation of water evaporating, but he believed that the water must boil for the water molecules to have enough energy to escape from the surface.
This is consistent with his interpretation of why nail-polish remover smells. He was able to interpret the fact that water molecules returned to the surface, in terms of energy and intermolecular forces.

HL: Okay, it’s showing water as a liquid. Molecules as moving around, bouncing around and it’s been heated and it’s just started to reach boiling point and some of the molecules are leaving the open liquid to the gas state.

Interviewer: Okay. Does it need to be boiling for that to happen?

HL: Yeah…the molecules need the, enough energy for it to, to leave the liquid state.

Interviewer: Okay. Can you describe any more finer details that you see?

HL: Some of the water molecules are coming back down. Maybe it’s because they don’t have enough energy to go from the liquid state into gas.

Interviewer: Yep…and just describe to me what’s happening to this particle here.

HL: It’s just bouncing around… It tried to leave but didn’t have enough energy to, so it came back down.

Interviewer: Mm hmm. What pulls it back down again…or does it just sort of drop back down?

HL: Maybe it’s the intermolecular forces… I don’t know, maybe they just fall back down… It’s intermolecular forces.

Interviewer: Which do you think it is? Just intermolecular forces?

HL: Yeah…Hydrogen bonding or something, the hydrogen’s still attracted to…the oxygen…pulls it down.

**Sodium Chloride Dissolving**

HL successfully identified the animation of sodium chloride dissolving in water. He noted the orientation of the water molecules towards the ions being pulled from the lattice.

HL: …That’s sodium chloride salt…solid salt, solid sodium chloride in the lattice, ionic lattice then when you add water, the water molecules pull…the ions away, off the lattice. Carry them away.

Interviewer: Okay. Now give the fine details.

HL: …When it’s in the lattice, the ion, the ions are shaking a little and water...the hydrogen is attracted to…the chlorine ion…and now the oxygen is attracted to the sodium ion so…hydrogen doesn’t touch it.
Aqueous Solution of Sodium Chloride

Once again, this student was able to identify the animation, this time of an aqueous solution of sodium chloride. He pointed out electrostatic attractions between the ions, between water molecules and between water molecules and ions.

HL: This is when the sodium chloride is dissolved into its ions. It breaks up and the water, water particles, the ions are still attracted to each other but the positive sodium and negative chlorine just want to get back together there.

Interviewer: Yep, but what happened? Did they get back together?

HL: But when they got back together in a second or so…it’s pulled apart again…When they bounce around the…hydrogen’s attracted to the other oxygen atom in the water molecule so, and the oxygen doesn’t touch the other oxygen…only the hydrogen does and vice versa.

Interviewer: …Anything else? How about in that shot?

HL: It’s the ion, chlorine ion. Hydrogen’s attracted to the chlorine ion and so it’s closest to it and the oxygen atom in the water molecules are not attracted to it…further away from it.

Precipitation of Silver Chloride

This student struggled to identify the animation of silver chloride precipitating, partly because visually he could not tell the difference between the silver ion in this animation and the sodium ion from the last animation. He thought the sodium chloride lattice was being reassembled.

HL: …I don’t know why it’s putting…the sodium chloride lattice back together…

Despite being shown and told that they were two different ions, he still could not identify the animation because he could not conceive of a solid forming out of solution.
HL: …I still don’t know why it’s rebuilding…it usually pulls them apart.

Interviewer: Do solids only dissolve? Can’t you form them?

HL: I thought they would dissolve. If you put, if you put a salt in water, it usually just breaks up…

Interviewer: You can’t think of any instances where solids are formed…in a solution?

HL: Nup…I always thought they always break up.

Interviewer: So do you think that all ionic solids are soluble?

HL: Soluble or insoluble, yeah

Interviewer: So…any ionic solid, you put it in water, it’ll break up?

HL: I’d say so. That’s what I thought. I’ve never really thought about it to be honest.

It wasn’t until he noticed the spectator nitrate ion that he developed some idea of what the animation was showing, and identified it as a precipitation reaction.

HL: …It’s a blue thing.

Interviewer: It’s a blue thing with three little red things off it…Can you figure out what that might be?

HL: Is it nitrogen…NO₃?  

Interviewer: Mm hmm.

HL: …I know what it is. It’s a…Precipitate, that’s it. It’s a precipitate! …You’ve got one solution…you pour the solution in there. It’s not soluble with water and so it forms a precipitate which is probably the lattice…NO₃⁻ ions are just floating around…

Interviewer: So what might you pour in to start with, you were saying?

HL: …the salt and…the water ones.

Interviewer: Say this is silver chloride.

HL: Okay, silver chloride…nitrate, I don’t know…maybe you had, say…some nitrate solution with the silver chloride.

Interviewer: So do you think you would actually pour a solution of silver chloride in there?

HL: No…no… Silver nitrate and…some chloride solution…maybe you have sodium chloride.

Interviewer: Yep, that’ll work.

HL: …aqueous sodium chloride and silver nitrate, mix ‘em…together you get a precipitate…silver chloride.

Interviewer: Okay and what’s the nitrate ion doing then?

HL: It’s lost the other ion so it’s just floating around. It’s a spectator ion.
Redox Reaction of Copper with Silver Nitrate

HL was unable to make sense of this animation, although he did identify the solution as silver nitrate. He also noticed that one lattice was being constructed while the other was being pulled apart.

HL: I don’t know…maybe you have silver nitrate…that might be silver. I’ve seen a nitrate ion…

Interviewer: What do you reckon was happening there?

HL: I really don’t know… It was sort of building another lattice on top and it’s pulling apart some of the yellow ones.

After struggling, the interviewer revealed that this was an animation of the redox experiment that had been performed earlier in the interview. He was then able to identify the solid and solution.

HL: Oh okay, so that’s a copper and silver nitrate. So I was right, that’s silver nitrate…

Interviewer: …So what do you think is happening now?

HL: It’s put the silver atom, the silver ion, it’s building it up into a lattice, the silver lattice and it’s pulling apart the copper, the copper one.

He found the electron transfer difficult to fathom, however, mistaking the gain of electrons for the loss of electrons. This seemed to result mainly from incorrect reasoning regarding whether a silver (II) ion will gain or lose electrons.

HL: Oh, it’s losing…the electrons…

Interviewer: What are losing the electrons?

HL: The silver. I’d say the silver’s losing the electrons, I think…the electrons might be going through the copper atoms.

Interviewer: So what did we start with in the solution…?

HL: The copper solid and the silver nitrate…

Interviewer: Okay, and does the silver in the solution, does that want to gain or lose electrons?

HL: …I’d say…silver Ag^{2+}…lose…2+… Yeah it wants to lose… It wants to lose 2 electrons…

Interviewer: …So it’s lost two electrons from there to there?

HL: I’d say so, yeah…yeah it has…NO_3^- , Ag^{2+}…the silver ion’s Ag^{2+}, so it’s got two excess electrons…
4.6. Case Study 3 (LH)

LH represents a student with low prior knowledge (pre-test score: 5) and high disembedding ability (GEFT score: 15).

4.6.1. Imagery Development

This section documents the development of LH’s images of substances assessed by the questionnaire, through the year. These data were collected from the pre-test, interviews 1–3 and the post-test.

4.6.1.1. Molecular Substances

General Features

In the pre-test, this student incorrectly suggested that molecular size decreases from solid to liquid to gas, stating as her reason that “solids are made up of more molecules”. By the first interview, she had formed the correct idea. She identified the VisChem animations as helping her develop this idea.

LH: The visual representations of solid, gases and liquids, they more or less showed them the same.

She maintained this idea and correctly stated in the post-test that “molecules are the same size, size doesn’t change as the substance changes”.

Liquid Water

LH did not attempt to represent liquid water in the pre-test. She reported zero confidence and no visual image. Earlier answers in the questionnaire, however, suggested that she perceived liquids to contain fairly closely situated, moving particles. By interview 1, she had applied the above ideas to liquid water. She felt that animations and drawing in laboratory classes helped her to develop this image.

LH’s image was not further probed in interviews. In the post-test, she seemed to have maintained the above image. She described liquid water as “water molecules reasonably close together but still able to move freely about.” In her representation, she did not show the structure of the water molecule but represented them as circles containing the formula “H₂O”.
Gaseous Water

As with liquid water, this student had no image of gaseous water on starting university chemistry. She did, however, understand gases to consist of widely spaced, moving particles; as demonstrated by her answer to the question directly probing the spacing in a gas.

By interview 1, she still claimed to have no visual image of gaseous water and was not confident enough to construct one from her ideas regarding gases, as the following quote demonstrates.

LH: I don’t know how to draw that one.

Interviewer: What do you know about gases?

LH: They freely move… They take up lots of…space.

Interviewer: …But you don’t have a mental image of…water in the gaseous state? Can you form one maybe with those ideas?

LH: Yeah, but I’m not too sure on it so.

She had also changed her mind about how far apart the molecules are in a gas, preferring an image in the questionnaire that had the molecules closer together than she had originally thought. This underestimation of the amount of space in a gas was carried through to the post-test.

By interview 2, she had developed the confidence to apply the above ideas about gases to gaseous water.

Interviewer: If you had to bring up a picture of what gaseous water looks like at a particle level, what would you see?

LH: Molecules of water?

Interviewer: Molecules of water. Yeah.

LH: I don’t know.

Interviewer: Would they be doing anything?

LH: Oh, they’ll be probably moving around lots cause it’s gaseous. In gas, there’s lots of room to move around.

She represented gaseous water similarly in the post-test, adding no key features to her image. Once again, water molecules were represented as circles containing the formula for water.
Solid Water

This student had no image of solid water (ice) at the start of the study. In interview 1, she described ice as containing closely packed molecules and attributed the development of this idea to drawing in laboratory classes and the VisChem videos.

Interviewer: Do you have any sort of an idea what ice or solid water would look like?
LH: Just molecules compacted together really tightly.
Interviewer: …Anything else going on in there?
LH: …I don’t think so.
Interviewer: Okay, how did you form your image of a solid being something…where the molecules are all tightly packed in?
LH: Just through drawing stuff through the prac…and the videos that have been shown.

In interview 2, she described her understanding of the vibrations in solid water and identified the VisChem animations as helping her develop this image. She still perceived the molecules as tightly packed.

Interviewer: If you zoomed down to the particle level of solid water or ice, what would that look like?
LH: It’ll be tightly compact…molecules of water because ice, … it’s frozen so there’s not a lot of room to move.
Interviewer: Okay, when you say there’s not a lot of room to move, is there any movement at all?
LH: Yeah, there’s little vibrations between each molecule.
Interviewer: … Where do you think you got that image of the vibrations of the molecules…in ice?
LH: Just from the visual representation that was shown in the lecture.
Interviewer: Okay, can you describe that visual representation to me?
LH: It’s just, you know, it was just showing the different stages of water.

This image was not developed further by the post-test. LH simply stated in the post-test that “water molecules are tightly packed into each other and vibrating”. She used the same model to represent water molecules as she used for liquid and gaseous water.

When asked in interview 3 if she wished to make any changes or additions to her representation of ice, she drew a new representation that showed the structure of each water
molecule using a ball-and-stick model, showing the relative sizes of the oxygen and hydrogen atoms. She could not offer an explanation for why water expands on freezing.

4.6.1.2. Ionic Substances

Solid Sodium Chloride

In the pre-test, LH incorrectly chose a representation of solid sodium chloride that showed NaCl molecules as the “best” representation. She was aware of the one-to-one ratio of sodium to chloride ions.

In interview 1, this student chose the correct representation of solid sodium chloride, reasoning that the particles had to be closer together than they were shown in her original choice.

Interviewer: Okay and why have you changed your mind about that?

LH: Oh just because of how close they are together, like the formulas.

She still, however, thought of each NaCl as a pair. When asked for a definition of ionic bonding, she replied that it was “Where one ion loses and one ion gains electrons”. Once again, she attributed the development of her image to drawing in laboratory classes.

During this interview, she also revealed her understanding of movement in solid sodium chloride, and credited the development of this idea to the VisChem animations.

LH: There’ll be a little bit of vibration, I suppose, but it’ll increase more as you heat it.

Interviewer: …and do you bring up a mental image of that when you’re thinking about it?

LH: Mm [nods]

Interviewer: Where did you get that mental image from?

LH: From the visual representations, through the videos we’ve been shown.

In interview 2, LH was asked to produce a diagram of solid sodium chloride. She drew a ball-and-stick representation, but acknowledged that she was also able to picture a space-filling model in her head. She initially failed to include charges on the sodium and chloride, and was therefore asked what held the lattice together. This led her to define an ionic bond as being
“between a positive and a negative charge.” She then added charges to the sodium and chloride ions to produce the drawing shown in Fig 1.14. She suggested that all bonds in the lattice were ionic bonds, with no difference between the different bonds. These comments suggest that she understood an ionic solid to consist of discrete positive and negative particles, and not NaCl molecules.

When asked about the spacing between the ions, she seemed less certain about the ions being closely packed than she did in the previous interview.

Interviewer: How far apart would these ions be if you were able to zoom down and have a look at it?

LH: Not very far apart, I don’t think. I’m not too sure.

LH maintained her idea of vibrations in solids, but picked up a misconception regarding other processes occurring at the molecular level.

Interviewer: Now, say you, you are watching a movie of this or something, some sort of visual representation like the ones of water and you zoomed down and had a look at it. Would you see anything happen?

LH: … They’ll be all vibrating against each other… Some might be breaking off and others forming and… I think, I’m not sure.

It was not clear from the interview how or why she developed the latter idea.

In the post-test, she selected the correct representation of solid sodium chloride, pointing out that it showed the ions to be closely packed and in a one-to-one ratio, an image she had
developed by the first interview. She also showed awareness of the structured nature of solid sodium chloride, a feature that was also present in her earlier ball-and-stick representation.

In interview 3, she criticised the diagram showing NaCl molecules only by pointing out that they were too far apart. This perhaps suggests that she believed there to be molecules in the correct representation. She was therefore, once again, probed about her understanding of ionic bonding. She seemed to conceive of NaCl as ion pairs but believed the bonding to be the same throughout the lattice. She described ionic bonding as being the balancing out of charges between a cation and anion, but could not explain why one ion-pair would be attracted to the next.

Interviewer: Can you describe the bonding between that sodium ion and the four surrounding chloride ions?

LH: Do you mean by like ionic bonding or?

Interviewer: Yeah. Describe your understanding of that.

LH: …It's just where the ions balance each other out pretty much, I think.

Interviewer: Okay, so you've got one sodium ion with a one plus charge and four chloride ions with a one minus charge. So how does that balance out?

LH: I don't know. I don't see it that way.

Interviewer: How do you see it?

LH: I just see them as like little pairs…But they're all like together…

Interviewer: Okay, so would you conceive of there being a different sort of bond between say those two and those two?

LH: No, I don't think so…

Interviewer: …So you're happy that every single bond in there is exactly the same?

LH: Mm

Interviewer: Okay, but you conceive of it as there being pairs in there so those cancel each other out?

LH: Yeah

Interviewer: Okay, so say that's a pair, that's a sodium, that's a chloride…they cancel each others charges out, those two cancel each others charges out, how is that one attracted to that one?

LH: I don't know…I have no idea.

In interview 3, she confirmed her knowledge of vibrations in solid sodium chloride.
Interviewer: How is your visual image different from what's pictured on the page there?

LH: They're just vibrating against each other.

**Aqueous Solution of Sodium Chloride**

In the pre-test, LH’s conception of aqueous sodium chloride was of “free” ions amongst water molecules.

By interview 1, she had developed a more sophisticated image of aqueous sodium chloride that featured separate hydrated ions among an abundance of water molecules.

LH: … It’s got more water molecules in it…to show that it’s in water, I suppose…so it’s hydrated and stuff…it shows the ions as ions…

Interviewer: …What else is wrong with this diagram here, the second one?

LH: I don’t know. They’re…the Cl and the Na atoms are attached, combined…it has a molecule, not as like free.

She was aware that the water molecules would orientate themselves towards the ions, due to attraction of opposite charges.

Interviewer: Do you know why they attract?

LH: …The negative ions attract to … the positive from the water molecules.

This student felt that drawing in laboratories was also responsible for her development of this image.

In interview 2, LH was asked to produce a diagram of aqueous sodium chloride. Initially, she produced a diagram that showed hydrated ions, but not the orientation of the water molecules and described it as follows.

LH: It’ll dissolve and the sodium chloride will become ions. They’ll be separated from each other and hydrated from the water.

It was not until after she drew a representation of an acidic solution that she returned to her depiction of aqueous sodium chloride and corrected the orientations of the water molecules. Her final diagram is given in Figure 4.14.
She was aware of the movement of the particles, but described it as vibration, similar to that which occurs in the solid. Her understanding of the nature of this movement was further probed in the following interview.

In the post-test, LH expressed comprehensive knowledge of the key features of ionic solutions, pointing out all key features other than movement.

By interview 3, she seemed to have reverted back to her original image of an aqueous ionic solution. When asked to produce a diagram of aqueous sodium chloride, she drew separate sodium and chlorides without charges on the sodiums, very little water and no interaction with water molecules. In earlier interviews, it was also evident that electrostatic attraction between water molecules and ions was a feature she did not seem to have fully integrated into her mental image. When shown her response to the post-test, she noticed that she had forgotten about this interaction.

Interviewer: Do you want to have a look over that and see if there's anything in here that you mentioned that's different from what you've represented here?

LH: You mean like I haven't drawn the water molecules as they are, connecting to the, well not connecting but…

Interviewer: You mean you haven't drawn the water molecules attracting towards the ions?

LH: Mm yep.

She was able to describe the orientation of the water molecules about the ions.

Interviewer: In here, you've mentioned wrong arrangement. What did you mean by that?

LH: Oh just how the water molecules are, cause they've got the hydrogens facing the sodium ions and here you've got the oxygens facing the sodium ion.

Once again, she revealed that she understood there to be movement at the molecular level. Her understanding of this was elaborated in this interview, suggesting she did perceive a difference in the nature of movement in the solid and the solution.
Interviewer: If you zoom down, either imagining this one or this one, whatever comes to mind when you picture an aqueous solution like this, is anything else happening in that?

LH: Just the vibrations between the molecules.

Interviewer: Okay and…is that vibration similar to the vibration you imagine in [solid] sodium chloride?

LH: …There'll be more movement in the liquid form than in the solid.

Interviewer: …How would [particles in the solid] be moving?

LH: Just back and forth hitting each other…

Interviewer: and how would [particles in the solution] be moving?

LH: All in different directions.

Precipitation of Lead(II) Iodide

LH had no prior understanding of the precipitation reaction between potassium iodide and lead nitrate and was therefore unable to produce a representation in the pre-test. By interview 1, she had developed some notion of the concept. Aqueous solutions of lead(II) nitrate and potassium iodide were represented as separate particles without charges or water molecules. She represented the products as molecules of potassium nitrate and lead(II) iodide. She was then questioned about her representation and decided to split the potassium nitrate into “ions”.

Interviewer: Okay, so you’ve got separate lead and nitrate and potassium and iodide and then they come together in groups?

LH: Mm

Interviewer: Can you explain…why one of these is a solid? Or are both of them solids or how do you perceive this, these products?

LH: Change this one [splits apart potassium nitrate]…it’s just showing that the potassium nitrate aren’t a solid like the way iodide is, they just form together.

She was then questioned about the meaning of the term “aqueous”. This prompted her to add water molecules to the representation, correctly oriented around the particles in potassium iodide. This led to the notion that the particles in the solution are charged.
Interviewer: When it says an aqueous solution, what does that mean?

LH: There’ll be…water in it.

Interviewer: …and what would the water be doing?

LH: …[draws]

Interviewer: Okay, so you’re hydrating them?

LH: Mm hmm.

Interviewer: …Okay, if…water molecules are directing themselves like this, does that mean that these have a charge?

LH: Yep.

Interviewer: So what charges would they have?

LH: …Oxygens…a negative charge so it would mean that potassium’s a positive charge.

Interviewer: Okay, so do you want to put that on? So you’ve actually got ions in the solution there, not atoms?

LH: Mm, I suppose so…And there’ll be all water molecules in there and throughout there but I can’t, don’t know which one’s negative or positive for lead or nitrate.

Interviewer: Okay, but you think they do have a positive and negative charge?

LH: Yeah

The final representation is reproduced in Figure 4.15.

**Figure 4.15** LH’s representation of the precipitation of lead(II) iodide, from interview 1

In the post-test, LH drew only a representation of the products. Solid lead(II) iodide was represented as a 3D cubic lattice with alternating lead and iodine particles. Aqueous potassium nitrate was represented as both molecules and “ions”. None of the particles in the representation had charges and no water molecules were included. The representation is
shown in Figure 4.16. LH was questioned about her representation during interview 3. The following is an excerpt of her explanation.

LH: I've just drawn the lead iodide as the solid or the precipitate.
Interviewer: So that's one of the products?
LH: Yeah, one of the products and...the potassium nitrate as the liquid, again one of the products of the equation.
Interviewer: Okay.
LH: I don't know what these are.
Interviewer: That's what I was just going to ask. Why do you have some of them grouped and some of them separate?
LH: ...I don't know.
Interviewer: Do you imagine them as together or separate?
LH: I imagine them closer together, like as a complete molecule.
Interviewer: Mm hmm
LH: I don't know why I had them separate there.

She still harboured the misconception that the aqueous solution contains molecules of potassium nitrate. Once again this student was questioned about her understanding of the term “aqueous”. She seemed less confident about the meaning of this term in this interview than she had been earlier in the year.

Interviewer: What does aqueous mean?
LH: I don't know.
Interviewer: When you write...aq after a chemical symbol in an equation
LH: It is a solution of chemicals
Interviewer: Okay, and what's in a solution?
LH: Mm, water and chemicals I think.
Interviewer: Okay, so would there be water in there, those final products?
LH: Yes probably, there'll probably just be water molecules floating around everywhere.
4.6.2. Interpretation of Chemical Symbolism

This section looks at LH’s ability to represent symbolic notation at the molecular level. These data were collected from the pre-test, interviews 1–4 and the post-test. Molecular representations were probed in interviews 1 and 3 (Sections 4.5.2.1–4.5.2.2), ionic representations in interview 2 (Sections 4.5.2.3–4.5.2.6) and equilibrium in interview 4 (Section 4.5.2.7). For further information regarding the content of the interview questions, see Table 4.3 (page 262) and Appendix C.

4.6.2.1. Symbolic Representations

LH incorrectly answered both questions in the pre-test relating to symbolic representations. In interview 1, she revealed that she was not confident in her ability to write formulae for molecular-level representations or vice versa. She could not explain how she came up with the representations in the pre-test.
Interviewer: Okay, now originally at the beginning of the year, you drew me a picture like this [molecule of \( \text{N}_2\text{O}_4 \)]. There's "two lots of 2 NO\(_2\)" written there. Do you want to describe to me what you were thinking when you drew that and whether or not you still agree with that answer?

LH: I can’t remember…

Interviewer: If you had to draw me a diagram of 2 NO\(_2\) now, what would you draw?

LH: …I don’t know.

Interviewer: Have you got any ideas what the NO\(_2\) represents?

LH: A formula.

Interviewer: Yeah, any idea of the structure of the, you said it was a molecule?

LH: Not really sure

In the post-test, she correctly represented 2 NO\(_2\) as two separate NO\(_2\) particles. She believed, however, that the molecular representation of \( \text{N}_2\text{O}_4 \) also had the formula 2 NO\(_2\). She was questioned about how one symbolic representation could have two different molecular representations. She did not consider this to be a problem.

Interviewer: Could you have two different molecular representations for the one formula?

LH: Oh, well that's…the top one's the same in a way because…they both have the nitrogen to two oxygen to them. That one's just written and that's more drawn like.

Interviewer: Okay, so do you see this representation as two separate NO\(_2\)s?

LH: Mm, no.

Interviewer: No? You seem them as joined.

LH: [yep]

Interviewer: Okay, so even though that they're joined and they're separate, could they be represented by the same formula?

LH: …Yeah.

Interviewer: Yeah? That makes sense to you?

LH: I think so.

4.6.2.2. Gas-Phase Reaction

Despite the fact that LH struggled with the molecular representations in the pre-test, she seemed quite comfortable producing molecular representations of the species in a gas-phase equation. When shown the first equation, she represented the reactants and products as
molecules in the correct stoichiometric ratios. When asked if she wished to modify her
drawing in light of the second equation, she replied that she would “probably space ‘em out
more… that’d probably be all.” Although she represented the products in separate boxes, she
realised that they would in fact be present as a mixture after the reaction. She produced a
further drawing of the mixture to demonstrate this but this time did not worry about
stoichiometric ratios.

4.6.2.3. **Strong Acid Solution**

LH could only provide a vague description of what the label “0.050 M H\textsubscript{2}SO\textsubscript{4}” means.

Interviewer: Can you tell me what that label means to you?

LH: …It tells you the solution.

Interviewer: Okay, which is?

LH: Sulfuric acid?

Interviewer: Good, yep.

LH: And it tells you the molarity…of it.

Interviewer: Can you describe to me what molarity means…?

LH: …Is molarity the concentration of the solution in it?

Interviewer: Mm hmm.

LH: So the concentration of…

Interviewer: What does the .05 mean?

LH: …I don't know.

Her molecular-level representation of aqueous sulfuric acid was quite sophisticated, however
(see Figure 4.17). She represented the acid as two separate hydrogen ions and a sulphate ion,
each surrounded by correctly oriented water molecules. She did not seem to realise that
hydronium ions, rather than hydrogen ions, exist in an acidic solution. She also
misrepresented the charge on the sulfate ion, rendering the overall solution charged.
4.6.2.4. Acid/Base Reaction

LH was unsure what would happen, at the laboratory level, if equal volumes of the above acidic solution and 0.10 M sodium hydroxide were mixed. After “seeing” the reaction, she concluded that the “ions would’ve mixed, just all mixed up” but was not sure whether or not a reaction had occurred. Eventually, she decided “it’d form water and something else”. After seeing an equation for the reaction, she produced a drawing of the products (see Figure 4.17). Once again, she showed separate ions in the correct ratios, properly hydrated with water molecules. She did not consider the electro-neutrality of the solution.

4.6.2.5. Precipitation

When shown the first equation for the reaction between potassium chloride and lead nitrate, LH was able to construct a “word equation” for what the reaction meant but felt that she could not represent the reactants and products at the molecular level without being told the states of each substance.

She was therefore shown the second equation from which she constructed the diagram shown in Figure 4.18. As with her other diagrams of aqueous ionic solutions produced in interview 2, she represented separate appropriately hydrated ions for the reactants and the product, aqueous potassium nitrate. Solid lead(II) chloride was represented as a 3D lattice. Charges were not included on “ions” in the lattice. She was once again questioned regarding her
understanding of ionic bonding. This led her to state that the lead and chloride in the precipitate were charged.

Interviewer: And what again is an ionic bond?
LH: …A positive and negative attraction.
Interviewer: Okay, so there are positive and negative attractions in there?
LH: Yep.
Interviewer: Okay, where are the negative and where are the positive attractions?
LH: Lead's the positive and chloride's negative.

When shown the final equation, LH only made one change to her representation, adding an extra nitrate ion to the products. She claimed that the third diagram best represented the reaction “cause it's just showing the ions separate and then what forms”.

Figure 4.18  LH’s representation of the “molecular equation” (with states given) showing the precipitation of lead(II) chloride

4.6.2.6. Complexation

LH seemed to recall the reaction represented by the given equations. Her description of what one might see in the laboratory is given below.

LH: In the first one, the copper oxide, is it copper oxide? …forms and then when you're adding the ammonia it disintegrates or whatever, it dissolves, I suppose.
Interviewer: Okay, so in the first case you'll see a solid form?
LH: Yeah, and then it'll disappear, more or less.
LH represented the solid copper(II) hydroxide in a similar fashion to the other ionic solids she drew in the same interview, as a 3D lattice with no charges on the “ions”. She was unsure what would happen at the molecular level when ammonia was added.

LH: The ions of the ammonia would be mixing with the solid…

Interviewer: What do you mean by the ions of the ammonia?

LH: …I was going to say the ions of nitrogen and hydrogen but then, they're still formed as one in the product…No, I'm not sure.

Interviewer: So…you can't…develop some sort of picture of how this might interact with this to form these products?

LH: Mm, no, not really.

She produced a simplistic drawing of the products of the second reaction showing two separate hydroxide ions, and a paired copper and ammonia (see Figure 4.19). She commented that the ratio of ammonia to copper should be four to one and that these ammonia molecules would surround the copper. She suggested that everything would be surrounded by water.

LH was then shown modified versions of the same equations, and asked about the meaning of the added water molecules. She suggested the first equation was just “showing that…the copper is hydrated by the water and that when the reaction occurs…the solid of copper hydroxide forms and the water's just left floating around”. On seeing the second equation, she modified her drawing to show hydrating water molecules around the copper ammonia complex, as shown in Figure 4.19. Although she realised there should be an extra ammonia molecule, she claimed that she could not fit it into the diagram. It is obvious from her diagram that she was not aware that two water molecules and four ammonia molecules would surround the copper ion in an octahedral fashion.

Finally, she was asked which set of equations best represented the reaction. She chose the
4.6.2.7. **Equilibrium Reactions**

**Equilibrium**

LH gave a definition of equilibrium that suggested she conceived of it as a kind of balance of reactants and products, where the rates of the forward and reverse reactions and the concentrations of reactants and products were equal on both sides.

Interviewer: The first thing I want to ask you is what you think an equilibrium reaction is.

LH: …It’s where the reactants and the products equal each other, sort of.

Interviewer: What do you mean by equal each other?

LH: …The forward reaction equals the reverse reaction.

Interviewer: Okay. Can you explain what you mean by equals?

LH: …they don’t actually like equal, equal but…

Interviewer: Are you talking about equal numbers of, like equal concentrations? Or equal rates or, or equal something elses?

LH: …Equal rates and concentrations I suppose.

To encourage the student to elaborate on her understanding of equilibrium, she was asked what the equilibrium sign meant. Through this questioning, she demonstrated some understanding of the idea that forward and reverse reactions are both able to occur, with some products forming while others are converting back to reactants. This is shown in the following excerpt.
Interviewer: Okay, so you’ve got two reactions at equal rates. What does this little sign here mean?

LH: It’s at equilibrium.

Interviewer: Okay, why’s it got one little arrow going one way and one going the other way?

LH: It’s saying it can either go that way, and so the reactants equal the products or it can be…products break down to be reactants again.

Interviewer: Okay, so how do both the forward and reverse reactions occur?

LH: I don't know. They just do.

Interviewer: Do they occur at the same time?

LH: Yep.

Interviewer: Yeah? How do they occur at the same time?

LH: I don't know. As the products are forming they're also breaking down…

Gas-Phase Equilibrium

Although she had some understanding of equilibrium, LH claimed to be unable to imagine equilibrium reactions at the molecular level. She refused, therefore, to produce a diagram of the given equilibrium reaction. Probing revealed that she believed that both reactants and products would be present in the mixture, in stoichiometric ratios. She did not understand that the equilibrium constant provided information about the ratio of products to reactants, but instead thought that it was an indication of the speed at which the reaction would reach equilibrium.
Interviewer: Are you able to bring up some sort of a mental image of what happens?

LH: Nup.

Interviewer: Would you be able to draw some sort of picture of what it might look like at equilibrium?

LH: Nup.

Interviewer: You just don't have an image of it at all?

LH: Nup.

Interviewer: What species do you think would be in there, in the reaction vessel? Just say that that's all in some closed container because they're all gases. What would be inside the container, if it was at equilibrium?

LH: Don't know…

Interviewer: Would you have like just reactants? Would you have just products? Would you have just reactants, then just products, or would you have a mixture of everything?

LH: You'd have a mixture of everything.

Interviewer: Okay, so you've got some of each of these species all in the reaction vessel? Okay, what does that K value there tell you?

LH: How fast it takes to get to equilibrium.

Interviewer: Okay, if you, say you've got all of these…in the vessel at one time…How would the numbers of each of those compare with each other?

LH: They're all equal.

Interviewer: And why do you say that?

LH: Cause they're all one, like there's no numbers in front of them.

Interviewer: So they're all one-to-one?

LH: Yeah…one-to-one ratio.

Interviewer: So you think that in the reaction vessel that there would be stoichiometric ratios of each of those?

LH: Yep.

When asked what would happen if extra NO was added to the reaction vessel, LH used LeChatelie’s principle to predict the shift towards more product. She could not explain this shift in terms of molecular-level processes.
Interviewer: Imagine that we add some more nitrous oxide to the vessel…some gaseous NO. What do you think would happen?

LH: More product would be formed.

Interviewer: Okay, can you describe what happens at a molecular level to cause that shift to occur?

LH: They're just trying to use up the extra nitric acid to make it at equilibrium again because by adding more it's not at equilibrium.

**Weak Acid Equilibrium**

LH represented boric acid’s dissociation in a similar manner to that described for the previous equilibrium system, showing stoichiometric ratios of the reactant and products mixed together. After questioning, she said that water would also be present. She expressed an understanding that reactions constantly occur. She did not appear to realise that hydronium ions form in acidic aqueous solutions.

Interviewer: Imagine that we zoom down to the molecular level again and we watch this reaction at equilibrium. What would you see?

LH: Just all the substances together… It'll just be similar to the first one…equal numbers of each of them… They'll be all mixed in cause it's an aqueous…

Interviewer: Okay, what does the aqueous mean?

LH: It's a solution.

Interviewer: Okay, so is there anything else in there besides those species?

LH: Water…

Interviewer: …Alright, so is there anything going on in the solution, if you were to picture that in your head, or if you were able to zoom down and watch what was going on, would anything be happening?

LH: They'll be constantly changing.

Interviewer: Mm hmm. What do you mean by that?

LH: Like they break these to form, they form that. That and that [react] and form that again.

She was then shown the modified version of the equation showing the hydronium ion and was asked if she wished to modify her diagram. She drew another diagram showing each of the substances in the new equation. She seemed to believe that the reactions were different because the second one had water as a reactant. She therefore did not seem to understand the role of water molecules in the dissociation of weak acids in aqueous solution.
LH: Just the water and the products… and the water would actually be a reactant as well… In the other one, it was just intermixed with it all.

Interviewer: Do you see these two reactions as being different?

LH: There is water in this one as well.

4.6.3. Interpretation of Macroscopic Phenomena

This section looks at LH’s ability to explain macroscopic phenomena. These data were collected from interviews 3 (Sections 4.5.3.1–4.5.3.2) and 4 (Section 4.5.3.3). Information regarding the content of the interview questions is given in Table 4.4.

4.6.3.1. Nail-Polish Remover

LH failed to give an explanation for what happens at the molecular level between opening a bottle of nail-polish remover and being able to smell the fumes. She believed that the smell must be the result of a chemical reaction occurring in the solution. She was unable to use her understanding of the states of matter to describe the processes occurring. Presumably, she did not see the relevance of such knowledge.

Interviewer: Can you give some sort of a description at a molecular level as to what might be happening when you can smell a liquid?

LH: Nope. Just all of the…acetate…just reacting against each other.

Interviewer: You think there's some sort of reaction going on in that container?

LH: Well for the smell to occur there would be.

Interviewer: Okay, so you're sort of thinking of it as a chemical reaction giving off smell? When you smell something in a chemical reaction, what are you generally smelling?

LH: I don't know.

Interviewer: Okay, what if I told you that there's no chemical reaction going on in there, that this is just a liquid solution of ethyl acetate…Can you think of any other reasons why it might smell?

LH: As a result of a chemical reaction.

4.6.3.2. Precipitation Reaction

LH was able to give an explanation at the molecular level of what happens when two white solids (potassium iodide, lead nitrate) are added to water, resulting in the formation of a yellow solid in the solution. She described the starting solids as having the same structure as
other ionic solids she had drawn or discussed earlier in the interview, for example, the structure of lead(II) iodide from the post-test. She saw the water moving in and separating the ions in each of the solids; ions moving together to form solid lead(II) iodide; and potassium and nitrate ions remaining in solution. She was able to link the experiment to the precipitation question in the post-test discussed earlier. Exposure to the experiment encouraged her to rethink her idea regarding the presence of potassium nitrate molecules as a product of the reaction.
Interviewer: So say you've got potassium iodide, just in the container there. What would that look like if you zoomed down to a particle level?

LH: Just solid potassium iodide.

Interviewer: What sort of a structure would that be in?

LH: …it'll be in like a net structure.

Interviewer: What do you mean by that?…

LH: …I think there's one in here…

Interviewer: Okay, similar to how you've drawn the lead iodide there? …Okay, and what happens as you put it in the water?

LH: The potassium iodide separate, like they separate from each other and become aqueous.

Interviewer: Okay, what causes it to separate from each other?

LH: Ah, the water molecules?

Interviewer: Do they take any part in the dissolving or do, do they just sort of move in and separate them, like how does that, how does the water help?

LH: Well it moves in and separates, dissolves the potassium iodide as well…the potassium and the iodide separate…

Interviewer: …How do the two solutions meet?

LH: Just by them moving along in the water.

Interviewer: So you see the ions as moving through the water?

LH: Yep.

Interviewer: Yep. Okay and what happens when they meet?

LH: They form the yellow stuff that's in there.

Interviewer: Yeah, what forms the yellow stuff?

LH: The lead iodide.

Interviewer: …So how do you picture what's left in that solution there?

LH: Up in the water?

Interviewer: Yep.

LH: Just the potassium and the nitrate going round…

Interviewer: …So…they don’t come together to react?

LH: No, I don't think they do.

Interviewer: Okay, so they're just left separate in the solution?

LH: Mm
4.6.3.3. **Redox Reaction**

LH constructed a very simplistic representation of aqueous silver nitrate, containing separate silver and nitrate ions but no water. She added water after prompting. She represented solid copper as copper(I) ions in a cubic lattice. She failed to show delocalised electrons.

This student was able to provide an interpretation of her observations of the reaction between solid copper and silver nitrate. She identified the blackish mass produced as silver and interpreted the resulting blue solution as meaning there was now copper in solution. She described the silver produced as being in a similar lattice structure to the solid copper, but was not sure whether the two metals would form separate lattices or connected ones. She replaced the silver in solution with copper.

Interviewer: So what do you see happening?

LH: The copper's turning black.

Interviewer: What do you think that black stuff is?

LH: It's silver…Maybe silver's reacting with the copper.

Interviewer: …Can you describe to me how the reaction occurs at a molecular level?

LH: …The silver nitrate will form just a nitrate solution and the copper and the silver form the product… Now it's changing again. It's gone blue.

Interviewer: …Okay, if you have a look at the colour of that solution there, what can you see?

LH: It's got copper in it.

Interviewer: How do you know that?

LH: Cause it's blue…

Interviewer: …So does that tell you anything else?

LH: That the copper does actually break down… I think in the products, in the solution there'll be copper…, the nitrate and the silver…and for the…. the crystals that was on it there'll be silver and copper…all, the silver and the copper would [turns page back]

Interviewer: Both be in like a lattice structure?

LH: Yeah, cause it's a solid…But I don't know if they would be a cubic together…Like with the copper and the silver mixed or if they'll be separate. I think they'll be separate.
4.6.4. **Interpretation of Molecular Representations**

This section looks at LH’s ability to interpret and critically analyse molecular representations. These data were collected from interviews 1 (Section 4.5.4.1), 3 (Section 4.5.4.1–4.5.4.2) and 4 (Sections 4.5.4.3–4.5.4.4). The structure of this section and the content of the interview questions are elaborated in Table 4.5 (see page 263).

4.6.4.1. **Modelling**

4.6.4.1.1. **Interpretation**

**Models of Water**

In the pre-test, LH chose the ball-and-stick representation of a water molecule as the one best representing its actual structure. She did not provide a reason for her choice. When shown multiple models of water molecules (Appendix C) during interview 1, LH chose what she thought to be the “best” representation of a water molecule based on familiarity. She preferred the space-filling representation (B) because it had been used in lectures and she felt it was easiest to understand and visualise. This student also felt that the Lewis structure (E) was a good representation because it described a bit about the bonding. She had little to say about the other models, other than that model A was confusing. Later in the interview, she was shown a 3D animation of a water molecule (space-filling representation) and could not identify non-correspondences between the model and the target. When probed further, she acknowledged that colour was used purely to distinguish between hydrogen and oxygen atoms; and that the hard shell appearance was “not necessarily that realistic” but just used so “you can see what it roughly looks like”. She was aware that features such as the protons, neutrons and electrons, although present in a water molecule, were not immediately visible in this model.

**Models of Solid Sodium Chloride**

In interview 3, LH was shown multiple representations of solid sodium chloride (Appendix C). She preferred models that were “plain and simple”, choosing model D, the formula, as the best representation. She also liked model B because she felt she understood it.
LH: That one 'cause I know what's going on. I can relate to it.

Interviewer: B?

LH: Yeah B.

Interviewer: Okay…so what's going on?

LH: Oh just like the sodium chloride intermixed and, well not intermixed but, there's a structure…vibrating and everything against each other.

Her preferences were guided by ease of interpretation. She felt that some models were simply easier to visualise. This may suggest that she believed in models as a communication tool, with communication enhanced through simplicity. However, her idea of “communication” was rather simplistic, incorporating only whether or not she could understand the model, with little concern for what information was communicated by each model.

*Quote 1:*

Interviewer: Why do you think you prefer the 2D structure to the 3D one?

LH: It doesn't look as confusing as the 3D one.

*Quote 2:*

LH: A would probably confuse some people because it's confusing me.

Interviewer: Okay, what confuses you about it?

LH: I don't know. Just the way it's set out.

During her discussion, she did volunteer some information regarding the different features shown in different representations.

*Quote 1:*

LH: E's the same as B but there's no vibrations and it's all 3D.

*Quote 2:*

LH: C shows where the bonds are, where E is just all tightly compacted and the bonds aren't shown.
4.6.4.1.2. Multiple Modelling

When asked in interview 1 why scientists might want to represent the one thing in so many ways, LH replied with the vague answer “just so people can see how it’s formed like because there’s no set way that you can visualise it.” She did not elaborate on exactly what she meant by this statement.

In interview 3, she was asked why we might represent solid sodium chloride in many different ways. Equally vaguely, she replied “just to show that it can be shown differently”. She believed that “when you…break it all down, they’re all the same…Just like E has more ions than B”. She did not see a significant difference in the models but just felt that they showed slightly different features. Finally, she decided that there were multiple models because “some people might find [certain models] easier to interpret and see”. Although she was starting to see the importance of a model in communicating information effectively, she did not seem to see the importance of different models for showing different features. She seemed content to choose a model that she liked and stick with it.

4.6.4.1.3. Development

In interview 1, LH was shown a 3D space-filling representation of a water molecule. She felt that for a water molecule to have been represented as such, someone must have seen one. She therefore felt that the representation was fairly close to what an actual water molecule looks like, and could not spontaneously identify any differences between the representation and the “real thing”.

Interviewer: Do you think that anyone has actually seen, ever seen a water molecule, or has seen atoms, ions, molecules?

LH: I suppose they would’ve or they wouldn’t be able to show a water molecule like that.

During interview 3, LH was shown an animation of an aqueous solution of potassium fluoride and was asked questions relating to scientific modelling. Once again, she revealed that she believed the animation to be close to reality, what you would actually see if you were able to zoom down to the molecular level. She did not seem to distinguish her understanding of the molecular level of an aqueous solution and “reality”. 
Interviewer: How close do you think this animation would be to what...an ionic aqueous solution would actually...be like?

LH: Probably really close... There's lots of water molecules in there, which, there are lots in an aqueous solution...and it's showing that the fluoride and the potassium are hydrated.

LH believed that models were developed by “someone who tried to show what was happening” but could not say how they were developed. She felt that they were designed to show students, for example, what goes on in an aqueous solution. Animations were considered useful to improve visualisation and make learning easier, as demonstrated by the following quote.

LH: ...make it easier to visualise what's going on. ‘Cause like pictures are good...like you can see everything but the animations actually...it feels like you're there when the chemical reaction happens...You're watching the actual process of it.

She felt as though the lecturer wanted her to know these ideas so she could interpret experiments in the laboratory by visualising what was happening; linking macroscopic phenomena to molecular-level processes. She also felt that animations were useful during study.

LH: Yeah, they are useful like when like I'm studying stuff, I can visualise what's going on and it's easier to understand like the reactions and chemicals and things.

LH believed that the model of an aqueous solution shown by the animation could be used to describe all aqueous ionic solutions and felt that she would only change her conception if she were told it was incorrect.

She was willing to concede that models of aqueous ionic solutions may have developed further since this representation was proposed, “through more experiments, if they've done more experiments” because “it might increase their knowledge of what’s happening”. Although she realised that experimentation plays a role in the formulation of models, she seemed to perceive it as a search for truth. LH was also willing to accept that scientists may imagine aqueous solutions in other ways, but felt that scientists would generally agree that the animation was a good representation of an ionic solution.
4.6.4.2. Criticism of Molecular Diagrams and Animations

Diagram 1: Dry Ice

LH did not see any problems with this diagram, simply stating that “it’s an alright diagram. It’s not bad”. When questioned about the use of a magnifying glass, she felt that this might mislead students about the size of the molecules.

LH: Well you don't usually use a magnifying glass to look at molecules.
Interviewer: Okay, why not?
LH: ’Cause you can't see ’em.
Interviewer: … Why can't you see them through a magnifying glass?
LH: ’Cause they're like tiny.

Diagram 2: Saturated Solution

LH was unable to criticise this diagram because she was unable to interpret it. She found the diagram confusing, mainly because she was not familiar with the process it was depicting.

Interviewer: What aspects of it are confusing?
LH: Just how they got the undissolved sodium chloride crystals on the bottom and then on this side the ions going into solution and then they're joining again.
Interviewer: Yeah, what don't you like about the undissolved sodium chloride?
LH: Oh, that bit's alright, it's just the ions dissolving and then ions crystallising. That's confusing.

Diagram 3: Electron Transfer

LH was happy with the representation of electron transfer, stating that “it’s really simple and straightforward”. She did not see any need to change it and did not feel that it would mislead novice students in any way.

Diagram 4: Precipitation

LH’s only criticism of this diagram was that “there's a whole big pile you have to read to actually understand what's going on”. She suggested reducing the amount of written text accompanying the diagram.
Animation: Dissolving

LH found this animation useful for showing sodium chloride dissolving. Once again she liked its simplicity. She made no criticisms or suggestions for improvement.

Interviewer: Okay do you think it's a…good animation of that happening?
LH: Mm [nods]. It shows what's happening so…
Interviewer: …Do you think there's any features of it that might be misleading? Is there anything that should perhaps be changed to make it a better animation?
LH: …I think it's alright. It's simple and it shows what's happening.
Interviewer: Okay, so you like the simplicity of it?
LH: Yeah. It's not like too confusing…

4.6.4.3. Analogical Modelling of Equilibrium

Analogy 1: Soccer Game

LH identified the players on the field as representing the products and players off the field as representing the reactants, but struggled to interpret the analogy further. She could see that “there is no change in the number of players on the field” indicated that the “number of products are always the same” but was confused as to why their identities would change. She understood that the products were always the same species.

Interviewer: You don't understand why their identities would be different?
LH: Well I understand in a game of soccer…in like a chemical…I don't understand how that would work.

She was also unhappy with the last sentence “there is no requirement that the number of players on the field or on the bench be equal” because, like HL, she thought that “in equilibrium they usually equal each other on both sides”. She suggested removing this sentence from the analogy.

Analogy 2: Juggling

LH felt that this analogy was simple and straightforward. She identified the correspondences to the reactants and products but misinterpreted the final sentence, “number of balls in the air
or in the hands always remains the same” to mean that the reactants and products are “equal to each other”, presumably in number.

Interviewer: So describe to me what it means to you, like what do you understand that to mean?

LH: It's saying that the balls are the same at each time. They're up in the air, then they're in the hands.

Interviewer: Okay, what do the "in the air" and "in the hands" correspond to?

LH: Reactants and products, so they're at equilibrium cause they're equal to each other.

**Analogy 3: Dancing**

LH identified the males and females as the reactants and the pairs as the products, and noticed that, in contrast to the last examples, this one used two different reactants.

LH: …It's actually using two different reactants.

Interviewer: Okay, and what are they?

LH: Males and females and they're single and then they get into pairs.

Interviewer: So what do the singles and the pairs represent? You said the reactants are males and females.

LH: Yeah and the pairs would be the products.

She also successfully interpreted the remainder of the analogy.

Interviewer: What about this "every time one couple splits and begins dancing separately another couple begins dancing together"?

LH: That's just keeping the equilibrium…so there will be separates, like the males and females separate and a couple dancing all the time.

Interviewer: …Do you have any idea what the last sentence is getting at?

LH: It's just like referring to what happens to the reactants. Saying to form the product the reactants have to like come together.

LH also thought this was one of the better analogies but was equally happy with the juggling analogy.
4.6.4.4. Interpretation of Molecular-Level Animations

Ice Melting

LH was able to identify what this animation represented. She pointed out vibrations and increasing movement as the liquid state was approached.

LH: Is it showing melting ice?

Interviewer: Mm hmm.

LH: It's showing how…at its solid, the ice, it vibrates against each other and as it becomes more liquid and melted they, the water molecules start to move around more vigorously.

She noticed that in the liquid state the water moved about in clusters, and was able to explain this in terms of hydrogen bonding.

LH: They're forming little, in the water, they're forming little groups, water molecules.

Interviewer: Okay, why would they do that?

LH: Just to hold the substance together, I suppose.

Interviewer: …What actually holds them together?

LH: The charges on like the…pluses on the hydrogen and the negatives on the oxygen…they like react against each other and hold each other together.

Her prior knowledge about solids being tightly packed seemed to affect her interpretation of the animation.

Interviewer: What other features might you point out to a student about the ice to start with? You said that they're vibrating.

LH: …They're in a solid, compact form.

When questioned about all the space shown in the animation, she did not seem to see that there was a contradiction. Instead, she demonstrated her knowledge of the fact that in ice there is space between the water molecules because when water freezes, it expands. Further questioning revealed that she believed there to be air (oxygen) molecules in the space, even though these were not represented in the animation.
LH: There's always space in ice…'Cause when we freeze water it gets larger…but I don't know what's in it. I think it's just air.

Interviewer: What do you mean by “air”?

LH: Just air pockets.

Interviewer: What's air made up of?

LH: …oxygen.

Interviewer: So you think there might be just other molecules from the air in those pockets?

LH: Yeah.

**Water Evaporating**

LH immediately identified this animation as water evaporating. She described the animation as follows.

LH: This is just showing the water molecules and it's coming up to the top. Now it shows the actual water molecules breaking off the other water molecules and evaporating.

She also noticed that some water molecules returned to the liquid state. She explained this in terms of the strength of the bonds between water molecules.

LH: Some of them come back down, like they fall back down.

Interviewer: Yeah, why might that happen?

LH: I don't know, unless they're condensing.

Interviewer: Okay. What about say…this one, what happens to that one?

LH: It's not evaporating…the bonds between the other water molecules is keeping it as water.

Interviewer: Okay, the bonding between.

LH: The bonding's too strong for it to evaporate away.

**Sodium Chloride Dissolving**

LH understood that this animation was showing a “solid going into aqueous solution” but she struggled to identify the solid, initially suggesting that the green balls represented copper.
LH: I think it's copper…

Interviewer: What makes you think it's copper?

LH: Just the green balls.

Interviewer: Would copper dissolve in water?

LH: No, I don't think so.

Interviewer: You think the green balls are copper?

LH: Mm hmm

Interviewer: What are those ones?

LH: I don't know…green's not copper. I don't know what the solid is.

Despite not knowing the substance dissolving, she went on to point out the features of electrostatic attraction and vibration in the solid.

Interviewer: Well, what's happening as we pour the water down?

LH: They're hydrolysing these little particle things… It's showing that the little grey balls are positive because the oxygen's going towards them…and the green balls are negative.

Interviewer: What else do you notice in this animation?

LH: The solid's vibrating closely together and when the…water molecules come in they're being pulled apart…and so the solid's breaking down.

**Aqueous Solution of Sodium Chloride**

LH first commented that this animation was the aqueous solution resulting from the previous animation. She pointed out the hydration of ions and the number of water molecules compared to ions. She could not explain why ions came together, then moved apart again.
Interviewer: So what features would you point out?

LH: …The hydrolysed green and grey balls…and all the water molecules… I don’t understand what's happening there, cause they [go to] join back up again but they don’t…

Interviewer: …What were you going to say about the water molecules?

LH: Just that there's lots of them.

Interviewer: Let's see that bit again. Why might they come together, do you think?

LH: I thought they were coming together to reform the solid but then they're in solution so…

Interviewer: Can't think of any reasons why they might…?

LH: Nup.

Interviewer: Okay, so you'd just point out that…the positive and negative balls are hydrolysed, there's water molecules around them and there's lots of water molecules compared to

LH: Yep, compared to the green and grey balls, there's more water molecules.

Precipitation of Silver Chloride

LH initially identified this animation as “reforming the solid structure again”. She experienced confusion regarding the presence of a “blue and red ball”, because this species had not been present in the previous animations. LH apparently believed that the solid from the previous animation was reforming. Therefore, she was shown the previous animation again so she could directly compare the particles. This enabled her to interpret the presence of the blue and red ball and identify the animation as a precipitation reaction.

LH: Well then, the blue ball would just be…something that's in the aqueous solutions in the water.

Interviewer: Okay, but where did it come from?

LH: From the reaction between the green and grey balls when they were in aqueous before they were turned to precipitating form…

Interviewer: …So you think it just comes from one of the solutions that were originally mixed?

LH: Yep.

Interviewer: Yep, does it do anything?

LH: No, it's just part of the aqueous solution.

The student then went on to point out that “the solid's vibrating and the water molecules in aqueous solution are moving freely”.

Redox Reaction of Copper with Silver Nitrate

LH was unable to make sense of this animation. She could see, however, that a new structure was being formed from the silver balls, and the yellow balls were dissolving into solution.

LH: Well, the yellow balls are in a structure…and the water molecules are bringing the little silver balls, like they form another structure and they're taking away some of the yellow balls [to] hydrolyse them somehow.

When she was told that it was a representation of the redox reaction she had been shown earlier, she felt that it made sense and was able to identify the “shieldy thing”, present on the atoms in the structure, as electrons.

Interviewer: This is actually a representation of the reaction I showed you earlier. So this is the copper and we had a solution of silver nitrate, so we've got the nitrate ion and the silver ion there and the silver depositing on the surface basically.

LH: Now it makes sense.

Interviewer: But when they deposit, they take a couple of electrons from the copper.

LH: Yeah I could see the little, like the shieldy thing
4.7. Case Study 4 (LL)

LL represents a student with low prior knowledge (pre-test score: 6) and low disembedding ability (GEFT score: 8).

4.7.1. Imagery Development

This section documents the development of LL’s images of substances assessed by the questionnaire, through the year. These data were collected from the pre-test, interviews 1–3 and the post-test.

4.7.1.1. Molecular Substances

General Features

This student’s main difficulty regarding the general features of molecular substances was associated with whether the size of the molecules changed in different states. In the pre-test, she suggested that molecules decrease in size from solid to liquid to gas, suggesting that “solids are bigger, whereas gases are smaller so they can move around more freely”. When asked about this idea during interviews 1 and 2, she still had little idea and admitted to having made a guess in the pre-test. However, she persisted with her original idea. In the post-test, she chose the same response and expressed total confidence in the idea that the size of molecules decreases from solid to gas. Her explanation had changed, however, and she showed low confidence in this explanation. She proposed that “gases are smaller, that’s why they can’t be seen. Solids are bigger and combine to form larger objects”.

Liquid Water

The only real change that occurred in this student’s image of liquid water over the year was the replacement of a generic circle to represent each particle, with a space-filling representation of a water molecule.

In the pre-test, she represented liquid water as circles moving relatively close to one another. By interview 1, her image featured space-filling representations of water molecules instead of circles.
LL: I didn’t actually draw…the two hydrogens on there… Actually, I didn’t even think of that when I was drawing it… Yeah, I’d draw little water molecules everywhere instead…I’d add two to every one, to every circle.

She attributed this development to VisChem videos shown in lectures.

LL: …Just from the video that he shows us, you can see it.

In the post-test, she represented liquid water as described above but did not mention movement of the water molecules. To given her the chance to mention the idea in interview 3, she was directly asked about movement in the liquid.

Interviewer: Okay, now in your representations of gaseous water and solid water, you've mentioned here floating freely and collisions and here you've mentioned vibrations. Do you think that there's any sort of movement happening in the liquid?

LL: Oh yeah. It moves around.

She still seemed aware of movement in the liquid state, despite failing to mention it in the post-test.

**Gaseous Water**

As for liquid water, LL initially represented gaseous water as a collection of circles. She mentioned large amounts of space between particles and movement, with high confidence in her answer. By interview 1, she had developed an image of a water molecule and suggested replacing the circles with water molecules in her representation. Once again, she felt that the VisChem video showing water in the three states helped her to develop her image.

In interview 2, she seemed to regress, unsure of what gaseous water was, without the questionnaire available as a clue.
Interviewer: I want you to describe your mental image or to bring up a mental image of gaseous water.

LL: Gaseous water?

Interviewer: At the molecular level.

LL: I wouldn’t have a clue. Okay, maybe it’s, I didn’t know, you could have the two combined together, I thought it was just gas and just water. Like, I don’t know.

Interviewer: Okay, so what’s your concept of gas?

LL: Gas is just particles that are floating around and they’re very far apart and water’s, water’s like the same but more closer together. So is gaseous water a mixture of like water and gas?

After directing the student to a definition of gaseous water, she suggested that “It’d probably just be far apart like normal gas”. The post-test seemed to reveal an improvement in her understanding. She represented gaseous water as a collection of discrete, widely spaced water molecules, moving freely and colliding. In interview 3, she was asked how she had developed this image but could not recall how she had come to her current understanding.

**Solid Water**

In the pre-test, LL represented solid water as a collection of tightly packed, fixed particles, each represented by a circle (see Figure 4.20). Once again, exposure to VisChem videos helped her replace the circles with representations of water molecules.

In interview 2, she mentioned that water molecules in ice vibrate. She attributed the development of this idea to animations that were shown in lectures.

LL: I think they’ll still be vibrating but only very, very little but they’re still compacted tightly together…vibrating.

Interviewer: How do you think you formed that image?

LL: …I think they had it in a computer, that visualise thing that [the lecturer] has.

The student’s image had not changed or developed further by the post-test. Her final image is shown in Figure 4.20.
4.7.1.2. Ionic Substances

Solid Sodium Chloride

LL initially chose a representation of solid sodium chloride that showed molecules of NaCl. By interview 1, her understanding had not changed. She still felt that solid sodium chloride was best represented by molecules of NaCl in a repeating pattern. She thought it was necessary to identify which sodiums were bonded to which chlorides, and to clearly demonstrate the one-to-one ratio of ions.

LL: Okay, because you can see that one, one sodium and one chloride ion combine together to form that salt, and so you can actually see in this diagram, that one of these is combined with one of them but with [the other representations] you don’t know which ones combined with them, they look in all different patterns… This one looks consistent, the same ideas being carried through, so that’s why I thought…

Interviewer: The same ideas just being carried through?

LL: Yeah.

Interviewer: What do you mean by that?

LL: …this one’s a repeated pattern…like every one of these, there’s one of these.

She was unable to describe the bonding in solid sodium chloride. She only knew ionic bonding to be what occurs between a metal and a non-metal. She attributed the development of her image to VisChem animations.
LL: When he showed the video, he actually showed what a sodium chloride looks like and then they added it to water and stuff like that…but I can’t remember what it looked like after the water… From the video, that’s how I see it. That’s what I think is the right one.

In interview 2, she produced a representation of solid sodium chloride that was more scientifically acceptable, featuring ions of sodium and chloride in a repeating pattern (see Figure 4.21). She also mentioned that vibrations occur at the molecular level. She was still unable to describe the bonding in sodium chloride, and could not specify whether separate ions or molecules were present in the lattice.

In the post-test, she chose the correct representation of solid sodium chloride based on the fact that “for each Cl\(^-\) ion there is an Na\(^+\) ion” and “the Na\(^+\) ions and Cl\(^-\) arrange themselves in a pattern”. She also felt that the particles should be touching.

By interview 3, she was unsure which representation was most adequate, tossing up between the correct representation and the representation showing molecules of sodium chloride. She felt that representation 3 best showed the idea that particles in a solid should be touching, but liked the fact that the other diagram showed which chlorides and sodiums were bonded. Although she seemed to know what solid sodium chloride might look like at the molecular level, she didn’t abandon her original ideas which now seem to conflict with the image she has developed. She retained the correct idea that the particles vibrate in the solid, even at room temperature.
Aqueous Solution of Sodium Chloride

LL’s image of aqueous sodium chloride showed considerable variability throughout the year. At the beginning of the year, she imagined there to be molecules of sodium chloride dispersed among water molecules. In interview 1, she initially agreed with this idea, then reconsidered her answer, suggesting that perhaps the ions would separate in water. She could recall information about water molecules orientating themselves towards the ions in a particular manner. She wasn’t sure how or why this occurred but knew that it would happen if the ions separated in solution.

LL: I don’t know…whether they split in the water. That’s why I don’t know. See, if they split, then it’d be this one because…I don’t know, the water molecules, something about polars or something and but this one, it looks right as well. I don’t know…

Interviewer: Okay, so if they’re molecules in the solution, you just think there’s molecules amongst water molecules and if they split, can you tell me more about that polar thing?

LL: Okay…well I’m just, I’m just assuming that…I don’t know which way it is around…whichever end’s more attractive or something but it turns around to face the sodium ion and they turn around the other way because…I can’t explain it…

She felt that drawings on the board and drawing her own representations might have helped her become aware of the idea of ion-dipole attractions.

LL: I’ve just seen them drawn itself on the board. I don’t think I’ve seen it on the video thing but I’ve seen them, I’ve seen them draw it on the board and I think they’ve, I don’t know if they have it in the actual worksheets. I can’t recall anything but, yeah I’ve just seen them draw it.

Interviewer: It’s mainly drawings?

LL: …I just kind of picked up on it…but they just basically said, you know, why they face, but I just can’t remember… Also, we had to do that for a practical, we had to draw. I remember we had to draw those things.

She also recalled the animation of sodium chloride dissolving but could not recall what the resulting solution looked like.

Interviewer: Okay, do you want to describe the video a little more, your image of it in your head?

LL: …I can’t remember, I don’t think he showed actually salt in millions of forms like this. He just showed what a salt molecule looked like or an Na thingy, it looked like one of them…and then he had, actually, actually I think, they just added water to it and you see water molecules floating around and I don’t know whether they’d split or not, I don’t know but before the water was added, they looked like this.
In interview 2, LL represented an aqueous solution of sodium chloride as separate ions surrounded by water molecules. She did not indicate ion-dipole attractions. She noted that there would be many more water molecules than ions.

In the post-test, she chose the correct representation of aqueous sodium chloride, commenting on the correct orientation of the water molecules, the ratio of water to ions, and the separate ions. In interview 3, she was once again asked to produce a diagram of aqueous sodium chloride before being shown her answer to the post-test. She produced a diagram similar to her original image of sodium chloride dissolved in water, featuring molecules of sodium chloride amongst water molecules (see Figure 4.22). Her water molecules were now represented as linear. The only key feature she seemed to retain was the ratio of water molecules to ions.

LL: Those are my water and these are my sodium chloride and they're bonded together…but there's a lot more of H₂O molecules than sodium chloride.

She was then asked to compare her representation to her answer in the post-test. She felt as if the structure of the question had interfered with her actual image. Her understanding of the orientation of water molecules around the ions seemed to have faded. She did not know when this idea would apply.

LL: …because when you fill something like this out, you see that there's three where they're separated…so you're more likely to think, oh okay it must be between these ones…more similar ones, so I…I don't know.

Interviewer: What about this? …You talk about the molecules facing in certain directions.

LL: Mm, see how you get the hydrogen facing the chloride and these ones facing away from them, from the whichever one it is. I don't know. I don't remember what I've done there.

Interviewer: So this would be more how you'd picture it?

LL: That's how I would picture it but put this in front of me and I'll make a guess, like I don't know.

Interviewer: Okay, so you think that the diagrams have given you some sort of clue as to what

LL: …it kind of draws me away from what I'm thinking…

She was aware that there would be movement at the molecular level.
Precipitation of Lead(II) Iodide

In the pre-test, LL did not provide an answer to the question on precipitation reactions, suggesting a lack of knowledge. In interview 1, she constructed an equation to describe what happens when an aqueous solution of lead(II) nitrate reacts with an aqueous solution of potassium iodide. She described the reaction as the swapping of cations and anions.

LL: Okay, so you’re adding these two together. Right, if I wrote it down I know that…I know that lead would probably, I’m just guessing right that they react with the opposite sign or the opposite valency or whatever it is and so they become different. I don’t know. I don’t know.

She deduced from practical experience that lead(II) iodide must be the resulting solid. She represented both reactants and products as single molecules (see Figure 4.23).

In the post-test, she correctly wrote the equation for the reaction and seemed to have moved closer to scientific acceptability in her response (see Figure 2.24). Her representations were now multi-particulate and a distinction was made between the solid and the solution in the
products, with the solid forming a cluster at the bottom of the container. She correctly identified the solid. In interview 3, she elaborated on her representation by giving the reactants and products more structure (see Figure 2.24), and realised there would be water present in the solutions. She once again imagined that ionic solutions contain molecules of the substance, with none of the molecules separating into ions.

Figure 4.24  LL’s representation of the precipitation of lead(II) nitrate, from the post-test

4.7.2. Interpretation of Chemical Symbolism

This section looks at LL’s ability to represent symbolic notation at the molecular level. These data were collected from the pre-test, interviews 1–4 and the post-test. Molecular representations were probed in interviews 1 and 3 (Sections 4.6.2.1–4.6.2.2), ionic representations in interview 2 (Sections 4.6.2.3–4.6.2.6) and equilibrium in interview 4 (Section 4.6.2.7). For further information regarding the content of the interview questions, see Table 4.3 (page 262) or Appendix C.

4.7.2.1. Symbolic Representations

LL’s initial representation of 2NO₂ was incorrect, even though her description, “two lots of NO₂,” was sufficient. She drew a molecule of N₂O₄. She noticed this error in the first interview.
LL: Without the 2 there, that means there’s one nitrogen atom with two oxygen atoms and the two means there’s two lots of those...so I wouldn’t join them together.

In the post-test, she suggested that the 2 out the front refers to the number of moles of NO₂ rather than the number of molecules.

Consistent with her answer to the first question in the pre-test, she labelled the molecular representation “2NO₂”. She corrected this to “N₂O₄” in interview 1 and answered this correctly in the post-test.

4.7.2.2. **Gas-Phase Reaction**

When shown the first equation for the gas-phase reaction, LL produced a representation showing stoichiometric ratios of each molecule, with reactants and products separated by plus signs. She described the equation in terms of the number of moles of each component. Later discussion revealed that she believed moles and molecules to be synonymous.

LL: Okay, you told me in your explanation that it was four moles of ammonia plus 5 moles of oxygen etc. How does the number of moles relate to the number of molecules?

Interviewer: I don’t understand. What do you mean by that?

LL: Well, here you’ve drawn 4 NH₃ molecules, or does that to you represent 4 moles?

Interviewer: … ‘cause isn’t just one mole that? Like one mole would just be one of them? So then it’s 4 times that one, so you’d get 4 moles.

When shown the equation with the states included, the only change she made was to separate the particles further to represent the gas state.

In interview 2, this representation was revisited. LL was still experiencing difficulty with the relationship between moles, molecules and number of particles at the molecular level. She no longer believed that the equation coefficients revealed the number of molecules.

LL: I know that just like because it, if that just says one, it just doesn't mean one of these…it’s a certain quantity of atoms…but if I was to draw this again, I’d probably draw a little bit more oxygen than…ammonia or whatever that is and I’d draw more water than whatever that is. Do you get me?

Interviewer: Okay, why would you change the numbers you had there?

LL: I wouldn't change the numbers, like but...okay say if I was going to draw this one, I wouldn't just draw four of these and six of them, I would draw lots of them but to look at it, you'd be able to see that there's more water than this.
4.7.2.3. **Strong Acid Solution**

LL had little confidence in her understanding of the label “0.050 M” on the sulfuric acid bottle, and could not give a detailed description of what it meant. She realised that it referred to the concentration of H$_2$SO$_4$ and tentatively proposed that water was the solvent.

LL: I know that with the .05 moles, it's like a type of concentration, like how many of that stuff is in it but I don't know. Is it, like I don't know if I can ask you this, but is there something that helps dilute it to that?

Interviewer: Yep.

LL: Is it water?

Interviewer: Yeah.

LL: …Okay, so basically that's its concentration really.

She represented the solution as molecules of H$_2$SO$_4$ amongst water molecules and commented that molecules should be close together in the liquid state.

4.7.2.4. **Acid/Base Reaction**

LL was unsure what would happen at a macroscopic or molecular level when sodium hydroxide was added to the above solution. She was therefore provided with an equation for the reaction. She described the reaction in terms of the swapping of cations and anions.

LL: These kind of like separate.

Interviewer: …What do they separate into?

LL: Their different structures…

Interviewer: Okay, so they split. What do they split into though?

LL: More simpler…isn't that like a minus and that's a plus…they'd go with the opposite signs, do you get me?

Interviewer: Mm

LL: And so that's how come you get your water and your sodium sulphate…and so this pairs off with that and that pairs off with that and…they're all soluble so that's how come they don't precipitate.

She was then asked to draw a representation of the products. She drew molecules of Na$_2$SO$_4$ dispersed among water molecules.
4.7.2.5. Precipitation

When shown a “molecular equation” for the precipitation reaction between potassium chloride and lead nitrate, without the states included, LL produced a diagram showing the reactants and products represented as molecules (see Figure 4.25). Stoichiometric ratios were not considered and water was not included. She identified lead(II) chloride as a precipitate, and hence drew a cluster of lead(II) chloride molecules at the bottom of the representation. She did not feel that it was possible to represent the relative numbers of each at the molecular level.

When shown the same equation with the states included, this student did not wish to change her representation. She made no comment about the “aqueous” states.

On being shown the full ionic equation for the precipitation, LL persisted with her original representation. She did not even consider separating the appropriate reactants and products into ions. She felt that equation 2, the “molecular equation” with states given, best represented the molecular level. This choice is most consistent with her representation showing molecules of each substance. She felt that the third equation was too long and confusing.

![Figure 4.25](LL's representation of the equations showing the precipitation of lead(II) chloride)

4.7.2.6. Complexation

LL seemed to recall this reaction, suggesting that you would see a precipitate form and then redissolve on addition of ammonia. Consistent with her other representations of ionic solids, she represented the solid copper(II) hydroxide as closely packed copper hydroxide molecules. She was able to construct an explanation for what happens at the molecular level when ammonia reacts with the hydroxide precipitate. She described it as an interactive process,
whereby ammonia pulls the copper from the lattice. At first, she was confused about where the hydroxide ions came from, then realised they were left behind when the ammonia removed the copper. Her representation of the products is shown in Figure 4.26. The diatomic species are hydroxide ions and four ammonia molecules are attached to each copper.

LL: Okay, pour ammonia down onto it and it clings to the copper and just like pulls it away and the… Doesn't ammonia have hydroxide ions in it? Something like that, I don't know…

Interviewer: Is that where you think those came from?

LL: Yeah.

Interviewer: Which part of the, which part of this is pulled away by the ammonia?

LL: The copper

Interviewer: So what does that leave?

LL: That leaves… Oh yeah! It leaves the hydroxide… by itself.

When shown the same equations with hydrating water molecules, she added water to her representation of the products of equation 1. She claimed that she understood there would be water molecules there because the solutions were aqueous. She was unsure whether to represent the extra water molecules on the copper ammonia complex attached or unattached.
4.7.2.7. Equilibrium Reactions

**Equilibrium**

LL’s first description of an equilibrium reaction included the idea of reversibility. She suggested that if you mix the reactants, you will form the products, and if you mix the products you will get the reactants.

She was asked what the term “at equilibrium” meant. She understood that both the forward and reverse reactions occur at equilibrium but at this stage did not elaborate on how that would occur.

LL: During equilibrium, these reactions occur, they keep going back and forth like that during the equilibrium.
Gas-Phase Equilibrium

LL’s concept of equilibrium was further probed in relation to the gas-phase equilibrium reaction. She saw the reaction as a migration of an oxygen atom from ClNO₂ to NO to produce CINO and NO₂ and vice versa. She represented this process as shown in Figure 2.27.

LL: There’s one oxygen atom that keeps going back and forward between…a and b, these things here [ClNO₂ and NO]… This’ll [O] move across to here [NO] and it’ll form that [NO₂] ’cause the oxygen atom’s gone there…and then they just keep switching back and forth like that, so sometimes you have [the reactants] and sometimes you have [the products].

Further discussion revealed that she perceived this reaction in multi-particulate terms, with some reactants going to products while some products were going to reactants.

Interviewer: Okay, do you just picture it as like the pair exchanging back and forth?

LL: Mm.

Interviewer: Okay, so at any one time in the solution, you would imagine that there are just either these or those?

LL: What do you mean by that? I don’t understand.

Interviewer: …Say if we took a snapshot, would you only have one pair?

LL: Nope, because there’s hundreds of different molecules in there doing different things…do you get what I mean?

Interviewer: Yeah

LL: So some of them might be doing this, some of them might be doing that.

She did not know what the relative amounts of reactants and products would be but she guessed it would be half products and half reactants in the solution. She was not aware of what the equilibrium constant represented.
LL was then asked to predict what would occur if extra NO was added to the reaction vessel. She proposed that you would get less products, but after thinking on it further, suggested you would get more products because more reactants would produce more product. She had little confidence in her response.

LL: So chloride nitrate \([\text{ClNO}_2]\), all of them will give off their other…oxygen atom to all of these \([\text{NO}]\) so there’ll be more of this stuff and more of this stuff.…oh, didn’t I just say less of it? See, I don’t know.

Interviewer: You’ve changed it to more, yeah.

LL: Yeah, so I suppose yeah, there would be more product.

**Weak Acid Equilibrium**

LL envisaged the dissociation of boric acid as the passing of a hydrogen ion back and forth between a boric acid molecule and a borate ion. She was aware that there would be a mixture of reactants and products present at any one time. She did not know what the acid dissociation constant was, however, and therefore did not indicate the relative amounts of reactants and products.

LL: What happens is, these are the [hydrogen] here and this [hydrogen’s] bouncing from this partner. This one becomes this and it keeps going back and forth…

Interviewer: Okay, so at any one time in the solution, what have you got in there?

LL: At any one time? It’s not just this and it’s not just that. It’s a mixture of all of them.

Interviewer: Okay, yep… Do you know what the…\(K_a\) value in this case means?

LL: Okay. Is it, I’m going to guess. No, I don’t know… I really don’t know. Something to do with an acid, I’m guessing, because it has a little “a” there.

She was then shown an equation for the reaction of boric acid with water. She produced a new drawing for the reaction that showed a hydrogen ion being exchanged between a boric acid molecule and a water molecule. She described this as an interactive process whereby water came and physically pulled the hydrogen from the boric acid.

LL: Okay, what happens is, this water comes along and it kind of pulls this hydrogen atom to there…and it becomes \(\text{H}_3\) and there’s whole heaps of reactions happening, just this hydrogen going back and forth, forming different molecules all the time, not all the time, just goes like this or that, this or that.
She stated that she thought this reaction was the same as the last, and yet represented it differently at the molecular level.

### 4.7.3. Interpretation of Macroscopic Phenomena

This section looks at LL’s ability to explain macroscopic phenomena. These data were collected from interviews 3 (Sections 4.6.3.1–4.6.3.2) and 4 (Section 4.6.3.3). Information regarding the content of the interview questions is given in Table 4.4 (page 263).

#### 4.7.3.1. Nail-Polish Remover

LL provided a simplistic but acceptable explanation of what might occur when a jar of nail-polish remover is opened. She suggested that molecules of ethyl acetate come out of the solution and eventually reach your nose. Her representation of the process is given in Figure 4.28.

#### Figure 4.28  LL’s representation of the evaporation of nail-polish remover

LL: Maybe some of the molecules just, I don't know, just, I couldn't tell you. My guess is that they just float away and they just kind of waft through the air, but only because I can smell them.

Interviewer: ...What do you think might actually get to your nose?

LL: The fumes from the...whatever the chemical's called.

Interviewer: Okay, it's ethyl acetate...so that's the formula for ethyl acetate, so if you've got ethyl acetate in there, what part of that do you think would actually get to your nose?

LL: I know nothing about this but I'd probably say all of it.

Interviewer: The whole molecule?

LL: Mm.
4.7.3.2.  Precipitation Reaction

LL predicted that, on adding solid potassium iodide and solid lead(II) nitrate to a large container of water, a delayed reaction would occur. The delay would be caused by the fact that the particles would initially be separated and would take some time to move through the solution and meet. She did not elaborate on what she would see when the reaction occurred.

After viewing the reaction, she successfully identified the products of the reaction.

LL:  …Potassium iodide is reacting with the lead nitrate…it's becoming lead iodide and potassium nitrate… They're just reacting together.

She attempted to describe the process by which this occurs.

LL:  …You drop them down here and they're separated at first and then they move along with the water. They're carried along by the water.

Interviewer:  What moves along?

LL:  The lead nitrate and the potassium, I'm guessing they get carried along through the water…just moves through the water and then they kind of meet half way and then they just react with each other.

Interviewer:  Okay, why do they move through the water?

LL:  Because the H₂O water molecules are just, they're not, they're moving so they kind of get carried along with the…water molecules.

She did not provide a description of the reactants or products at the molecular level.

4.7.3.3.  Redox Reaction

LL represented solid copper as closely packed copper atoms. She represented silver nitrate as molecules dispersed amongst water molecules (see Figure 4.29).

LL:  Because it’s a solid, all the…atoms are compacted closely together and because it’s a solution and it’s aqueous, it’s got…all liquid molecules around it and it’s not as compacted together and they just pass…each other…

She predicted that she would see bubbling when copper was reacted with silver nitrate. On seeing the reaction, she drew and explained what she thought might be occurring at the molecular level (see Figure 4.29).
LL: I’m just drawing one layer of copper because it takes forever. We get our silver nitrate comes along like…it is NO₃ isn’t it? Okay…comes along and I’m guessing that the copper pulls, I don’t know, the nitrate towards it and then that kind of just, the silver just goes away, just floats on top of that, I think.

Her representations of the products of the reaction are shown in Figure 4.29. She predicted that silver and copper nitrate would form but her interpretation of this at the molecular level was somewhat distorted. In line with to her description reported above, she saw the nitrate being attracted to the copper surface, where it was deposited and bonded with copper to produce copper nitrate. This then resulted in silver being left on its own, producing the grey substance seen in the reaction.
Figure 4.29   LL’s representation of the reactants, products and mechanism of the redox reaction between solid copper and an aqueous solution of silver nitrate
4.7.4. **Interpretation of Molecular Representations**

This section looks at LL’s ability to interpret and critically analyse molecular representations. These data were collected from interviews 1 (Section 4.6.4.1), 3 (Section 4.6.4.1–4.3.4.2) and 4 (Sections 4.6.4.3–4.6.4.4). The structure of this section and the content of the interview questions are elaborated in Table 4.5 (page 263).

4.7.4.1. **Modelling**

4.7.4.1.1. **Interpretation**

**Models of Water**

LL had a preference for the space-filling representation of a water molecule. She could not really explain why she preferred the representation, but just felt “you just look at it and you can just visualise it”. She could not elaborate on why she thought it was easy to visualise. Later, she revealed that the animations shown in lectures may have influenced her preferred model, perhaps rendering the space-filling model easier to visualise.

LL: [The lecturer] puts it on the…oh what’s it called, power point, I don’t know. What’s it called where he brings it up on the screen and he shows you the, how it moves and that? Yeah, they have all those ones on that and you can actually see it.

Interviewer: Okay, are you talking about those little video representations?

LL: Yeah, the video things he plays, yeah. You can actually see all the water molecules and stuff… I understand that more than I would if these were floating around.

When describing what she thought of some of the other models, LL tended to concentrate on the ease of representing a substance using the model. She felt that the space-filling representation was most appropriate for representing small molecules, but for larger more complex molecules, a symbolic or ball-and-stick representation would be more appropriate. This suggests an understanding that models are purpose-built.

LL: For a more, for a simple one, that would be a good one. Like but if you had say one with like seven joined to it, you wouldn’t be able to see it properly in a diagram like that, so one of these ones would be more appropriate. But for simple ones, that, you can see it, like it’s easy to understand.
She did not like the Lewis structure because she felt it was too complicated, especially if you were representing complex molecules. She admitted though that it would be useful to show bonding in the molecule.

LL: This one, it’s just too much, there’s too much information…you can see which electrons they’re sharing and whatever so…

Interviewer: But do you think that that might be useful for some purposes?

LL: …Yeah for some, because some people might not understand, you know, how they bond or something…so that would be okay but when you’ve got lots and lots of different ones coming off…that would be the wrong one to do.

She did not like the 3D ball-and-stick representation because it would take too long to draw and did not have each atom labelled.

LL: …If you were drawing it like, it’d take longer ‘cause you’ve got to draw all the sticks and everything…basically these ones are more convenient to draw when you have to draw at the molecular level or whatever… These aren’t labelled either…

She did not understand representation A.

LL did not feel that the 3D VisChem representation of a water molecule was an accurate description of a water molecule. She was able to identify some of the non-correspondences between the model and target. She believed that the hard surface appearance represented the outside of the electron cloud and that the colours were used to aid understanding of the model.
Interviewer: Is there anything about that representation that you think might not be exactly what it looks like then?

LL: I don’t think it’d be like a ball…like two balls connected to it. I think it’d be more like…

Interviewer: You think it’s probably not a hard structured ball?

LL: No, it’s not a hard structure, it’s, I wouldn’t have a clue.

Interviewer: Do you know anything about the structure of each of those atoms?

LL: How they’re made up?

Interviewer: Yeah.

LL: Well I know how you’ve got like the nucleus and then, and that’s made up of protons and neutrons and then you’ve got like the electron cloud around it, so yeah.

Interviewer: So how does that electron cloud fit in with this sort of…round ball structured thing?

LL: Well you’d have like, I’m assuming that the edge of the electron cloud would be a circle. Like that’s where it finishes…

Interviewer: Okay, so it’s sort of like an outer surface?

LL: Yep.

Interviewer: Okay, and what about the colours?

LL: I don’t, I wouldn’t…do I think they’re the real colours? No, no, I think they just, it just make it easier for people to understand, the different colours.

Models of Solid Sodium Chloride

LL favoured the physical 3D model of sodium chloride because “you can actually see it”. She disliked E because it did not explicitly show the bonds. She felt model C was too complex and model D was too limited in the amount of information displayed, only showing the ratio of ions. She noted that B showed vibrations, but not bonding or three-dimensionality.

She therefore realised that different models portrayed different features but did not seem to see this as serving any purpose. She expected a certain level of complexity from a “good” model – it needed to portray a certain amount of information but still remain simple.

4.7.4.1.2. Multiple Modelling

LL accepted the use of different models because she felt that different models were required for different learning styles.
LL: Because different people understand like differently… People have different ways of understanding different concepts…I mean, see this one works for me but someone else might understand it more looking at that one.

Her earlier comments (Section 4.6.4.1.1) also hinted at an understanding of the use of different models for different purposes.

4.7.4.1.3. Development

This student, although lacking in confidence, showed a fairly developed understanding of modelling. She suggested that no-one has actually seen atoms and molecules because they are too small, but that our images of them have been constructed on the basis of mathematical data, for example.

Interviewer: Do you think that anyone has actually ever seen atoms or molecules?

LL: I’m guessing not because… just how they describe it’s so small because I remember saying, I remember hearing or reading it that in just one grain of sand there’s more atoms than on the beach …so I’m just guessing that you won’t be able to see it…they’ve just through, I don’t know, mathematics and stuff, they’ve just been able to work out what they look like.

Interviewer: Okay, yep, well how close do you think they’ve got with this representation? Do you think that that would be what it actually looks like?

LL: I wouldn’t have a clue.

Like HL, this student evaluated the “accuracy” of the animation of an aqueous solution of potassium fluoride based on a comparison with her own mental model. She felt that the portrayal of movement and distance between particles were adequate for a solution.

Interviewer: How close do you think that this animation is to what the molecular world of an aqueous solution would…

LL: Pretty close.

Interviewer: What makes you think it's pretty close?

LL: Because they're not, they're not like air, they're not just going everywhere, but they're not compacted together. You see, they're still moving around and they're fairly close… They're just kind of rumbling all over each other.

LL was unable to make a suggestion as to how representations of solutions were developed. Her responses to why representations of solutions were first developed, and why animations were designed to portray these ideas, both focused on helping learners understand.
Quote 1:

LL: To help better understand, I don't know
Interviewer: Okay, to help better understand. To help who better understand?
LL: People wanting, not wanting, but having to learn, I don't...
Interviewer: Okay, so what do you think is the purpose of producing animations like this to?
LL: For people like me.

Quote 2

LL: When they're saying that this atom reacts with this atom and this is what happens, I'm like...like I know what they're talking about but I can't, I don't know how it happens... So these animations, it shows you how...so it makes it a lot easier to understand.

She felt that her lecturer wanted her to learn these ideas so she would be able to visualise what happens at the molecular level. This then enabled her to understand these processes.

LL: He wants us to actually visualise what's happening at a molecular level...because then we'll just probably better understand what he's going on about.
Interviewer: Okay, do you think that these images or the visualising of these images is any use to you?
LL: Mm.
Interviewer: In what way?
LL: I understand what's happening.

LL felt that the ideas shown in the animation were transferable to all other aqueous ionic solutions and wasn’t sure what might convince her otherwise. However, she felt as though her understanding was simplistic, although relevant for her level of study, and that models of aqueous solutions had probably been developed further. This suggested that she was open to the possibility of having to learn more complex models as her study progressed. She was not aware of any other models of ionic aqueous solutions.

4.7.4.2. Criticism of Molecular Diagrams and Animations

Diagram 1: Dry Ice

Although LL thought this was a good representation of dry ice at the molecular level, she was able to make a couple of relevant criticisms of the diagram.
LL: …This one’s good. I like that because it shows you close up what actually…what dry ice is made out of and it shows here, it shows you in more depth each, those molecules up here in depth.

She pointed out that the molecules should be more closely packed and that the vibrations of each molecule could have been shown.

Interviewer: Do you think that students might develop any misleading or incorrect idea from that representation?

LL: Maybe…because the molecules are more compacted together. That looks like they’re floating around…and you could’ve drawn a bit of the vibrations around them.

**Diagram 2: Saturated Solution**

Like LH, this student was unable to critically analyse this diagram because she could not interpret what it represented, perhaps due to a lack of relevant prior knowledge.

**Diagram 3: Electron Transfer**

LL felt that she understood the diagram of electron transfer from a sodium atom to a chlorine atom, suggesting that it showed “how they’re joining together” and “how atoms share electrons”. She made no criticisms or suggestions for improvement of this diagram. She felt that it would not mislead novice students in any way.

**Diagram 4: Precipitation**

Once again, LL did not point out any misleading features in this diagram. She felt it was comprehensible and was unlikely to mislead students.

LL: …That’s pretty good. That’s understandable.

Interviewer: You don’t think there’s any features of it that might mislead students?

LL: Nope, ‘cause it shows you here that that’s what lead nitrate looks like, potassium iodide and that’s what it looks like when you join the two together. You can see which ones go with like which. You can tell the lead and the iodide go together, whereas the potassium and the nitrate just float around freely.

**Animation: Dissolving**

LL was able to make sense of this animation.
LL: The water’s coming down and they, some of them, attach themselves to the sodium, some of them attach themselves to chloride, and they pull them away from the lattice and they just kind of go away and float around somewhere else.

Her only criticism was that she thought it was too complex. She suggested introducing simpler animations first, then building up to this one.

*Quote 1:*

> LL: …It's good but I didn't understand what was going on first, it was a bit, I think there was too much to focus on at first

*Quote 2:*

> Interviewer: Do you think that students might develop any misleading or incorrect ideas from this animation?
> LL: Probably not.
> Interviewer: So you’d be quite happy to use that to teach someone about sodium chloride dissolving?
> LL: But probably not…make it so complex at first.
> Interviewer: Okay.
> LL: You start with a something more smaller and then something like that.

### 4.7.4.3. Analogical Modelling of Equilibrium

**Analogy 1: Soccer Game**

LL seemed to struggle to interpret this analogy appropriately. Misinterpretation resulted from her attempt to relate the analogy to the gas-phase equilibrium system discussed earlier in the interview.

She appeared to understand how the idea “their identities are different” corresponded to an equilibrium reaction, although in her explanation she did not specify which component of the analogy she was actually referring to.

> LL: …When it turns into here it doesn’t necessarily mean that this will give back its oxygen atom to that molecule that it took it from… It could be floating along and it can see another one that looks like this and it could pass it, the oxygen atom back to a totally different person.
This student seemed to have difficulty in directly relating the description in the analogy to her concept of equilibrium. The following excerpt describes the process via which an oxygen atom is passed back and forth between reactants and products. The student took this idea from the gas-phase equilibrium reaction discussed earlier in the interview. It seems that she may have likened this to the movement of the soccer ball in the game of soccer, although she didn’t explicitly state this.

LL: Say for example this is player one and it swap s, they kind of, that passes it on and that becomes number two and this kind of becomes the main centre of attention, and that goes off and then that one say passes another oxygen atom, no, yeah it becomes that, gets two oxygen atoms and that kind of, once its passed it off that kind of goes out of the picture and this becomes the main person and then it just keeps going like that.

She was unsure what the players on the field or on the bench represented. She imagined that all the particles present would be on the field, that is, contained in the one reaction vessel. She suggested that the sentence “there is no requirement that the number of players on the field and the bench be equal” referred to the fact that there is a constant number of particles present.

LL: Nothing changes, all the molecules, there’s exactly the same amount of atoms, same number of, oh, yeah same number of molecules, nothing changes, it’s just the oxygen atom, oxygen atoms just move around a bit.

The confusion continued when she attempted to interpret the statement “there is no requirement that the number of players on the field and the bench be equal”. She proposed that this meant there could be more of one reactant than another.

She felt that the most misleading component of the analogy was the statement “an old player must leave”. She did not understand where this player would go, or by her understanding, why a particle would be excluded from the reaction vessel. In her defence, a limitation of the analogy is certainly that the reactants and products are compartmentalised. LL could not see the correspondence because her notion of products and reactants all in one vessel was correct and did not match the analogy.
Interviewer: Could you draw any incorrect conclusions about equilibrium from this analogy?

LL: …probably an old player must leave.

Interviewer: Okay, why, why do you think that’s…?

LL: …Well, where does it go? Like, I don’t know. Does it disappear? … See, ‘cause you said an old player must leave so that’s like…once…this thing here passes its oxygen atom on here, you say it leaves and this one becomes a new player… So then, what happens to this, it just, it doesn’t just leave. Does nothing else happen to it?

Interviewer: Okay, so do you see what’s happening on the field as being everything that’s happening in your reaction mixture?

LL: Yeah.

**Analogy 2: Juggling**

LL failed to relate this analogy to the process of equilibrium.

**Analogy 3: Dancing**

LL presented a novel interpretation of the dancing analogy in an attempt to relate it to her mental model of the equilibrium process derived from the gas-phase equilibrium example (Section 4.6.2.7). She seemed to see the equilibrium as similar to that depicted in Figure 4.30 [a] rather than the intended mechanism shown in Figure 4.30 [b].

LL: …When they're talking, dancing alone, they're talking about…I’m guessing the oxygen atom’s a female, from that so, see how it’s got the zero two…two oxygen atoms here, that means it’s a male and a female dancing together and then it swaps…this passes that onto that one, so this person’s now dancing alone and this one now has got a female partner with it…And every time one couple splits, which means oxygen splits away from the molecule and goes to another one, that’s what it means, another couple begins dancing together.

![Figure 4.30](image)

*Figure 4.30* Equilibrium mechanisms to describe the “dancing analogy”. [a] LL’s interpretation of the analogy [b] Intended interpretation of the analogy.

One concept that she did seem to grasp was the interactive nature of the process.

LL: This one, the male comes up to here and kind of tries to pull the oxygen atom away from the other molecule.
Like other students, this student felt that this analogy was the most appropriate for describing chemical equilibrium because she could most easily “relate...that situation to an equilibrium”.

4.7.4.4. Interpretation of Molecular-Level Animations

Ice Melting

LL was able to identify the animation of ice melting. She pointed out the structured lattice and described the change in movement upon reaching the melting point. Her preconception of solids as being closely packed seemed to influence what she observed in the animation.

LL: Well you can see that they’re all in a nice pattern...so they kind of look like solids, they’re closely packed together and then they start vibrating and then they start just going everywhere so. Is it ice?

Interviewer: Mm hmm. Okay, so if that’s tightly packed, why can we see right down the centre there?

LL: I don’t know. I don’t know.

Interviewer: So what’s happening now? You said it’s vibrating.

LL: Yep and now they’re just going to move everywhere...

Interviewer: So what’s happened?

LL: It’s melting.

Water Evaporating

LL seemed more confident in her identification of this animation. She interpreted the movement of the water molecules to mean that liquid water was represented. She believed the water was being heated because it was being converted into a gas at the surface. She was able give a vague explanation, in terms of attraction, for why some water molecules return to the surface. She did not notice this feature before her attention was directed to it.
LL: I know. I know what it is! Is it water that is being heated and the molecules are on the top...’cause see they’re moving around heaps more easily, so it suggests it’s water and some at the top, they’re just rocketing off, turning into a gas and just go off...

Interviewer: ...Are there any minor details that you notice?

LL: Nope.

Interviewer: Okay... Watch what happens to this one. What did you notice about that one?

LL: Coming back again?

Interviewer: Yeah, why would it come back again?

LL: I don’t know.

Interviewer: No ideas?

LL: Well, maybe one of its oxygen atom is attracted to H₂O molecule...there’s attraction there, so it was brought back again.

**Sodium Chloride Dissolving**

The student seemed to make some sense of what was happening in the animation of sodium chloride dissolving, but limited understanding of the chemistry prevented her from more fully interpreting it. She pointed out many important features including the vibrations, the structured lattice, water molecules moving in and separating the particles, and the direction of the water molecules towards the particles. She could not explain why the water molecules were attracted in such a way.
LL: Okay, we’re looking at a solid that is being immersed…we’ll say was sitting in the bottom of a beaker and water has been added to it and what they’re doing is, the water molecules are coming down and…separating, the greens ones and the grey ones.

Interviewer: Yeah, so what do we call that process?

LL: I couldn’t tell you.

Interviewer: Okay, do you know what the green and the grey ones are?

LL: …Could it be sodium chloride?

Interviewer: Mm hmm… Are there any other details there that you wanted to point out?

LL: How they’re all shaking all the time, even when they’re a solid…They’re in a pattern. Isn’t it called a lattice?

Interviewer: It is. Do you notice anything about the water molecules?

LL: The way their…hydrogen atoms…facing the molecule, the atom.

Interviewer: Yeah, what does that tell you about it?

LL: I don’t know. It attracts. I don’t know. I couldn’t tell you. I don’t know why they face it like that.

Interviewer: Okay and what’s that one doing?

LL: The hydrogen atoms are facing outwards instead of inwards.

Aqueous Solution of Sodium Chloride

Once again, the student was able to identify the animation. She pointed out the fact that there are many more water molecules than ions; a feature she consistently mentioned throughout the year in relation to her image of aqueous sodium chloride. She also mentioned the sodium and chloride coming together, then separating again, attributing this to an attraction between the particles that could be overcome by water molecules. She did not mention the hydration by water molecules.

LL: I’m guessing that’s sodium chloride dissolved in an aqueous solution.

Interviewer: Mm hmm. What details would you point out there?

LL: That there’s a lot more hydrogen. No, a lot more water molecules than there is the sodium and chloride. The sodium and chloride joined together for a minute, then they separated again.

Interviewer: Why would they do that?

LL: I don’t know, a little bit of attraction but then the water molecules stole them back off each other again.
Precipitation of Silver Chloride

Like other students viewing this animation, LL thought that the sodium chloride lattice was being reconstructed.

LL: Obviously, the water molecules are taking the sodium chloride back and they’ve got some other new blue thing but I don’t know what it is.

She therefore understood that a solid lattice was being formed. The only explanation she could come up with was that water was being evaporated off. She could not explain the presence of the nitrate ion.

LL: They’re taking it back to the lattice…but they’re playing with something else now, ‘cause it had a blue thing before.

Interviewer: Right. Yeah, so, they’re building up a lattice?

LL: I don’t know. They’re taking them all back, see he’s taking these, see putting them back together and they’ll take ‘em back to the main thing…lets it go…and then they’ve found a new thing to play with over there.

Interviewer: Oh this thing…so you don’t know what that is either?

LL: Nup.

Interviewer: Under what circumstances would they be putting a lattice back together or building up a lattice? Can you think of any…?

LL: If it’s…I don’t know.

Interviewer: So you’re getting some sort of solid building up in solution there. Can you think of any examples where that’s happened in the lab?

LL: …Could they be evaporating the water molecules? I don’t know.

Interviewer: They could be, but that wouldn’t explain the blue thing.

LL: I don’t know.

Redox Reaction of Copper with Silver Nitrate

LL was unable to identify this animation without input from the interviewer. She noticed a few details, including vibrations of the copper lattice and the formation of the silver lattice. She related the formation of the silver solid in the animation to the actual experiment conducted earlier in the interview, although she did not realise that the animation was showing the same reaction. She once again noticed the presence of a nitrate ion but could not identify it.
LL: Okay, obviously it’s…some atom connected to…the water molecules, comes down. That solid kind of forces that grey thing off it and I’m guessing it would form like a, see the layer on that? [refers to earlier experiment], like a layer on top of that.

Interviewer: Yep. So what do you think the yellow might be?

LL: …I don’t know. I couldn’t tell ya.

Interviewer: Did you notice what happens to the yellow balls?

LL: They’re vibrating, they’re moving.

Interviewer: Mmm

LL: Oh, they’re taking them too…Oh, I didn’t see that. No, I don’t know what this is. See I don’t know what that blue thing is…Is it a nitrogen, the blue?

Interviewer: Blue’s nitrogen. Yeah.

LL: I don’t know…

When she was told what the animation represented, she was able to make some sense of it. She was able to identify each of the substances present. She related the formation of the silver lattice on the surface and the presence of copper ions in the solution to her observations at a macroscopic level.

LL: Is that the copper, that’s just copper?

Interviewer: The yellow? Yeah.

LL: The silver is silver nitrate. No, not the silver nitrate. Just the silver…there goes the nitrate…Here the water molecules also pull a, a silver off the, no a copper. I don’t know. I don’t know. I couldn’t tell ya. I don’t know.

Interviewer: You’re always going so well and then you stop. So how does that bit relate? You said that before.

LL: That’s the yucky stuff on top of it.

Interviewer: Yeah, and so what’s happening to the copper?

LL: The copper is being pulled away by the water molecules and that’s kind of in the solution around it.

Interviewer: Okay so like, what evidence is there from the experimental work that that’s happening?

LL: Colour of the solution? The colour of it.
4.8. Discussion

Although all four students in this study had similar post-test scores, within the range 18 to 21, the following analysis outlines differences between the four students in terms of the scientific acceptability of their images, stability of those images, their ability to apply ideas, and their ability to interpret animations. It demonstrates differences in consistency in the use of mental models, deep thinking and conceptual understanding and, where possible, attempts to link these differences to prior knowledge and disembedding ability.

4.8.1. Development of Imagery

4.8.1.1. HH

HH made some progress with his images of water and sodium chloride through the course of the year. Most of these changes occurred in the first few weeks of semester, when the ideas were taught. These changes seemed stable, and the resulting mental models served as the basis for his interpretation of symbolic, molecular and macroscopic representations.

HH’s descriptions suggested that he worked from concepts rather than mental images. He generally spoke of non-visual concepts such as “energy” or “excitement” and was more reluctant to mention movement. This was also demonstrated by the fact that he did not pick up on the idea of vibrations in solids (ice and solid sodium chloride) until later in the year, when he acquired the notion that motion ceases only at absolute zero (see pages 270 to 271). This “observation” is supported by the fact that he was identified as a “verbaliser” on the CSA questionnaire (see Chapter 3, Sections 3.5.2 and 3.7.1.4).

This student’s basic ideas regarding liquid and gaseous water remained fairly consistent throughout the year, except for the abandonment of auto-ionisation in liquid water (see pages 268 to 269). The same effect was noted in the results presented in Chapter 2, which suggested that exposure to VisChem animations might cause some students to retract ideas of hydrogen bonding and auto-ionisation in liquid water due to powerful images featuring only water molecules. HH’s image of solid water had improved by interview 1, with the inclusion of structure and hydrogen bonding, and later with the addition of vibrations (see page 270). His mental models of liquid and solid water were not refined enough to enable him to come up
with an explanation for why water expands when frozen (see page 270). HH felt that VisChem animations had helped with his ideas about the states of matter.

His ideas of solid sodium chloride remained excellent and fairly consistent throughout the year, although he did not express a knowledge of vibrations until interview 3 (see page 271). He felt that VisChem animations had served to confirm his ideas on ionic solids. His understanding of aqueous solutions was highly refined by interview 1 (see page 272). He had also developed an interactive model of the dissolving process from viewing the relevant VisChem animation. His ideas regarding precipitation were correct and consistent throughout the year (see page 272). He was aware of all the relevant details but always resisted drawing the structure of the precipitate and water molecules, and insisted on representing solutions in beakers with water levels indicated with a line. He identified drawing in laboratory classes as helping to confirm his ideas.

4.8.1.2. HL

By the post-test, the mental images of HL had developed considerably, but the inconsistencies evident in these images over time and the instability of his mental models cast doubt on how deeply these ideas were learnt. In applying these mental models, described in Sections 4.72–4.74, HL often seemed to struggle mentally between co-existing scientifically acceptable and alternative mental models of phenomena, for example, whether or not ions in solution separate or form molecules.

HL’s images of liquid and gaseous water showed an interesting and inexplicable progression through the year (see Figure 4.6, page 305). Simply looking at his responses to the pre- and post-tests suggests that the images improved with the development of ideas such as hydrogen bonding, movement and collisions. In interview 2, however, he represented atoms of hydrogen and oxygen instead of discrete water molecules. For liquid water, this representation was inconsistent with his notion of water molecules in solutions. The student could not identify what caused these oddities in his mental imagery, as he believed that he had developed all his ideas regarding the states of matter in high-school chemistry. For solid water, he progressed from an image showing atoms of oxygen and hydrogen, interlinked, with no discrete water molecules, to the correct model showing discrete, vibrating water molecules in a structured lattice. He did not express this latter image until the post-test. When and how
he developed this correct idea is a mystery, insofar as he once again attributed the development of the image to high-school chemistry. This student was unable to use his mental models to construct an explanation for why water expands when frozen.

HL’s mental model of solid sodium chloride may have improved slightly over the year but his basic image of a closely packed structured lattice remained consistent (see page 307). In interview 1, he revealed his knowledge of the vibrations of ions and he retained this idea through the year. In early interviews, it was difficult to tell if he believed there to be atoms or ions in the solid. By the post-test, he seemed to have resolved this issue. Early in the year, he seemed to express the misconception that ionic bonds only occur between ions that exchanged electrons in the process of forming the bond. There was some evidence that he had developed the correct conception of bonding in ionic solids by interview 3. His conception of an ionic solid appears similar to one described by Taber (2001):

“Tajinder fitted his understanding of the ionic bond to the nature of ionic solids by supposing that the ions were equally attracted, though not equally bonded, to their neighbours.” (p. 745)

HL’s image of aqueous sodium chloride improved through the year, but did not develop fully (see page 310). He was initially aware of the idea of separate ions in solution, and added to this the notion of ion-dipole forces of attraction. He perceived the particles to be moving. The number of water molecules he imagined surrounding each ion increased with each subsequent interview, but never reached six. He also underestimated the amount of crowding in the solution and the ratio of water molecules to ions, and hence never chose the “most correct” representation in the questionnaire. Apart from these ideas, his image was adequate. He felt that drawing in laboratory classes and the animation of sodium chloride dissolving had helped to improve his image.

HL’s understanding of precipitation reactions evolved through the year, but he experienced much confusion and uncertainty about how to represent the molecular level (see page 314). His prior conception that the reaction involves merely the “swapping of partners” between two molecules, to produce two new molecules, seemed to dominate his thoughts and inhibit his development of the correct idea. This was most noticeable in the final interview in which he could not decide whether to pair up ions in the reactants and products and needed
prompting to propose a scientifically acceptable image of the precipitate produced. It may be that he was in the process of moving from the incorrect prior image to a more scientifically acceptable model.

4.8.1.3. LH

From a low level of prior knowledge, LH showed extensive progress in the development of her images over the period of the study. Many of these improvements developed during first semester, prior to attending interview 2. Some of the ideas she developed seemed to be incompletely integrated into her mental model, however, for example, the ion-dipole forces in solutions. These ideas were often did not recalled spontaneously.

LH claimed to have no images of solid, liquid and gaseous water when starting university. She did, however, have a basic understanding of the differences between solids, liquids and gases. By interview 2, she had applied these ideas to water in the three states to produce reasonable images: liquid water as close, moving particles; gas as more widely spaced moving particles; and solid as closely packed, vibrating particles (see pages 343 to 345). She carried these images to the post-test. Her mental models did not enable her to explain why water expands when frozen. She identified drawing and seeing VisChem animations as helping to improve her imagery.

LH’s image of solid sodium chloride showed enormous progress from pre-test to post-test but interviews revealed that she lacked confidence in different aspects at different times during the year (see page 346). By interview 1, LH had moved from the incorrect image of solid sodium chloride having discrete molecules to a more correct model featuring closely packed particles, vibrating. She maintained the idea of vibrations for the duration of the study. In interview 2, her ball-and- stick representation demonstrated her understanding of the structured nature of the lattice. She revealed, in discussion, a correct understanding of the bonding. She was less sure about the close packing of the molecules, however, perhaps due to the influence of the ball-and-stick model. Her image had not developed further by the post-test. LH conceived that pairs of ions, the charges of which are balanced, make up an ionic solid, but believed the bonding to be consistent throughout the lattice. Her conception is reminiscent of that described in Chapter 2, Section 2.2.3.3.3, under the heading “ions not
molecules”. LH felt that producing drawings of the molecular level and exposure to VisChem animations had influenced the development of her image.

LH’s images of aqueous sodium chloride (see page 349) showed some inconsistency over the year, seeming to reach its peak at the post-test, soon after which the image would no longer be directly assessed by exams in the subject. Her initial image was one of “free” sodium and chloride ions in aqueous solution. By interview 1, she had added the ideas of hydration and ion-dipole forces. She attributed this development to drawing in laboratory classes. Interview 2 revealed that she had not fully integrated these ideas into her mental model, as she produced a representation with hydrated ions without orientating the water molecules; she returned later to add this feature. In the post-test, she demonstrated a thorough knowledge of the key features of aqueous sodium chloride and interview data suggested this was a dynamic image. When asked to produce her own representation in interview 3, she reverted to her original conception and only recalled recently learnt ideas after being shown her response to the post-test. It is possible that images in the post-test triggered her ideas about ion-dipole attractions. Although she was aware of these ideas, they did not seem to be recalled automatically with her image of aqueous sodium chloride.

LH initially had no image of a precipitation reaction (see page 351). She developed some notion of the idea over the year but it never quite reached scientific acceptability. By interview 1, she had developed the idea that separate particles in each of the solutions come together when mixed to form molecules. Probing led her to split the “spectator” species in the products into separate “ions”, leaving the solid as molecules; and to add water to her representation. These ideas were not integrated into her understanding. Her post-test representation of the products featured a 3D cubic lattice for the precipitate, but the spectator solution featured both molecules and “ions”. Therefore, she had not yet resolved the issue of how the solution is represented. Once again, no water molecules were included. Interview 3 exposed her uncertainty of the term “aqueous” and the student revealed imagining the spectator solution as containing molecules of potassium nitrate. She was therefore unable to transfer her ideas about an aqueous solution of sodium chloride to solutions in this precipitation reaction.
4.8.1.4. LL

LL had some understanding of the states of matter at the beginning of the year and she was able to add some features to her images by the end of the year (see page 380). However, she experienced confusion with some key ideas, including the size of the molecules in the three states of matter and the concept of a gas. She also had difficulty with concepts underlying the structure of ionic solids (see page 383) and solutions (see page 385). Based on her post-test scores, she appeared to make substantial progress on her visual images. However, her discussion suggested that her understanding of the underlying concepts was weak and her more scientifically acceptable ideas were not strongly held.

The main progress in this student’s images of the states of water was her ability to visualise “water molecules” rather than simply circles. She attributed this change to having seen VisChem animations. She also added the feature of collisions to her image of gaseous water and vibrations to solid water. Difficulty in conceiving water as a gas was a problem, in interview 2. Prior to this, she may have used the multi-particulate representations provided in the pre-test as clues on how to draw her own representations. She seemed to have resolved this issue by the post-test.

LL selected an incorrect model of solid sodium chloride in the pre-test but had moved to the more scientifically acceptable image by interview 1. By the end of the study, she had developed the ideas of close-packing, a repeating pattern, the ratio of sodium to chloride, and vibrations of ions. However, she could not describe the bonding and was unsure as to whether the substance contained distinct ions or molecules.

Similar confusion arose in her discussions of the aqueous solution of sodium chloride. Over the course of the year, she seemed to develop the notion that solutions contain separate ions, with water molecules arranged in a certain way around them. However, she did not understand why or when this occurred. These ideas seemed to surface just after being taught them and around the time of administering the post-test. She claimed that she learnt these ideas from drawings on the board and her own representations. Although these ideas featured in some of her explanations over the year, in interview 3 she revealed that she imagined there to be molecules in solution surrounded by water molecules. The only key features that she
seemed to retain were that the ratio of water molecules to solute particles is high and the particles have movement.

Her images of molecules in solution were transferred to her image of precipitation (see page 387). She initially had no knowledge of precipitation reactions. By interview 1, she had developed the alternative conception regarding the “swapping of partners” in the molecular reactants to produce new molecular products. By the end of the study, she had progressed to a multi-particulate image. Reactants and products were still represented as molecules, with the “partner swapping” idea intact, but she drew a distinction between the resulting precipitate and the solution by clustering the molecules in the solid together at the bottom of the beaker. She understood there would be water present, although she did not represent it.

4.8.1.5. Comparison of Students

A qualitative overview of the case studies seems to support the hypothesis that the high prior knowledge/high disembedding ability student (HH) would show superior mental models of molecular and ionic substances, and that the low prior knowledge/low disembedding ability student should show the least developed mental models. HH’s mental models were relatively consistent over the year and were scientifically acceptable. LL’s images showed some improvement but she struggled with underlying concepts, and therefore found it difficult to develop and retain scientifically acceptable ideas. HL and LH were aware of some of the underlying principles of their images but demonstrated inconsistencies, misconceptions and/or competing cognitive frameworks.

The accuracy of LH and LL’s images of an aqueous solution of sodium chloride seemed to peak some time during semester 1. By interview 3, they had reverted to their original conceptions of this solution, as shown in the pre-test. Students were aware of the ideas shortly after having learnt them but did not retain them over the long term. This may be an example of students maintaining scientifically acceptable ideas while they are needed and then discarding them when they are no longer deemed important, as discussed by Harrison and Treagust (1996). By interview 3, these students had completed their end-of-semester exam and therefore would not be tested further on their image of sodium chloride solution. It is likely, therefore, that these students only learnt these ideas in a superficial manner. For these students, lack of deep learning may be related to their lack of prior knowledge about
solutions. The students with higher prior knowledge retained the ideas they developed about solutions.

There may be some difference in the way students with high and low disembedding ability undergo conceptual change. A possible difference lies in the nature of the inconsistencies in the students’ changing models over time. The basic models of water and sodium chloride of the students with high disembedding ability (HH, LH) tended to remain fairly consistent once developed, apart from the addition or loss of particular key features. For example, HH abandoned the idea of dissociation of water molecules in liquid water and LH randomly introduced and abandoned ideas of ion-dipole forces in solution. Students with low disembedding ability (HL, LL), on the other hand, tended to have competing, co-existing mental models of phenomena. For example, HL had co-existing models of the states of water (discrete molecules or separate atoms) and LL showed co-existing models of aqueous solutions (molecules in water or separate ions electrostatically attracted) that seemed unrelated to each other. This observation is consistent with the nature of disembedding ability. Students with high disembedding ability would be expected to see the model as a collection of parts, from which they can add or subtract specific components. Low disembedding ability, however, would view each competing image as a whole. Students with low disembedding ability may, therefore, experience more difficulty moving from alternative frameworks to more scientifically acceptable models because they need to entirely replace an existing image, whereas students with high disembedding ability need only add or subtract single features to an existing model. These conclusions are only tentative because the number of students in this study is small. This is an area worthy of further investigation.

Only HH showed both confidence and understanding of precipitation at the molecular level. All other students showed progress towards a scientifically acceptable model. HL and LH fluctuated between correct and incorrect ideas regarding whether or not to separate the ions in solution, and were not initially aware of how to represent the precipitate. They needed further probing to direct them towards a correct understanding. LL never reached an appropriate representation, maintaining a molecular framework. This progress is consistent with the predicted order of ability. It is reminiscent of Pines and West’s (1986) proposed model of conceptual development, showing students gradually intertwining spontaneous knowledge with formal knowledge. These results, however, are inconsistent with the model of conceptual change proposed above based on disembedding ability.
The most commonly mentioned influences on students’ mental images were the VisChem animations or videos and students’ own drawings of the molecular level. Every student mentioned both of these learning strategies as affecting their images. Once again, this emphasises the point made in Chapter 2, that the animations need to be used according to best practice methods, which include students producing their own drawings of the molecular world.

One final comment relates to the difference in the way HH expressed his ideas compared with the other students. That is, he tended to talk in terms of concepts or ideas, and less commonly of visual images. This could simply be related to superior understanding. Alternatively, it could be related to cognitive style. The CSA (Chapter 3, Sections 3.5.2 and 3.7.1.4) revealed that HH is a verbaliser and that the other students are all imagers. If this is the case, it suggests the importance of discussing key features of images in terms of concepts, for example, introducing the idea of absolute zero and its relationship to movement when showing that particles in solids vibrate. Furthermore, it supports the importance of probing students’ mental models using both diagrams and descriptions.

4.8.2. Applications of Mental Models of Molecular Substances

4.8.2.1. HH

HH was able to use his mental models of molecular substances to interpret symbolic, macroscopic and molecular representations.

He successfully translated between formulae and molecular representations, realising after some deliberation that ratios of moles and molecules would be equivalent (see page 274). His ability to draw links between his mental models of molecular substances and molecular equations was highlighted by the fact that he felt that he could not represent the equation without information about the states of each substance. On being given the states, he applied his mental model of a gas (widely spaced, randomly dispersed, moving particles) to his representation and description of the gas-phase reaction (see page 274).
HH made an attempt to use his mental models of evaporation and gases to explain why nail-polish remover might smell (see page 282). His explanation revealed, once again, his tendency to think in concepts rather than in visual images, mentioning ideas like pressure, volatility and energy. Although his discussion was somewhat haphazard, it was possible to extract a molecular-level explanation from his ramblings. He seemed to conceptualise ethyl acetate molecules in the liquid state evaporating to gas. He visualised these molecules floating around in the gas state, dispersing with air particles and becoming increasingly concentrated. A proportion of these molecules would then reach the nose. He attempted to apply his model of increasing energy with an increase in temperature to explain how the molecules might gain enough energy to evaporate, but realised his model was insufficient to explain the current situation. His attempts show an ability to think about macroscopic phenomena in terms of concepts and images at a molecular level.

HH used his mental model of a molecular solid (collection of particles in a fixed structure) to criticise the diagram of dry ice, suggesting that the molecules were placed too randomly (see page 292). He also expressed the idea that molecules are extremely small particles and was able to use this mental model to criticise the use of a magnifying glass in the diagram.

Although he could not recall the animations of ice melting and water evaporating, he used his existing mental models to interpret them (see pages 297 to 298). He provided conceptual explanations for many of the visual features he noticed, i.e., he discussed ideas not immediately present in the animations. Some of these explanations were plausible but not scientifically acceptable. For example, he suggested that water molecules leaving the liquid state may return due to a loss of energy. The student may be moving towards expertise in the area, as novices tend to concentrate more on surface features of animations (Lowe, 1987; Kozma & Russell, 1997; Russell et al., 1997). Table 4.11 summarises the images pointed out by HH and the related concepts discussed by him when viewing these animations. Visual features of the animations allowed this student to construct an explanation for why ice expands when frozen. This suggests that, with access to a correct model, this student was able to move from the molecular-level representation to related macroscopic phenomena.
<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Melting</td>
<td>Structured lattice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lattice breaks apart</td>
<td>An increase in heat increases the energy of the particles, allowing them to overcome intermolecular forces</td>
</tr>
<tr>
<td></td>
<td>Water molecules face each other in a particular direction in both the liquid and solid states</td>
<td>• Polarity of water molecules • Attraction between positive and negative</td>
</tr>
<tr>
<td></td>
<td>Molecules are closer together in liquid water</td>
<td>Molecules are more attracted to each other</td>
</tr>
<tr>
<td>Water Evaporating</td>
<td>Molecules floating away from liquid</td>
<td>Equilibrium between liquid and gas states</td>
</tr>
<tr>
<td></td>
<td>Molecules return to surface</td>
<td>Molecules lose energy*</td>
</tr>
<tr>
<td></td>
<td>Molecule pulled back to surface</td>
<td>Molecules attract each other</td>
</tr>
</tbody>
</table>

*misconception

| Table 4.10 | Details and concepts mentioned by HH when viewing animations of ice melting and water evaporating |

### 4.8.2.2. HL

In interviews and the post-test, HL successfully translated between formulae and molecular representations (see page 316). He demonstrated this ability in his representation of the gas-phase molecular equation (see page 317). However, he did not spontaneously link the equation to his mental models at the molecular level, as he was content to represent the equation simply as molecules in their stoichiometric ratios. Even when shown an equation with the states included, he showed limited ability to transfer ideas of gases to the substances in the equation, simply suggesting that there would be mixing of reactants and products.

HL’s mental model of the conversion of a liquid to a gas featured the notion of boiling but did not allow for evaporation of a liquid below the melting point. He used this incomplete mental model in his interpretations of why nail-polish remover smells (see page 325) and the animation of water evaporating (see page 338). The fact that he applied this model to different situations suggests that he found it functional, as it allowed him to describe the fact that molecules break away from a liquid surface into the gas state with the addition of energy.

HL did not use his mental model of a molecular solid to criticise the diagram of solid carbon dioxide (see page 333). He did, however, reveal his understanding of the size of molecules by suggesting the absurdity of using a magnifying glass to view the molecules.
The visual details this student pointed out in the animations of ice melting and water evaporating (see pages 337 and 338) are summarised in Table 4.11, together with associated concepts. The concepts mentioned for the animation of ice melting were macroscopic, unlike HH’s discussion, which concentrated more on concepts at the molecular level. This student was also able to produce an explanation for why water expands when frozen, based on visual features in the animation of ice melting (see page 338).

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Melting</td>
<td>Structured lattice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Molecules start to vibrate</td>
<td>Substance is being heated</td>
</tr>
<tr>
<td></td>
<td>Vibrations increase</td>
<td>Substance is being heated further</td>
</tr>
<tr>
<td></td>
<td>Lattice breaks apart</td>
<td>Substance has reached melting point</td>
</tr>
<tr>
<td></td>
<td>Water molecules stay together intact on melting</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Molecules are closer together in liquid water</td>
<td>Water expands when frozen</td>
</tr>
<tr>
<td></td>
<td>There’s space between the rows in ice</td>
<td>Water expands when frozen</td>
</tr>
<tr>
<td>Water Evaporating</td>
<td>Molecules moving</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Molecules move to gas state</td>
<td>An increase in heat increases the energy of</td>
</tr>
<tr>
<td></td>
<td></td>
<td>the particles</td>
</tr>
<tr>
<td></td>
<td>Molecules return to surface</td>
<td>Molecules have insufficient energy</td>
</tr>
<tr>
<td></td>
<td>Molecule pulled back to surface</td>
<td>Molecules attract each other <em>via</em> hydrogen</td>
</tr>
<tr>
<td></td>
<td></td>
<td>bonding</td>
</tr>
</tbody>
</table>

Table 4.11 Details and concepts mentioned by HL when viewing animations of ice melting and water evaporating

4.8.2.3. LH

LH struggled to correctly translate between molecular and symbolic representations of $2\text{NO}_2$ and $\text{N}_2\text{O}_4$ (see page 354), yet was able to appropriately draw molecular representations for components of a molecular equation, in the correct stoichiometric ratios (see page 355). When shown the equation with states included, she applied some aspects of her mental model of gases to her molecular-level representation: spacing of the molecules and mixing of the products. She therefore showed some ability to move between the molecular and symbolic levels of thinking, for molecular substances.

This student did not apply her mental models of molecular substances to the nail-polish remover problem (see page 364). Instead, she inappropriately used a mental model of a
chemical reaction that produces a gas in an attempt to explain why nail-polish remover might smell.

LH struggled to criticise the diagram of dry ice (see page 372). She did not use her mental model of a solid to critically analyse the representation. Only when asked directly about the magnifying glass did she propose that it might mislead students about the size of the molecules.

The student was able to identify both of the water animations, and point out many of the relevant details (see pages 375 to 376 and Table 4.12). However, she seemed to contradict herself when talking about the spacing in ice. Her mental model of solids, as being closely packed, seemed initially to influence her discussion of features in the visual display. However, this did not stop her from discussing the space in ice and relating it to the fact that water expands when frozen. Her comment that air particles fill the spaces in ice might be an attempt to accommodate the two ideas. The concepts she mentioned were mostly macroscopic, except when she spoke about intermolecular bonding.

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Melting</td>
<td>Molecules vibrate in ice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Molecules start to move around</td>
<td>Substance has reached melting point</td>
</tr>
<tr>
<td></td>
<td>Water molecules move about in clusters</td>
<td>Hydrogen bonding holds the molecules together</td>
</tr>
<tr>
<td></td>
<td>Water molecules in ice are compacted together*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>There’s space between the molecules in ice</td>
<td>Water expands when frozen</td>
</tr>
<tr>
<td>Water Evaporating</td>
<td>Water molecules break away from the surface</td>
<td>Water is evaporating</td>
</tr>
<tr>
<td></td>
<td>Molecules return to surface</td>
<td>Water is condensing</td>
</tr>
<tr>
<td></td>
<td>Molecule pulled back to surface</td>
<td>Bonding between water molecules is too strong for molecule to evaporate</td>
</tr>
</tbody>
</table>

*misinterpretation

Table 4.12 Details and concepts mentioned by LH when viewing animations of ice melting and water evaporating
4.8.2.4. LL

Apart from some confusion over the meaning of the term “moles”, LL was able to translate between molecular representations and formulae and produced a representation of the molecular equation showing the stoichiometric ratios of each substance (see pages 388 to 389). When shown the states of each substance, she suggested that the molecules be drawn further apart to represent the gas state. To some extent, therefore, she was able to link her mental model of a gas to the equation and move between molecular and symbolic levels of thinking.

LL was able to conceive of processes occurring at the molecular level when a bottle of nail-polish remover is opened, suggesting that molecules of ethyl acetate float up from the liquid state into the air (see page 396). This shows an ability to think about macroscopic phenomena at a molecular level, even if her explanation at this stage was somewhat simplistic.

LL showed a surprising ability to use her mental model of a molecular solid to critically analyse the diagram of dry ice (see page 404), pointing out that the molecules should be more closely packed and vibrating.

This student was able to interpret both animations (see pages 409 to 409 and Table 4.13) but her voice-overs for the animations were brief and her discussion of underlying principles limited. Most concepts she mentioned were macroscopic in nature. Her prior understanding of solids being closely packed seemed to influence how she saw the animation and she could not explain why there were tunnels of empty space in the lattice.
Chapter 4  Examination of Students’ Mental Model Development

4.8.2.5. Comments and Comparisons

HH outperformed the other students in his ability to apply his mental models of molecular substances. LH had little success at applying her images and fell at the other end of the spectrum. This is consistent with the relationship between prior knowledge and deep learning. LH had the lowest prior knowledge of molecular substances; HH had the highest.

There seemed to be little difference in students’ ability to see features in VisChem animations, apart from the fact that only the students with high disembedding ability (HH, LH) pointed out the clustering/hydrogen bonding in the ice-melting animation. This is easily explained by an increased ability to notice details in complex displays, compared with individuals with low disembedding ability.

HH showed superior understanding of the concepts underlying features in the VisChem animations and, in fact, tended to concentrate on finding reasons for why things were happening in the display rather than just pointing out visual features. This may be due to his greater prior knowledge and consequent understanding of the molecular level resulting in the adoption of a deep approach to learning. This is consistent with the statistical analysis (Chapter 3) revealing that deep learning affected outcome on the post-test. As pointed out earlier, this approach is consistent with an expert interpretation of a visual display (Chi, Feltovich and Glaser, 1981; Lowe, 1987; Kozma & Russell, 1997; Russell et al., 1997). Alternatively, his interpretation of the animation may be a result of the fact that he mentally stores his ideas relating to the molecular level as concepts. It may be hypothesised that

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice Melting</td>
<td>Structured lattice</td>
<td>The substance is a solid</td>
</tr>
<tr>
<td></td>
<td>Water molecules in ice are closely packed*</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Molecules start vibrating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Molecules start to move around</td>
<td>The substance is melting</td>
</tr>
<tr>
<td>Water Evaporating</td>
<td>Molecules move around easily</td>
<td>Water is in the liquid state</td>
</tr>
<tr>
<td></td>
<td>Molecules move to gas state</td>
<td>Water is being heated</td>
</tr>
<tr>
<td></td>
<td>Molecule pulled back to surface</td>
<td>There’s an attraction between water molecules</td>
</tr>
</tbody>
</table>

*misinterpretation

Table 4.13 Details and concepts mentioned by LL when viewing animations of ice melting and water evaporating
verbalisers show a greater tendency towards deep learning because it may be easier to recall verbal ideas if they are rooted in a conceptual framework. Imagers, on the other hand, might find it easy to recall certain ideas simply because they are embedded in a visual image and therefore may feel it is unnecessary to learn the underlying concept. Recall of information is enhanced through the use of imagery (Paivio, 1971; Johnson-Laird, 1983; McIntosh, 1986; Kosslyn, Behrmann & Jeannerods, 1995; Jones et al., 2001). Differences in learning approaches of imagers and verbalisers in chemistry is an area worth investigating.

One of the students with low prior knowledge (LL) showed the least conceptual understanding of the visual features in the animations. This is consistent with a novice’s perception of a visual display (Lowe, 1987; Kozma & Russell, 1997; Russell et al., 1997).

There was some evidence that misconceptions might inhibit students’ ability to see key features in an animation. Both LH and LL conceived of solids as containing closely packed molecules, and suggested that this was a feature of the animation showing ice, despite the fact that tunnels of empty space are visible in the animation.

Discussion of animations provided further insight into the way VisChem animations can be used to improve students’ mental models. Comments by students provide evidence that the evaporation animation might be useful for demonstrating the key feature of intermolecular attraction, as proposed in Chapter 2. Students were generally able to rationalise the return of a water molecule to the surface in terms of intermolecular attraction. Along similar lines, the expansion of water on freezing can be discussed in relation to the ice-melting animation, to help students develop their mental models. No students were able to produce an explanation for why water expands when frozen from their own mental models, but three were able to construct an explanation when viewing the animation of ice melting.

4.8.3. Applications of Mental Models of Ionic Substances

4.8.3.1. HH

HH appropriately applied his model of aqueous ionic solutions to interpret, at a molecular level, formulae for a strong acid solution (see page 275) and the products of an acid-base reaction (see page 276). He understood the concept of concentration at both symbolic and
molecular levels. He used the ideas of separate ions, hydration and ion-dipole attractions in his representations of ionic substances. He was able to correctly interpret the subscripts in the formulae in terms of ratios of ions at the molecular level. Therefore, once again, he demonstrated the ability to translate between symbolic and molecular levels of thinking.

This student demonstrated his ability to move between all three levels of thinking when interpreting precipitation reactions, suggesting a well-developed mental model of the process. He successfully interpreted various equations for the precipitation reaction at a molecular level (see page 277); was able to predict the outcome of a precipitation reaction at a macroscopic level and describe the structure of the reactants and products (see page 283); and successfully identify a VisChem animation showing the process (see Table 4.15), by referring to his knowledge of solubilities acquired in the laboratory (see page 300). When encouraged to discuss particular aspects of his representations of precipitation reactions, it was apparent that he utilised his mental models of ionic solids and solutions. When discussing the dissolution of solids at a macroscopic level, he was able to describe what happens at a molecular level. Precipitates were perceived as 3D ionic lattices featuring the correct ratio of ions. Solutions featured the ideas of separate ions, hydration and ion-dipole attractions.

HH’s deep understanding of ionic solids and solutions was exemplified through his interpretation of the complexation equations (see page 278). He first gave a brief description of what would occur at the macroscopic level. He was able to apply his model of an ionic solid to copper(II) hydroxide. More impressively, however, he applied his ideas of ionic solids dissolving in water to an ionic solid dissolving in ammonia and used his image of a hydrated copper ion to produce an appropriate representation for the tetraamino complex ion. This further demonstrates his ability to move from the symbolic to the macroscopic and molecular levels.

HH’s understanding of ionic solids and solutions was further illustrated by his ability to critically analyse some previously unseen diagrams (see pages 292 to 294) and a poor animation of sodium chloride dissolving. His criticism of the animation, in particular, revealed his sophisticated image of sodium chloride dissolving (see page 294). In relation to diagram 3, this student did not see any problem with representing the formation of sodium and chloride ions by the exchange of an electron from a sodium atom to a chlorine atom (see page 293). This may indicate a fault in his mental model of the formation of ionic solids.
HH seemed familiar with both animations involving sodium chloride (see pages 299 to 300). He comprehensively pointed out the key features in the animation of sodium chloride dissolving and introduced further key features when discussing the animation of an aqueous solution of sodium chloride. Table 4.15 shows the visual details and associated concepts discussed by HH in relation to animations of ionic substances.

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Chloride Dissolving</td>
<td>Water molecules tear ions from lattice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lattice structure of NaCl</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cations and anions are different sizes</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrogen end of water molecule points</td>
<td>• Polarity of the water molecule</td>
</tr>
<tr>
<td></td>
<td>towards chloride ion, oxygen end points</td>
<td>• Attraction of positive and negative</td>
</tr>
<tr>
<td></td>
<td>towards sodium ion</td>
<td>charges</td>
</tr>
<tr>
<td></td>
<td>Movement of molecules</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydration of ions</td>
<td></td>
</tr>
<tr>
<td>Aqueous Solution of Sodium Chloride</td>
<td>Sodium and chloride ions come together</td>
<td>Attraction of positive and negative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>charges</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Polarity of the water molecule</td>
</tr>
<tr>
<td></td>
<td>Ratio of water to ions is high</td>
<td></td>
</tr>
<tr>
<td>Precipitation of Silver Chloride</td>
<td>Lattice Structure</td>
<td>Silver nitrate and a chloride solution</td>
</tr>
<tr>
<td></td>
<td></td>
<td>are mixed</td>
</tr>
<tr>
<td></td>
<td>Nitrate ion floating around</td>
<td>Silver chloride forms a precipitate</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Nitrates are soluble</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Polarity of the water molecule</td>
</tr>
</tbody>
</table>

Table 4.14 Details and concepts mentioned by HH when viewing animations of sodium chloride dissolving, aqueous solution of sodium chloride and precipitation of silver chloride

4.8.3.2. HL

HL tended to use a combination of erroneous and scientifically acceptable mental models of ionic substances. In some circumstances, these models seemed to compete, causing HL considerable confusion. His alternative models were more simplistic than the scientifically acceptable ones, and therefore tended to dominate his thought, at least on initial exposure to the question. Questioning or prolonged thought often enabled him to come to a more correct explanation. In other cases, he formed a composite explanation containing features of his correct and incorrect models. His alternative framework seemed to consist of the following ideas:
- Ionic solutions contain molecules of solute.
- Ionic precipitates are made up of one or more molecules.
- Chemical reactions involving ionic species occur via a “swapping of partners” mechanism.
- Equations can be represented at a molecular level simply by drawing the reactants and products as molecules in stoichiometric ratios.

These ideas arose in his interpretation of the formula for a strong acid (see page 317) and equations for the acid-base reaction (see page 318) and precipitation reactions (PbCl₂ – page 319; Cu(OH)₂ – page 322). For these reactions, he seemed to have an understanding of processes occurring on a macroscopic level, so was able to make links between the macroscopic and symbolic levels. He also understood the concept of concentration at the symbolic and molecular level. He simply struggled with his images of substances and reactions at a molecular level. One factor influencing this student’s mental imagery may have been the way equations are sometimes written. This student adopted the framework outlined above when shown a “molecular” equation of a precipitation reaction and moved towards scientific acceptability when shown a full ionic equation. This reinforces the concern expressed by Sleet (1993) for using “molecular” equations to represent ionic reactions.

The student was able to apply some key features of aqueous ionic solutions to the examples discussed in interviews. For example, some of his representations feature water molecules appropriately oriented around charged species (for example, see Figure 4.10, page 317). He was also able to interpret the precipitation reaction shown to him, in terms of processes at a molecular level, and give an acceptable, albeit brief, description of the products (see page 326). This experiment was conducted after discussion of a similar precipitation reaction in the same interview, where the student had eventually constructed a reasonable image of the process. He was therefore able to link the macroscopic phenomena to his recently constructed mental model of the molecular level.

The above conceptions highlight that this student had difficulty moving from symbolic representations to scientifically acceptable molecular-level representations. Although this student’s mental models of sodium chloride were reasonable, he seemed to find it difficult to apply these concepts in different situations. Images drawn by this student showing his
adoption of some recently taught concepts may indicate a move towards scientifically acceptable mental models.

HL’s uncertainty over ionic substances and reactions was apparent in his criticisms of the textbook animation and diagrams (see pages 334 to 335). He made few criticisms overall, and the ones that he did make, unprompted, were not associated with his mental models of ionic solutions or reactions. Instead, they revealed his understanding of the size and structure of atoms, molecules and ions. He exposed again the flaw in his mental model of solid sodium chloride, suggesting that ion exchange occurs as represented by the given diagram when sodium and chlorine come together to form a solid. This misconception was apparent in his mental model of solid sodium chloride, as outlined in Section 4.7.1.2 above.

Consistent with the fact that this student had a reasonable image of aqueous sodium chloride, he had little difficulty interpreting animations of sodium chloride dissolving and sodium chloride in aqueous solution (see page 340). He pointed out many relevant features and showed some understanding of the underlying concepts (see Table 4.15). He initially struggled with the animation of the precipitation reaction, however (see page 340), consistent with the confusion he experienced when discussing precipitation in earlier interviews. After much deliberation, he came to a correct understanding of what the animation was showing. Details of his final explanation are given in Table 4.15. This provides further evidence that the scientifically acceptable model was available to this student but not easily accessible.
Chapter 4  Examination of Students’ Mental Model Development

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Chloride Dissolving</td>
<td>Water molecules pull the ions from the lattice and carry them away</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lattice structure of NaCl</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ions in the lattice vibrate</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrogen end of water molecule points towards chloride ion, oxygen end points towards sodium ion</td>
<td>• Oxygen is attracted to the positive sodium.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• Hydrogen is attracted to the chloride ion.</td>
</tr>
<tr>
<td>Aqueous Solution of Sodium Chloride</td>
<td>Sodium and chloride separate in solution</td>
<td>Ions are present in solution</td>
</tr>
<tr>
<td></td>
<td>Sodium and chloride ions come together</td>
<td>Attraction of positive and negative charges</td>
</tr>
<tr>
<td></td>
<td>Sodium and chloride are pulled apart again</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water molecules bounce around</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrogen end of water molecule points to the oxygen end of another water molecule</td>
<td>Hydrogen is attracted to the oxygen atom in another water molecule</td>
</tr>
<tr>
<td></td>
<td>Hydrogen end of water molecule points towards chloride ion, oxygen points away</td>
<td>Hydrogen is attracted to the chloride ion. Oxygen is not attracted.</td>
</tr>
<tr>
<td>Precipitation of Silver Chloride</td>
<td>Silver nitrate and sodium chloride solutions are mixed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lattice is being assembled</td>
<td>A precipitate of silver chloride forms</td>
</tr>
<tr>
<td></td>
<td>Nitrate ion floating around</td>
<td>Nitrate has lost its partner ion and is now a spectator ion</td>
</tr>
</tbody>
</table>

Table 4.15  Details and concepts mentioned by HL when viewing animations of sodium chloride dissolving, aqueous solution of sodium chloride and precipitation of silver chloride

4.8.3.3.  LH

Despite showing inconsistencies in her mental models of aqueous sodium chloride and precipitation over the year, in interview 2, LH successfully used ideas of separate ions, hydration and ion-dipole attractions to draw representations of the formula for a strong acid (see page 355), and equations of acid-base (see page 357) and precipitation reactions (see page 357). She also showed correct ratios of ions in solutions, suggesting she understood the subscripts in the formulae, but sometimes failed to include charges or added incorrect charges, sacrificing electro-neutrality. Despite this, she showed not only an ability to apply information appropriately but also to interpret symbolic representations at a molecular level. The strength of her mental links between molecular-level representations and equations was emphasised by the fact that she was reluctant to draw a representation of the precipitation equation without states included.
In interview 2, LH was also able to apply her ideas about ionic solids to precipitation reactions - the formations of lead(II) chloride and copper(II) hydroxide. As with her representation of sodium chloride drawn in the same interview, she failed to include charges on the ions.

She showed an ability to move from the macroscopic phenomena of a precipitation reaction to an appropriate description of the molecular level (see page 364). Seeing the reaction even encouraged her to reconsider her image of a precipitation reaction, discussed earlier in the same interview, which featured molecules instead of ions in the resulting aqueous solution.

LH was able to describe what would occur at a macroscopic level for the complexation equations (see page 358). However, her representation of the molecular level of the products of the second reaction (complex ion) was simplistic. It showed little evidence of the application of ideas of ionic solutions. Her modified representation showed inappropriate transfer of the idea of ion-dipole forces, with water molecules surrounding the complex with hydrogen ends towards ammonia molecules and oxygen ends towards the copper.

LH demonstrated a very limited ability to critically analyse diagrams and animations (see pages 372 to 373). She tended to accept these representations, preferring simple diagrams to ones she perceived as confusing or too detailed. She accepted the concept of electron transfer, as depicted by diagram 3, and expressed approval of the diagram.

This student was able to point out appropriate visual details in the animations (see pages 376 to 378 and Table 4.16) and understood the processes being depicted. However, lack of prior knowledge perhaps prevented her from identifying specific substances in the animations (or possible examples), the particles present, the types of lattices present, etc. She therefore referred to grey and green balls rather than sodium and chloride ions.
Chapter 4  Examination of Students’ Mental Model Development

4.8.3.4. LL

LL produced representations of equations involving ionic species from a molecular framework similar to that used by HL. She also found stoichiometric ratios confusing and after interview 1, did not represent them. She was also more consistent with the molecular framework in the transfer problems than HL.

Considering this student’s confusion over whether to separate and hydrate sodium chloride in water, it is not surprising that she ignored these ideas when representing related substances and processes. LL represented aqueous solutions of sulfuric acid (see page 390) and sodium sulfate (see page 390) as molecules amongst water molecules. She described the acid-base reaction (see page 390) and precipitation equations (see page 391) in terms of “swapping of partners” and represented reactants and products of the precipitation reaction as molecules, despite being presented with a full ionic equation of the precipitation reaction. She represented lead(II) chloride and copper(II) hydroxide precipitates as collections of molecules. She made some attempt to demonstrate the difference between the solution and precipitate at a molecular level, which suggests she made an attempt to link macroscopic

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Chloride Dissolving</td>
<td>Water pulls apart the solid</td>
<td>Solid going into aqueous solution</td>
</tr>
<tr>
<td></td>
<td>Oxygen is pointing towards the grey ball</td>
<td>The grey balls are positive</td>
</tr>
<tr>
<td></td>
<td>The green balls are negative</td>
<td>Water is hydrating the particles</td>
</tr>
<tr>
<td></td>
<td>Solid is vibrating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Particles in solid are closely packed</td>
<td></td>
</tr>
<tr>
<td>Aqueous Solution of Sodium Chloride</td>
<td>Green and grey balls are surrounded by water molecules</td>
<td>Green and grey balls are hydrated</td>
</tr>
<tr>
<td></td>
<td>Green and grey balls come together</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Ratio of water to solute particles is high</td>
<td></td>
</tr>
<tr>
<td>Precipitation of Silver Chloride</td>
<td>Solid is being reformed</td>
<td>Green and grey balls precipitate</td>
</tr>
<tr>
<td></td>
<td>Presence of a blue and red ball</td>
<td>Aqueous solutions containing the green, grey, blue and red balls were mixed. Blue and red ball is part of the resulting aqueous solution.</td>
</tr>
<tr>
<td></td>
<td>Solid is vibrating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water molecules are moving</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.16 Details and concepts mentioned by LH when viewing animations of sodium chloride dissolving, aqueous solution of sodium chloride and precipitation of silver chloride
observation to molecular representation. Her representations suggest, however, that she had not developed an ability to appropriately visualise the symbolic level at the molecular level.

Perhaps most surprising was this student’s description of the process of complexation (see page 391). She was able to give a description of observations in the laboratory. She then described an interactive process reminiscent of the dissolving of an ionic solid in water, to explain how the complex forms at a molecular level. However, she was unable to apply an image of a hydrated ion to determine the structure of the complex ion. Her representation of the products after complexation mimicked the first equation, featuring separate hydroxide ions and molecules of Cu(NH$_3$)$_4$. Therefore, although she had not mastered the finer details of the structures of substances at a molecular level, she possessed mental models of chemical reactions that involve dynamics and interaction. It is rare for a novice to develop this sort of mental model under traditional chemistry instruction. As outlined in Chapter 1, students often conceive of the molecular world as static (Novick & Nussbaum, 1981; Andersson, 1990; Pereira & Pestana, 1991; Lee, 1993) and non-interactive (Ben-Zvi et al., 1987). Emphasis on these features of the molecular level using animations may help new students to develop a more dynamic, interactive model of chemical processes.

This student did not provide a thorough description of the molecular-level processes occurring when a precipitation reaction was performed for her (see page 397). She was, however, able to predict the products of the reaction, presumably by applying the “swapping of partners” mental model.

LL’s critical analysis of diagrams relating to ionic substances closely resembled LH’s attempts (see pages 405 to 406). She made no critical comments related to her mental models of solutions and precipitation. Like LH, she judged diagrams on whether they were comprehensible. She accepted the electron exchange mechanism depicted in diagram 3 and felt that it was not misleading.

LL was just as capable of noticing features in the animations as other students (see pages 410 to 412 and Table 4.17). Her lack of prior knowledge, however, appeared to influence her understanding of the underlying concepts. This was reflected most strongly in her inability to identify the precipitation reaction. This inability was not surprising, considering that the animation was removed from her mental model of precipitation.
## Table 4.17

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium Chloride Dissolving</td>
<td>Water molecules separate the green and grey balls and take them away</td>
<td>Solid could be sodium chloride</td>
</tr>
<tr>
<td></td>
<td>Solid is vibrating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lattice structure of NaCl</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydrogen end of water molecule points towards green ball, oxygen end points</td>
<td>There’s an attraction</td>
</tr>
<tr>
<td></td>
<td>towards grey ball</td>
<td></td>
</tr>
<tr>
<td>Aqueous Solution of Sodium Chloride</td>
<td>Ratio of water to sodium and chloride is high</td>
<td>Sodium chloride dissolved in aqueous solution</td>
</tr>
<tr>
<td></td>
<td>Sodium and chloride ions come together</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Sodium and chloride separate again</td>
<td>There was some attraction between the ions,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>then water pulled them apart again</td>
</tr>
<tr>
<td>Precipitation of Silver Chloride</td>
<td>Lattice is being reformed</td>
<td>• Water molecules are taking the sodium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>chloride back to the lattice.</td>
</tr>
<tr>
<td></td>
<td>Presence of a blue ball</td>
<td>• Possibly evaporation of water molecules</td>
</tr>
</tbody>
</table>

### 4.8.3.5. Comments and Comparisons

Out of the four students, HH and LH seemed most successful at interpreting equations of ionic reactions at the molecular/ionic level. HL and LL utilised the alternative molecular framework in these transfer situations. They did not adopt this framework for their models of sodium chloride as a solid or solution at that time. This suggests that the latter students only had a surface understanding of these ideas, and had not made conceptual links between equations and models of substances at a molecular level. It is possible that disembedding ability may influence the ability to extract relevant information for transfer. High disembedding ability may enable a student to see discrete ideas that can be used in other situations. Students with low disembedding ability may see each image as a whole and not as a collection of ideas, as suggested earlier. If there are two mental models available, the more firmly established model is likely to dominate in transfer situations.

HH excelled in his ability to analyse critically. HL was able to make some criticisms, unrelated to his mental models of ionic substances. This is not surprising considering the
uncertainty he demonstrated in this area. LH and LL were unable to make relevant criticisms of the diagrams in relation to the chemistry portrayed. It is tentatively suggested, therefore, that levels of prior knowledge may influence students’ ability to analyse critically. This has obvious consequences for the use of diagrams in teaching chemistry. Novice students are likely to accept representations given to them without question. Misconceptions may arise from such blind acceptance (Hill, 1988; Harrison & Treagust, 1996). As pointed out by Hill (1988), first-year students may not be able to “read and interpret diagrams in a critical manner and recognise their limitations.” This study has provided further evidence that the student’s levels of experience and understanding of chemistry are likely to influence this ability.

None of the students felt that the transfer-of-electron diagram was misleading in the way it represented the formation of an ionic bond or ionic compound. Different authors have commented on the possible deleterious effects of using such diagrams, such as the effect on students’ understanding of the bonding in ionic compounds (Taber, 1997; 2001) and of the driving force behind chemical reactions (Sleet, 1993). Disturbingly, students tended to like this diagram due to its simplicity, compounding the problems associated with using such a diagram in teaching.

The effects of prior knowledge were most prominent in students’ interpretations of VisChem animations. The students with low prior knowledge appeared to have more difficulty with the underlying concepts of the animations and were more likely to refer to “coloured balls” rather than sodium and chloride ions. This is consistent with the discussion above on expert–novice differences in interpreting visual displays such as animations. There seemed to be no difference in students’ ability to see features in the animations, as was predicted by the model of perceptual processes described in Chapter 3.

Use of both the animation of sodium chloride dissolving and of the aqueous solution of sodium chloride might be necessary to communicate key features to students. The animation of dissolution seems particularly suitable for demonstrating the idea of ion-dipole forces; the animation of the solution is more suitable for showing the ratio of ions to water, the separate ions, and the attractive charges on the ions.

None of the students recalled the precipitation animation from lectures and all found it difficult to interpret. All but one were eventually able to identify it as a precipitation reaction,
but so much effort was put into making sense of the animation that students failed to comment on the finer details. Misinterpretation was common, with students assuming that solid sodium chloride was being reassembled. This occurred due to the similarity of the colour of the sodium and silver ions. Therefore, this animation needs to be used with care. Direct attention should be drawn to the fact that different ions are represented and students should be shown animations of sodium ions and silver ions simultaneously, so they see and believe the difference. If students are not aware that a different solid is being formed, they will not succeed in interpreting this animation as a precipitation reaction, and the animation is likely to create more confusion than good.

### 4.8.4. Advanced Topics: Equilibrium and Redox

#### 4.8.4.1. HH

HH seemed reasonably comfortable with the idea of equilibrium. He was able to envisage it as an interactive process, whereby forward and reverse reactions occur simultaneously in different parts of the reaction vessel (see page 279). He recalled how the K value could be calculated but was unable to link this value to his molecular-level representation and hence was unsure if the reactants and products would be present in stoichiometric ratios. His mental model was developed enough to allow him to give a brief explanation of why addition of more reactant might cause the equilibrium to shift to the right (see page 281).

In relation to acid-base equilibrium reactions, he was aware of the presence of the hydronium ion and discussed its presence even when it was not represented as such in the equation. He admitted, however, that he visualised the hydrogen ion, and this is what he drew in his initial representation.

HH’s ability to interpret the equilibrium analogies varied (see page 295). He was able to identify some correspondences in each of the analogies. He had particular difficulty relating his correct ideas about equilibrium to statements in the soccer game analogy. This perhaps reveals problems with the analogy itself, in not being close enough to the target situation. Identification of non-correspondences arose due to flaws in the student’s mental model rather than in the analogy.
HH appropriately represented the reactants of the redox reaction, using his mental models of metals and solutions. He interpreted the macroscopic phenomena appropriately and hence identified the products of the reaction. Although he was unable to describe how the reaction proceeded, he was able to provide appropriate representations of the products after constructing an equation. During this discussion, HH moved between all three levels of thinking – from macroscopic to molecular to symbolic to molecular (see page 285). This thinking allowed him to immediately identify and explain the redox animation shown later in the interview (see page 300 and Table 4.19).

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redox Reaction</td>
<td>Yellow lattice</td>
<td>The yellow substance is copper</td>
</tr>
<tr>
<td></td>
<td>Presence of nitrate ion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A layer of silver is deposited on the lattice</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Surface</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Water takes a copper from the lattice</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silver gains electrons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Due to charges, two silvers would be deposited for each copper removed.</td>
</tr>
</tbody>
</table>

Table 4.18 Details and concepts mentioned by HH when viewing an animation of a redox reaction between copper and silver nitrate

4.8.4.2. HL

HL seemed able to grasp the idea of equilibrium as a process whereby forward and reverse reactions occur simultaneously, at the same rate (see page 322). The main flaw in his model was that he believed the reactants and products to be present in stoichiometric ratios (or that the amount of reactants and products were equal at equilibrium). He could not interpret the equilibrium constant. There was also some evidence that he mentally segregated the reactants and products, as demonstrated by the separation of the reactants and products in his representation of the molecular level (see page 324). It is common for students to envisage equilibrium reactions as consisting of two independent and separate compartments (Johnstone, MacDonald & Webb, 1977; Nakhleh, 1992). This student was able to predict the effect of adding more reactant to the system by referring both to Le Chatelier’s Principle and to processes at the molecular level.
HL understood what the $K_a$ value represented and his explanation challenged his conception that the reactants and products exist in stoichiometric ratios, and that amounts are equal at equilibrium. He was unable to resolve this issue.

His representations of acid/base equilibria were dependent on the way the equation was written. That is, he represented either hydrogen ions or hydronium ions, depending on the species written in the equation (see page 324). This suggests that, for novices, visualisation of the molecular level is likely to be governed by how the equation is written.

HL’s interpretation of the analogies (see page 335) suggested that his conception of the amount of reactants and products being equal was firmly established. His interpretation of the dancing analogy (see page 337) provided further evidence that he mentally separated reactants and products. Apart from these issues, he was able to point out many of the correspondences in the analogies, thereby revealing his understanding of simultaneous forward and reverse reactions. Once again, identification of non-correspondences arose from a mismatch between the student’s mental model and the analogy, often when the student’s idea was incorrect.

HL’s representation of solid copper was primitive and his representation of aqueous silver nitrate consistent with his molecular conceptual framework, described on page 431. He was unable to predict the products of the reaction between these substances and struggled to interpret the experimental observations. He did not produce a representation of the products until shown an equation. He used his mental model of the reactants to suggest that nitrate gains a copper, leaving behind its silver on the copper surface. Not surprisingly, he found the animation of the reaction difficult to interpret. His incorrect notion that silver would lose electrons inhibited his ability to correctly interpret the electron transfer depicted by the animation.
Table 4.19 Details and concepts mentioned by HL when viewing an animation of a redox reaction between copper and silver nitrate

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redox Reaction</td>
<td>Presence of a nitrate ion</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Presence of silver balls</td>
<td>Silver nitrate might be present</td>
</tr>
<tr>
<td></td>
<td>A new lattice is being built on top of the existing lattice</td>
<td>A lattice of silver is being constructed</td>
</tr>
<tr>
<td></td>
<td>Yellow balls are being pulled from the existing lattice</td>
<td>A lattice of copper is being pulled apart</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Silver is losing electrons*</td>
</tr>
</tbody>
</table>

*misconception

4.8.4.3. LH

LH had only a partially developed mental model of equilibrium (see page 360). She could not visualise the process at a molecular level, but just knew that the reaction could proceed either way and that all species in the equation were present at any one time in the reaction vessel (see page 361). She had the misconception that the reactants and products would “be equal” at equilibrium. She seemed to conceive of this as being like a balance, with equal amounts of reactants and products. She also believed that the reactants and products would exist in stoichiometric ratios. She did not understand the equilibrium constant, but suggested it might be an indication of the speed at which the reaction reaches equilibrium. This misconception has been noted in previous research (Banerjee, 1995). Although she was able to predict the effect of adding more reactant to the equilibrium mixture, she could not explain this at a molecular level. This is not surprising considering her lack of visual image.

Like other students, LH represented the dissociation of boric acid (see page 363) using a hydrogen ion for the first equation and hydronium for the second. She did not introduce water molecules until they were present in the equation. This, once again, supports the notion that students’ images of the molecular level are largely directed by the equation, especially for new situations. This student even believed that the equations showed different processes.

LH was able to point out some correspondences in each of the analogies (see page 373) but had most success interpreting the dancing analogy (see page 374). Like HL, she identified non-correspondences where the analogy did not match her misconception that the amounts of reactants and products are equal at equilibrium.
LH was able to construct a basic explanation for the redox reaction (see page 364). Her representations of the reactants and products were sloppy and lacked detail. Some errors were also present. They did feature, however, the idea that copper is a structured lattice and silver and nitrate ions are separate in solution, but a lack of correct charges on ions would have hampered her ability to interpret the reaction in terms of electron transfer. The student appropriately identified products formed in the reaction based on experimental observation and made a reasonable attempt to describe the changes at a molecular level. Even though this student had some understanding of the reaction, she was unable to understand the redox animation without assistance (see page 379), as shown by the lack of concepts mentioned when viewing the animation (see Table 4.20).

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redox Reaction</td>
<td>Yellow lattice structure</td>
<td></td>
</tr>
<tr>
<td></td>
<td>A new structure is being formed from silver balls</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yellow balls are taken away and hydrated</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Presence of “shieldy thing”</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.20 Details and concepts mentioned by LH when viewing an animation of a redox reaction between copper and silver nitrate

4.8.4.4. LL

LL understood equilibrium to be a situation in which forward and reverse reactions could occur simultaneously in different regions of the reaction vessel (see page 393). She appeared to perceive it as an interactive process. Like other students, she had the misconception that there would be equal amounts of reactants and products present at equilibrium and could not interpret the equilibrium constant. LL was unsure of the effect of adding more reactant to an equilibrium mixture, but attempted to determine the effect by considering what would happen at a molecular level.

LL’s mental model of equilibrium seemed always to involve the swapping of a single atom back and forth between two species (for example, see page 394). It cannot be determined from the data whether she had this notion before the interview or interpreted all equilibrium situations in the interview in terms of the first equilibrium reaction shown to her.
For the two equations of the dissociation of boric acid (see page 395), this student provided different explanations at the molecular level but claimed that she thought they were the same reaction. This, once again, highlights the difficulty students experience in interpreting equations at the molecular level, and the confusion instigated by having different equations for the one reaction.

LL used her mental model, as outlined above, to interpret the given analogies (see page 406). Because of the specific nature of this mental model, she was unable to make sense of the juggling analogy and provided alternative interpretations of the other analogies. Some confusion she experienced in interpreting the soccer analogy seemed due to the fact that she correctly envisaged an equilibrium reaction as occurring in a single vessel, whereas the analogy physically separated the reactants and products.

Consistent with her other molecular-level representations, this student represented aqueous silver nitrate as molecules in water, and copper as a collection of closely packed copper atoms (see page 397). She predicted the products of the reaction between these substances but provided an erroneous description of how this would occur and the structures of these products. She therefore showed an inability to link the macroscopic and molecular levels. It is not surprising then that she failed to make sense of the redox animation (see page 412) without assistance from the interviewer. She did, however, draw a link between the experimental work and the molecular-level representation. Table 4.21 shows the details identified by this student before and after assistance from the interviewer.

<table>
<thead>
<tr>
<th>Animation</th>
<th>Visual Detail</th>
<th>Concept</th>
</tr>
</thead>
<tbody>
<tr>
<td>Redox Reaction</td>
<td>Formation of new lattice</td>
<td>A solid layer is formed like in the earlier</td>
</tr>
<tr>
<td></td>
<td></td>
<td>experiment</td>
</tr>
<tr>
<td></td>
<td>Yellow structure is vibrating</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Yellow balls are being taken from</td>
<td>Copper is being pulled away by the water</td>
</tr>
<tr>
<td></td>
<td>the lattice</td>
<td>molecules. This changes the colour of the</td>
</tr>
<tr>
<td></td>
<td></td>
<td>solution.</td>
</tr>
<tr>
<td></td>
<td>Presence of a nitrate ion</td>
<td>The solution is silver nitrate</td>
</tr>
<tr>
<td></td>
<td>Presence of a silver ball</td>
<td>The solution is silver nitrate</td>
</tr>
</tbody>
</table>

Table 4.21 Details and concepts mentioned by LL when viewing an animation of a redox reaction between copper and silver nitrate
4.8.4.5. Comments and Comparisons

All students seemed to be aware that in an equilibrium system, the forward and reverse reactions occur simultaneously at the same rate, such that reactants and products are both present at any one time. LH, however, did not have a visual image of the process. The three students with mental images were able to predict the outcome of adding more reactant to the system. This is consistent with the notion that visual images can assist in problem solving (Kosslyn, 1995). These finding suggest a positive impact of animations on students’ mental models, when compared with misconception research suggesting that students often appear to have no image of the multi-particle, interactive, dynamic nature of equilibrium reactions (Nakhleh, 1992; Jordaan, 1993; Garnett, 1998).

A notable flaw in the students’ mental models of equilibrium was that they believed reactants and products to be in equal amounts or present in stoichiometric ratios. This misconceptions has been noted elsewhere (Hackling and Garnett, 1985; Nakhleh, 1992; Garnett, 1998). This misunderstanding may have arisen from an everyday understanding of the term equilibrium, demonstrating the effect of inappropriate language in chemistry and the effect of prior knowledge on learning. Similarly, students enter science education with a layperson's understanding of terms such as "shells", "clouds", "melting" and "bond". If they make interpretations based on their established definitions, then misunderstanding is likely to result. The problem of scientific language as a barrier to learning is widely reported (Sleet, 1993; Ebenezer & Gaskell, 1995; Harrison & Treagust, 1996; Schmidt, 1997; Boo, 1998; Gabel, 1999).

The equilibrium constant had little or no meaning for these students. This could be addressed during instruction through a more thorough linking of the K value to molecular-level representations, perhaps via an interactive computer simulation that allows students to alter the K value (perhaps by adjusting the temperature) and observe the effects on a molecular-level representation.

Prior knowledge effects, if any, were not particularly pronounced for the concept of equilibrium. This is probably because the content of the questionnaire used to measure prior knowledge was not directly related to equilibrium. This is consistent with the conclusions of Chapter 3 that suggest that prior knowledge of sodium chloride and water at the molecular
level was not useful in topic-transfer situations. However, in this case, it could be argued that the students with low prior knowledge had more restricted mental models. LH did not have a mental image of the process and LL had a narrow view of the equilibrium process as involving the passing around of a single atom. No effects of disembedding ability were detected.

All four students tended to experience some difficulty in interpreting the analogies, even though they had some basic knowledge of equilibrium reactions.

The two-sidedness of the soccer analogy seemed to confuse students, who had the image that reactants and products are generally not physically separated. The two-sided nature of some analogies has been previously criticised (Johnstone et al., 1977). The statement in the soccer analogy that “identities are different” also seemed to cause much confusion, as the chemical world “identity” is determined by composition. Each molecule of NO, for example, does not seem to have an individual identity. Therefore, this comment was probably too far removed from the students’ mental models.

Students had difficulty pointing out relevant non-correspondences. Firmly held misconceptions, such as there being equal amounts of reactants and products, led students to inappropriately criticise certain parts of the analogies. Non-correspondences were also blamed when students’ struggled to relate a feature of the analogy to their concept of equilibrium. The identification of a non-correspondence may therefore result either from a limitation of the student’s mental model or a weakness in the analogy. These are aspects that would need to be given special attention if using the analogy in teaching. Use of an analogy may be particularly valuable in cases where it confronts or conflicts with a misconception, e.g., an analogy that demonstrates that the reactants and products need not be in equal amounts.

Difficulties experienced by students indicate that, if left alone to interpret analogies, as is often the case with analogies in text-books (Thiele & Treagust, 1995), they may incorrectly identify the correspondences. This may have negative effects on the their mental models and once again stresses the importance of discussing analogies with students, pointing out their strengths and limitations (Thiele & Treagust, 1995). Not surprisingly, students liked the analogy that they could most easily interpret. The dancing analogy was selected as the favourite as it appeared to most closely match students’ mental models.
Students’ responses to the boric acid question provided another example of the effect of the equation on students’ images of the molecular world. Only HH commented on the presence of hydronium ions when shown the equation containing a hydrogen ion. Other students only introduced the hydronium ion when it was present in the equation. This suggests that students with limited understanding of acids at the molecular level are likely to assume that the equation gives an indication of the species present. This is also consistent with the fact that no students represented hydronium ions in their depictions of sulfuric acid discussed earlier.

Only HH was able to identify the redox animation without assistance from the interviewer. This is consistent with the fact that his interpretation of the redox experiment was closer to scientific acceptability than those of the other students. This is another indication that prior knowledge will influence students’ ability to interpret animations and emphasises the importance of providing assistance in their interpretation, especially for novices. Students’ interpretations of the redox experiment, at a molecular level, suggest the importance of developing basic images of substances prior to introducing more complex topics. A lack of correct images of metals and ionic solutions is likely to impair students’ understanding of redox reactions.

### 4.8.5. Modelling Ability

To minimise bias due to the preconceptions of the author, the student profiles and collated responses were studied by another academic, and modelling levels were assigned to each student, based on a thorough review of Grosslight’s (1991) comments. The author and the academic discussed the assignments until agreement was reached. Because questioning in these interviews focused on different areas of modelling, it was difficult to tell whether students’ modelling abilities had changed over the semester. Therefore, modelling abilities were allocated based on a general overview of the students’ comments in interviews 1 and 3. In a case study by Harrison and Treagust (2000), general modelling ability was assigned to a student based on his use of models over the course of a year.

#### 4.8.5.1. HH

Much of HH’s discussion of models (Section 4.3.4.1, pages 286 to 291) suggests that he was operating at level 2 modelling ability. He saw models as being useful for assisting
understanding. He identified suitable uses for different models and viewed models as being purpose-built. He saw models as fluid, in the sense that he expected they would change or develop over time, and he expected to be confronted with more advanced models in the future. He accepted the presence of multiple models, showing competence at identifying correspondences and non-correspondences between the model and target. However, he still believed that one model was better and more realistic than others. He therefore realised there is not a one-to-one correspondence between the model and reality, but still concentrated on the reality being portrayed, suggesting level 2 modelling. This was particularly evident in his discussion of the space-filling model, when he suggested that it was close to what a water molecule would actually look like (with some deliberate simplifications to aid understanding), whereas the other models were just representations. His conception of the remaining models was probably closer to that of a level 3 modeller. Although he was able to note unrealistic features of the VisChem water molecule, it is possible that the perceived “reality” of the animations slowed his progress to level 3 modelling ability.

4.8.5.2. HL

HL was classed as a level 2/3 modeller (see pages 328 to 333). He understood that models are not replicas of the target situation and was able to identify some correspondences and non-correspondences between the models and their targets. His inability to select the “best” models attested to his acceptance of multiple models and a realisation that no one model is inherently better than the others. HL conceived of different models as being useful for showing different features and explaining different ideas. Choice of model would be determined by the idea that was to be explained. This suggests an understanding of models being purpose-built and used in explanation. He seemed to have moved beyond thinking of models as portraying reality, suggesting, for example, that different scientists may have different explanations of the same phenomena. He believed models were developed to explain phenomena observed in experiments and then to explain these ideas to others. He therefore saw models as being communicative and explanatory tools. He did not mention models as tools for testing ideas or making predictions, so he did not appear to have reached level 3 modelling ability. As with HH, his conception that VisChem animations were quite realistic may have hindered his progress to the next level.
4.8.5.3.  LH

LH was rated as a level 1/2 modeller (see pages 368 to 371). She focused on the reality being portrayed by certain models, suggesting that a water molecule could not be depicted unless someone had actually seen one. She demonstrated limited ability to identify correspondences and non-correspondences. She began to realise that different models can be used to show different features, such as electron arrangements, but did not articulate this as a reason for multiple modelling. Most of her discussion of models and reasons for modelling focused on the use of models for enhancing visualisation. She did not elaborate on what made one model easier to visualise than others. It is likely that the familiarity and concreteness of the models played a role. This student seemed to have an unquestioned acceptance of multiple models, with her suggestion that “there’s no set way that you can visualise it”. She believed that all models of the one substance ultimately represented the same thing and that perhaps there is some redundancy in having more than one. This idea, coupled with the notion that different models suit different people, suggests that she does not realise the reasons for having different models of the same substance but feels that choice of model is based purely on personal preference. She did suggest, however, that models might change due to experimentation and advancement of knowledge.

4.8.5.4.  LL

LL was also rated as a level 1/2 modeller but with a leaning towards level 2 (see pages 400 to 404). She seemed to express a willingness to view modelling at level 3, but apparently didn’t exhibit this understanding because she lacked the appropriate knowledge of chemistry. Like LH, she made decisions about the “best” representations based on how easily she could visualise them. Once again, this could be attributed to the familiarity with the model and the concreteness of the model. In interview 1, she said little about correspondences and non-correspondences in relation to the models of the water molecule, except in regard to the VisChem animation. She was able to identify non-correspondences in the animation, showing that she was aware that there is not a one-to-one correspondence between model and target. Her discussion of the other models focused more on appropriate uses of each model based on the ease of representing substances using the model, suggesting an understanding that models are purpose-built. These purposes were related to communicative ability, suggesting level 2 modelling. In interview 3, she discussed the models of sodium chloride in relation to features shown in each animation. She used this information to judge the quality of the
representations, and did not seem to appreciate that this might serve a purpose. Like LH, LL saw different models as different ways of showing the one concept such that any model would be suitable, depending on the learning style of the person and not the task at hand. This contradicted her discussion of the most appropriate uses of different models. LL understood that models may be developed based on mathematical data, but commented that this enabled scientists to show what a molecule looks like. She believed that models were designed to facilitate understanding, perhaps by improving visualisation. She accepted that models might develop further and that she would probably be confronted with more complex models as her knowledge progressed.

4.8.5.5. Comments and Comparisons

In general, modelling ability appeared to be influenced by prior knowledge, as predicted. The students with high prior knowledge appeared to have a stronger grasp of modelling than the students with low prior knowledge. However, the modelling abilities of the students with high prior knowledge were not as high as initially predicted. No student consistently demonstrated level 3 modelling ability; the interviewed students were simply not experts. There are several plausible explanations for this:

1. *The teaching did not encourage students to develop level 3 modelling ability.*

Modelling was not explicitly taught to students and no opportunities were given for students to use models to test ideas, predict or solve problems, as recommended by Treagust *et al.* (2000). Furthermore, teaching may in fact have inhibited the development of students’ modelling ability. Students were commonly instructed to imagine what they might see at a molecular level, creating a sense of realism.

2. *Exposure to VisChem animations inhibited development of modelling ability.*

No student exhibited level 3 modelling when discussing reasons for the development of molecular-level animations. For example, no-one mentioned that mental models resulting from exposure to animations could be used for predictive purposes.
Furthermore, the vividness of the VisChem animations may have encouraged these students to see them as portrayals of reality (with some modifications), despite the fact that the animation video specifically stated that the animations are just a way of thinking about the molecular level and not a depiction of reality. Designers of VisChem were aware of this issue and produced teaching resources to accompany the animations to help students develop their understanding of scientific modelling. These resources were not utilised in the teaching of these students.

3. Methods used to probe students modelling ability did not encourage students to reveal level 3 understanding.

In defence of the students, it is possible that the “concrete” models discussed in interviews, using animations and drawings as stimuli, were not conducive to identifying level 3 understanding. If students had been asked to discuss more mathematical or abstract models, it is possible that they would have mentioned ideas discussed by experts in Grosslight’s study, such as the use of models for formulating and testing ideas, and making predictions.

The study demonstrated that prior knowledge and experience with chemistry influence students’ modelling ability, as suggested by Grosslight’s work. Incorporation of explicit teaching relating to modelling might remedy some of the concerns outlined above.

### 4.9. Conclusions

This study examined the ways some individuals learn in chemistry and drew comparisons between students, with reference to their prior knowledge and disembedding ability. Following is a summary of the findings relating to the possible general effects of prior knowledge and disembedding ability on students’ mental model development in chemistry and their ability to interpret animations. A specific discussion of the hypotheses for each student is the provided. Due to the small sample size, conclusions stated are speculative and refer only to this sample. Further research is needed to substantiate or generalise any claims regarding the effects of prior knowledge and disembedding ability. Possible avenues of further research are discussed in Chapter 5.
4.9.1. **Effects of Prior Knowledge**

The extent of prior knowledge appeared to affect development of scientifically-acceptable mental models, ability to apply mental models of molecular substances, ability to critically analyse, conceptual understanding of animations and modelling ability.

With HH, these abilities appeared to occur in conjunction with a deep learning style. The students with low prior knowledge reverted to original conceptions of ionic solutions after instruction was complete, suggesting a more surface approach to learning. These observations are consistent with the results emerging from the statistical analysis in Chapter 3, suggesting that deep and surface learning influenced outcomes on the post-test and topic-transfer test, and that prior knowledge correlates negatively with surface learning. The effects of deep and surface learning were not controlled for in these case studies.

Misconceptions and everyday understandings appeared to influence students’ interpretation of models and chemical terminology, and hence inhibit their ability to develop scientifically acceptable ideas. This was the case, for example, in students’ interpretation of the packing of molecules in the ice melting-animation, their interpretation of equilibrium analogies and their understanding of the term “equilibrium”. The effect of prior alternative conceptions on learning is included in a model of model-based learning described by Clements (2000) and models of conceptual change described by Pines and West (1986).

4.9.2. **Effects of Disembedding Ability**

The effects of disembedding ability were not as pronounced. It was hypothesised that conceptual change mechanisms might be different for students with high and low disembedding ability, as evidenced by changes in students’ models of molecular and ionic substances over time. It was proposed that students with high disembedding ability might view their mental model as a collection of parts, from which they can add or subtract specific features, whereas students with low disembedding ability might view co-existing, competing images (pre-existing and formally taught) as whole units, and thus fluctuate between the models. Whether students attempt to integrate new information *via* conceptual development, resolution or exchange (Pines & West, 1986) may be influenced by the disembedding ability of the student. The students with low disembedding ability in this study had not fully achieved conceptual exchange, as some of their original models co-existed with taught ones. The
difficulty in achieving conceptual exchange may contribute to the poor performance of students with low disembedding ability on the post- and transfer tests. This hypothesis, however, was not carried through to students’ mental models of precipitation reactions examined in the post-test. The development of this image for most students appeared to occur via conceptual development, with students slowly developing and improving their mental models towards the target system, while retaining some earlier conceptions.

Differences were found between students with high and low disembedding ability in their interpretation of “molecular” equations involving ionic species. Students with high disembedding ability were more likely to use their acceptable mental models of ionic solids and solutions to represent these equations. Students with low disembedding ability were more likely to use their alternative “molecular” conceptions. This was interpreted as an increased facility in students with high disembedding ability to identify and extract relevant information from long-term memory, for transfer. The influence of disembedding ability did not seem to extend to the interpretation of molecular representations or macroscopic phenomena. It is not surprising that no effect was found with molecular representations, because students “molecular” conceptions were relevant to these situations.

4.9.3. **Interpretation of Animations**

The students with high prior knowledge were, in general, more able to discuss ideas not immediately observable in animations. Understanding of the redox topic improved a student’s ability to interpret a previously unseen animation of the redox process.

There seemed to be little difference in individual students’ abilities to identify relevant features in the VisChem animations, except that only students with high disembedding ability noticed the intermolecular bonding in the ice-melting animation. Whether disembedding ability does in fact influence students’ ability to notice relevant features in animations, as proposed in Chapter 3, is therefore an area of ambiguity and requires further investigation.

No effects of disembedding ability or prior knowledge were found on students’ use of animations as learning aids. All students mentioned animations as helpful in developing their images.
Although the students’ mental models improved during the year, often after being shown animations in lectures, many misconceptions persisted. The most prominent was the idea that molecules are present in ionic solids and solutions. HH was least likely to demonstrate misconceptions, indicating again the positive effects of high prior knowledge combined with high disembedding ability. This also indicates that the use of animations to dispel misconceptions might be futile, depending on the characteristics of the students.

4.9.4. Examination of Hypotheses

It was fairly clear from the interviews that HH outperformed the other students in most areas examined. He did indeed possess excellent mental models of the molecular and ionic substances shown in the animations, and demonstrated a unique ability to use these models in new situations. He was able to point out and explain relevant details in animations even when he did not recall the animation or had not seen it previously. Although his modelling ability was not as sophisticated as predicted, he did appear to have a comparatively good understanding of models and modelling. Furthermore, HH appeared to use deep thinking in his responses, spontaneously drawing links between his existing knowledge and the new problems with which he was confronted. He also demonstrated metacognitive abilities as part of this approach, showing an awareness of the fact that he was applying his mental models. Chin and Brown (2000) describe deep learners as having the ability to "generate an answer when they do not have an immediate ready-made solution to a problem" and that this ability "embodies ideas of creativity, lateral thinking, and fluency in the generation of ideas." Deep learners, in their study, were able to generate on-the-spot explanations for their observations and were able to describe non-observable phenomena. They also engaged in frequent metacognitive activity. The adoption of deep-learning strategies by HH is likely to have contributed to the apparently superior abilities of this student, supporting the statistical analysis outlined in Chapter 3.

HL showed reasonable mental models of substances shown in the animations, as predicted, but showed more progress than was expected. He demonstrated some ability to apply knowledge but not at the level predicted. This may be explained by the fact that this student did not show a tendency to use deep thinking. HL was able to point out and explain relevant features in animations, but did not restrict his discussion to global features as had been
expected. He showed the highest modelling ability of the four students, although he did not reach level 3 modelling ability.

As predicted, LH showed significant progress with her images through the year, but her mental models did not seem quite as sophisticated as HH’s. She succeeded to a certain extent in directly applying her knowledge, especially for ionic substances, counter to the hypothesis. She appeared to have difficulty with applying knowledge that required deeper thinking. LH was able to point out the relevant details in animations but had some difficulty explaining the details, as predicted. She showed restricted understanding of models and modelling, rating as a level 1/2 modeller, consistent with the initial hypothesis.

LL appeared to struggle more with her mental models than the other students but certainly showed some progress through the year, as predicted. She showed greater ability in applying her knowledge than was expected, particularly with molecular substances for which her knowledge was reasonable. She could point out details in animations beyond just the global features, but did have trouble explaining the concepts underlying these features. She rated as a level 1/2 modeller, as predicted, but her discussion suggested that with improved knowledge of chemistry, she would advance easily to level 3 modelling ability.

From the above discussion, it can be seen that prior knowledge and/or disembedding ability are reasonable indicators of the sophistication of students’ mental models of the substances depicted by animations, and of modelling ability. Combinations of prior knowledge and disembedding ability were not sufficient to predict students’ ability to apply information or their ability to point out details or global features of animations. It is likely that other factors, such as study style, are operating when knowledge is being applied. The ability to see details in animations may only be affected by disembedding ability when the stimulus is new (first-time exposure to VisChem animations) and the student is left to decipher the animation on their own. In most cases in this study, students had seen the animations before and the relevant details had been pointed out to them. These students had also developed an ability to “read” animations – recognising familiar features such as the vibrations in a solid, and the hydration of ions.
4.9.5. Further Comments

The improvement in students’ mental models from pre-test to post-test says little about the way in which students’ ideas develop and change over time. Detailed case studies are required to closely examine mental model development. In this study, it was clear that the road to improvement is not necessarily smooth or linear. Students oscillate between scientifically acceptable and alternative mental models. They may recall certain features at one point in time and completely forget them at another. Students may retain certain ideas for a period of time and then discard them. Alternatively, there might be a changeover period when students are attempting to integrate or exchange their old models with new ones, negotiating which are more fruitful, make more sense to them or are simply easier to understand. Most students in this study were still in the process of developing the scientifically acceptable models taught at first-year level, but without further interviewing it cannot be determined whether these students completed the transition from alternative to scientifically acceptable mental models during their degree. The fact that students might not have developed these basic models by the end of their first year of chemistry suggests the need to reiterate the ideas in subsequent years of study, before presenting ideas that build on these initial models.

This study provides further evidence of the difficulties some students experience in relating the symbolic level to processes at the molecular/ionic level. The available evidence suggests that the use of multiple equations to represent a single chemical process can be confusing for students, who are likely to represent these equations differently at a molecular level. This occurred because students tended to interpret each equation as a literal representation of the molecular level. This further emphasises the dangers of using “molecular” equations to represent ionic processes, as discussed in Chapter 2 (Section 2.3.2.2), and hence the importance of using equations that most closely mimic the molecular-level processes. This is obviously most crucial for novices, who do not have the prior knowledge necessary to appropriately interpret the more abbreviated symbolic representations.

Students’ interpretations of diagrams and animations in this study support two important aspects of learning from visual representations (diagrams and animations). Firstly, the level of prior knowledge affects a student’s conceptual understanding of representations and their ability to interpret new visual representations. Secondly, as pointed out by Tasker (1998) and Pint and Ametller (2002), poorly designed or explained representations may contribute to the
development of misconceptions. As a consequence of the first statement, this is likely to be most detrimental where prior knowledge is low and the ability to critically analyse is poor. These students are more likely to accept representations given in textbooks or by instructors, without question, especially if they appear simple.

The study also elucidates some new tools for probing student understanding and for improving conceptions. The critical analysis of diagrams, analogies and animations appears to be a successful method for revealing students’ misconceptions. The high-level thinking involved in such exercises suggests that these tools may also be useful for enhancing student learning. Such exercises require students to have not only adequate knowledge of the concepts, but also the ability to apply this knowledge and the confidence to challenge representations designed by “experts” (textbook writers, lecturers, etc.). Encouraging students to practice critical thinking skills may well promote deeper learning, as well as enhancing students’ modelling abilities.

Students’ drawings may also be a worthwhile tool to encourage deep learning and enhance the development of mental models. Drawings can provide hard copies of students’ conceptions at particular points in time, enabling students to see changes in their ideas over time. Viewing these changes might spark reflection and metacognition, resulting in re-evaluation of their current mental models.

### 4.9.6. Summary of Findings

The small sample in this study does not allow for a generalisation of results because there is no guarantee that the students in this study were a representative group of first-year students, or of the population. In fact, the students’ post-test results do not follow the expected trends, suggesting that these students are not representative. The findings, however, help substantiate some of the claims from the quantitative analysis in Chapter 3:
• Prior knowledge has an effect on the development of students’ mental models and ability to interpret animations;
• A combination of high prior knowledge, high disembedding ability and deep learning results in superior mental models of chemical phenomena and the ability to apply these mental models to new situations;
• Disembedding ability acts in some way to assist in the transfer of information to new situations;
• Deep and surface learning appear to be significant factors in the development of students’ mental models and their ability to apply these models;
• Low prior knowledge may result in a surface approach to learning.

Furthermore, it can be tentatively concluded that prior knowledge has an effect on critical thinking ability and modelling ability.
Chapter 5

Conclusions

The VisChem animations were designed to address a dominant concern in chemical education relating to the prevalence of misconceptions among students of all ages and experience. The production of these visual aids was seen as an appropriate method for helping students develop scientifically-acceptable and useful mental models of substances and processes at the molecular level, which might lead to a more meaningful understanding of chemistry.

The major focus of this thesis was, therefore, to determine if students learn from these resources and under what conditions this learning occurs. These data can then further inform the development of animations, the design of multi-media programs and the delivery of instruction. The studies presented in this thesis reveal that the factors involved in teaching and learning from animations and developing mental models are complex. Effectiveness will depend not only on how the animations are presented but also the nature of the students who are receiving the instruction.

This final chapter endeavours to amalgamate the key findings of the research presented in Chapters 2 to 4 with reference to the aims of the project outlined in Chapter 1. The chapter presents recommendations for effective incorporation of visual representations into chemical education, based on these key findings. Contributions to current literature in the field are discussed and avenues for further research proposed.

5.1. Conclusions

5.1.1. Project Summary

The central aim of the studies outlined in Chapter 2 was to examine the effectiveness of using VisChem computer animations to help students develop useful and acceptable mental models of chemical phenomena. It was concluded that VisChem animations had an instrumental effect on students’ mental models: assisting in the learning of specific key features of molecular and ionic substances, improving students’ confidence in their ideas and the
vividness of their images, and enabling some students to visualise substances and systems not depicted by the animations. Furthermore, third-year students who had seen animations in first-year chemistry had more detailed mental models than those who had not, they recalled animations two or more years after instruction and commented on the positive effects of having seen them. The most significant benefit appeared to be the establishment of multi-particulate, dynamic, interactive and three-dimensional images of the molecular world.

Chapter 3 presented a proposed model of the perceptual processes involved in interpreting an animation, with which to examine factors that might affect a student’s ability to construct acceptable and useful mental models of chemical phenomena. Based on the results of multiple regression analysis, it was proposed that prior knowledge, disembedding ability and deep and surface learning had the most significant effects on the development and the sophistication of students’ mental models of substances shown in animations and their ability to apply these mental models to new situations. These results provide support for the proposed model. A follow-up study, replicating aspects of the original study, confirmed the role of prior knowledge, and to a lesser extent disembedding ability, in students’ mental model development. The case studies in Chapter 4 provided further evidence for the effects of prior knowledge and disembedding ability on students’ mental model development, and supported the influence of deep or surface study styles on learning outcomes.

Based on the analysis of Chapter 2, it was proposed that the potential benefits of using VisChem animations, and perhaps animations in general, rely on the method of delivery. Moreover, the results of Chapters 3 and 4 indicate that students’ personal characteristics influence their ability to develop and use appropriate mental models. Recommendations for the use of VisChem animations, based on the above findings, are given in Section 5.1.2. These recommendations take into account the discussion in Chapter 2 relating to why students may not have developed certain key features, and also consider the model of perceptual processes involved in perceiving an animation, presented in Chapter 3.

5.1.2. **Recommendations for Use of VisChem Animations**

Some ideas have emerged from the research regarding how VisChem animations might best be presented to maximise their effectiveness. This section uses the model of perception presented in Chapter 3 as a framework to support and explain suggestions for the effective
incorporation of VisChem animations into the teaching of chemistry. These recommendations initially emerged from the studies conducted in Chapter 2, relating to the effectiveness of using VisChem animations in the teaching of first-year chemistry. Many of these recommendations are consistent with the “best practice” protocol (see Appendix F) introduced in Chapter 2, some of which was not adopted by the lecturer. The case studies presented in Chapter 4 provide further evidence for the general recommendations. Some of the recommendations are interrelated, so there is some overlap between the different suggestions.

**Consider the Prior Knowledge of Students**

The long-term memory stores information that we use to interpret incoming stimuli. That is, our perceptions are based partly on our previous knowledge and experiences. De Bono (1996) proposes that “Perception is by far the most important part of thinking” (p. 47). Several educational researchers have commented on the influence of prior knowledge on students’ ability to learn from models in science (Dyche, McClurg, Stepans & Lois Veath, 1993; Duit & Glynn, 1996; Clement, 2000; Greca & Moreira, 2000; Jones *et al.*, 2001). The results of this research re-emphasise the important role of relevant prior knowledge in learning. A comparison of the 2000 and 2001 data in Chapter 2 (Section 2.2.4) demonstrated that prior knowledge influences the development of students’ mental models. The importance of prior knowledge was further emphasised in Chapter 3 where it emerged as one of the most important factors contributing to the sophistication of students’ mental models and their ability to apply these mental models. Finally, Chapter 4 examined areas where prior knowledge was acting to enhance or inhibit the development of mental models, revealing differences between students with high and low levels of prior knowledge in their modelling abilities, their ability to critically analyse scientific diagrams and their ability to discuss VisChem animations conceptually. These findings support the inclusion of the long-term memory (LTM) in the model of perception and indicate the need to consider prior knowledge when using animations in teaching.

It is clear that in order to *fully* interpret certain animations students need to understand certain chemical concepts such as electrostatic attraction, the differences between atoms, ions and molecules, and the polarity of a water molecule. The results of Chapter 3 indicate that students with basic knowledge of ions, atoms and molecules prior to instruction showed the greatest improvements in their mental models of substances shown in animations. If students
do not have this relevant prior knowledge, their interpretation may fail, even if their attention is directed to the relevant features of the animations.

To make students aware of their existing mental models before showing animations is a technique included in the “best practice” protocol (Appendix F) to address the issue of prior knowledge. Although beneficial, this suggestion does not allow for any modifications to the teaching if the appropriate prior knowledge does not exist.

Each VisChem animation contains a set of key ideas. A mental image derived from an animation may or may not contain all these ideas. The particular ideas that students retain for their own mental images will, in part, depend on their prior knowledge. Ideally then, animations will be used to teach only the key features that the students are capable of learning, based on their prior understanding. General features of the molecular level, such as movement and its multi-particulate nature, are easily interpretable and can be pointed out to novices on the first viewing of an animation. As the knowledge of the students increases, the same animations can be shown again, with emphasis on different key features, such as the structure of individual particles and the interactions between them. Note that students with low prior knowledge showed great improvements in their mental models (Chapter 2), so it appears there are many key features in the animations accessible to novices, under the conditions used in this study. The students with even lower prior knowledge, however, showed limited conceptual understanding, as indicated by the fact that they were generally less able to apply their knowledge (Chapter 3) or discuss the concepts associated with the animations (Chapter 4). The important point, therefore, is that the key concepts relevant to each animation should be discussed before the animation is shown. Animations complement but do not replace the teaching of these concepts.

**Focus Attention on the Relevant Features**

In Chapter 2, insufficient emphasis on certain features of the animations during instruction was proposed as a reason for the lack of recall or knowledge of those key features. This is consistent with the proposed model of perception; the attention networks need to be activated for meaningful learning to occur.

Students with high prior knowledge may notice relevant details in animations, unassisted. Other students will need to have their attention directed to the relevant features by the
instructor. In the “best practice” protocol, it is recommended that a verbal narrative be provided when showing animations, to guide students’ attention to the important features. This is particularly important in the case of novices, whose attention may otherwise be centred on the more “perceptually compelling” (Lowe, 2001) or surface features (Kozma & Russell, 1997) of the display. The importance of providing a verbal narrative has been emphasised in a number of studies, although reasons for its inclusion varies (Mayer & co-workers, 1991, 1992, 1998; Russell et al., 1997; Burke et al., 1998). In the case of the 2000 study described in Chapter 2, the verbal narrative was necessary but insufficient to guide the assimilation of some of the less obvious features. Jones et al. (2001) provide a possible solution.

“There will be cases where most novices fail to see what is important in an animation. One corrective strategy is breaking a continuous transformation down into static snapshots, which are then annotated and compared.” (p. 11)

Other possible approaches include: stopping and starting the animation sequence to discuss certain features and ideas and cutting the animation down into smaller, more manageable sequences which can be individually discussed before showing the entire sequence.

**Encourage a Deep Approach to Learning**

Simply focusing the student’s attention on key features is insufficient for meaningful learning. The results of Chapter 3 revealed that deep learning plays a role in mental model development. These results were supported by research in Chapters 2 and 4 demonstrating that students can and will learn ideas from animations by rote, especially if they have low levels of prior knowledge.
For deep learning to occur, information must be processed by the working memory (WM) and then related to existing knowledge in the LTM. Links can also be established between different concepts or images already present in the LTM. Students who participated in this research, who adopted deep-learning approaches and limited their use of a surface approach, developed more detailed mental models of the substances shown in the animations and were more successful at answering topic-transfer problems.

Therefore, to achieve the maximum effectiveness from animations, students need to be aware of how the animations relate to their existing knowledge and to other material being taught (see Figure 5.1). Some general instructional methods for helping students relate material include self-questioning (metacognition) (Sleet, 1993; Johnstone, 1997), concept mapping (White & Gunstone, 1992; Regis, Albertazzi & Roleto, 1996), relational diagrams (White & Gunstone, 1992), creativity exercises (Trigwell & Sleet, 1990) and brain-storming techniques, such as word association (White & Gunstone, 1992). Class discussion and questioning were mentioned throughout Chapter 2 as means of drawing students’ attention to certain key features in the animations and emphasising their relevance. Discussion, either as a class or in small groups, is an extremely useful tool with which to enhance a deep understanding of the subject matter, as outlined by Wood with Sleet (1993).
“Discussion can promote active learning because in effective discussion students can:
• express what they have learned in their own words;
• think critically about new knowledge and ideas;
• justify any decisions they make which are based upon the new knowledge and ideas;
• be prepared to admit to uncertainty and lack of knowledge; and
• be prepared to admit incorrect thinking and the superiority of another’s ideas without loss of self-esteem.” (p. xiii)

It is highly recommended that class or group discussion be incorporated into instruction before and after the animations are shown. Its content will depend on the ideas being presented in the animations.

Proposing thought-provoking questions to students to encourage them to think more deeply about certain concepts relating to their mental models was also discussed in Chapter 2. As demonstrated in the interviews in Chapter 4, questioning can encourage students to evaluate and reconsider their mental models, and direct them towards more scientifically acceptable explanations.

Relate Animations to Prior Knowledge

If students are exposed to new ideas when viewing animations, there may be a reluctance to incorporate these new ideas into their existing images or concepts, especially if the new concepts contradict their existing knowledge. In this research, this was evident in relation to the ideas of movement (Chapter 2), electrostatic attractions between water and ions (Chapters 2 and 4) and the separation of ions in solution (Chapter 4), to mention a few.

Techniques such as brainstorming the relevant ideas, and drawing mental images prior to viewing animations (as suggested in the “best practice” methods but not adopted in the instruction) may be useful in helping students extract the relevant information from the LTM, to be used when interpreting the animations. Producing drawings before viewing the animations can also serve as a “conceptual change” strategy; by adopting the prediction–observation–explanation (POE) protocol (White & Gunstone, 1992), students can predict what something will look like at the molecular level, then observe where their representation differs from the animation.
Encourage Understanding and Acceptance of Key Features

Encouraging acceptance and understanding of key features should also help students integrate new features into their existing knowledge. This should be achieved by emphasising the importance of each key feature in relation to everyday or chemical examples, experimental results, and calculations, thus providing reasons for why certain features are part of the model.

One everyday example used in this research was the idea that water expands when frozen. Students realised that their mental models were inadequate to explain this phenomenon but found it difficult to modify their models to accommodate this observation. When shown an animation of ice melting, some students were able to devise an explanation. The remaining students might have benefited from a group discussion after viewing the animation.

In the effectiveness studies presented in Chapter 2, the number of students incorporating the idea of gaseous collisions into their mental models of a gas was low. Discussion of the idea that reactions in the gas state occur as a result of molecules randomly colliding might help to highlight the importance of this feature.

The misconception that ionic solutions contain only molecules of the ionic substance was common among students in this research. Students could be taught that a current flow in a solution indicates the presence of ions. Through experimentation, students could be encouraged to construct models of molecular and ionic solutions that account for the extent of current flow. Animations can then be used as a feedback mechanism with which students could “check” their conclusions.

In Chapter 2, it was proposed that relating the animations to calculated values could be used to emphasise certain key features. Sleet (1993) has used calculations to promote the development of correct images of the molecular world. Calculating the number of water molecules present per formula unit in a 1 M solution could, for example, be used to emphasise the ratio of water molecules to ions. Interpreting chemical calculations at the molecular level should encourage a deeper appreciation of the values determined. Calculations are all too commonly considered just an algorithmic exercise.
Relate Images of Animations to New Situations

Students may endeavour to use their images of animations in new situations without prompting, as was the case with some first-year students (Chapter 2, Section 2.2.5.3) who used their images of animations to answer transfer questions; and third-year students (Chapter 2, Section 2.4.3.2) who identified the animations as a good foundation for further study and identified various topics and subjects where they found recollection of animations useful. Comments by first-year students (Chapter 2, Section 2.2.5.4) suggested, however, that the tendency to visualise decreases for topics where visualisation is not encouraged. Furthermore, some third-year students felt that including animations beyond first year would have assisted with second- and third-year topics. Teachers may, therefore, need to instruct students to refer to their mental images of a particular animation when it is relevant to the new topic or idea, or show the animation again in relevant topics, with emphasis on different attributes of the animation. New animations could also be related to previously shown animations by encouraging students to recall the original animation before showing the new one.

To encourage students to *use* their mental models derived from animations, they should be required to solve problems, for example to:

- *Propose* possible molecular-level structures and processes;
- *Explain* phenomena or experimental results;
- *Predict* the outcomes of reactions; and
- *Critically analyse* other molecular representations.

Examples of these types of activities were used in both interviews and questionnaires throughout this research, to probe the students’ understanding; for example, in predicting the outcome of the reaction between solid copper and an aqueous solution of silver nitrate or explaining why nail-polish remover smells. It is likely that such activities promote deep thinking.

When different models or techniques (symbolic notation, ball-and-stick models, *etc.* ) are used to teach related concepts, students should be encouraged to draw links between the information gained from these different sources and the animations, so that the knowledge of the different features doesn’t become compartmentalised. For example, if symbolic drawings
are used to teach about intermolecular forces, students should be encouraged to find these forces in the animations.

**Use Animations to Teach Visual Concepts**

Based on the results of the first-year chemistry and longitudinal studies outlined in Chapter 2, the VisChem animations appear to be most effective when they are used to teach visual concepts. According to the model of perception, some of the more obvious features (colour, movement, three-dimensionality) are registered automatically by the brain. Perhaps then, it is not surprising that ideas such as movement and three-dimensionality are commonly mentioned when students are specifically asked about the animations. Unfortunately, however, because they are so easily grasped, these features are often taken for granted by students, who fail to acknowledge them as important features when producing representations of specific substances. Therefore, such features must be brought to students’ conscious awareness (working memory) by being mentioned in a verbal narration and included in drawings, and by encouraging students to solve problems requiring a multi-particulate, dynamic and three-dimensional image.

For the animations to reach their full potential, their processing must go beyond the features that are automatically registered (attention networks, WM and LTM need to be activated). When a verbal narration is used with the VisChem animations and appropriate learning techniques are adopted (such as student drawings and explanations of the relevant chemistry), other visual features, such as the orientation of water molecules, are transmitted effectively.

In Chapter 2, the failure to mention certain key features was attributed to the difficulty associated with visualising the concepts and hence representing them in animations. For example, the fact that ionic solids are constructed from ions, not atoms, is difficult to represent visually and may be best taught using another method. For this particular example, modification of the animation *via* the addition of labels (Na\(^+\), Cl\(^-\)), would serve to integrate the symbolic notation with the molecular-level representation. These labels could be removed once the instructor had established the key ideas. A similar approach could be adopted for features like intermolecular forces, by including additional notation to represent bonds and partial charges, which could later be removed.
Some animations are also better at representing certain features than others. The most effective instruction will use the animation best suited to the concept. For example, the students described in Chapter 4 commonly mentioned attractive forces when questioned about aspects of the “water evaporating” animation. Researchers working on pedagogical content knowledge (for example, Mulhall, Milroy, Berry, Gunstone & Loughran, 2000) propose that certain instructional methods are best suited to teaching particular concepts, to enhance the effectiveness of the instruction. Such an approach might involve the use of animations.

**Present Ideas Visually, Verbally and Conceptually**

Working memory consists of visuospatial and phonological components (Baddeley, 1992) and, according to dual-coding theory (Paivio, 1971), information may be stored as propositions or images in the LTM. Riding’s (1998) cognitive styles analysis revealed individual differences in students’ preferred modes (visual or verbal) of processing information in the WM and storing information in the LTM.

The visual display of ideas, therefore, might not suit all learners. Research in Chapter 3 suggests that the use of animations decreases the gap between imagers and verbalisers, bringing the mental models of imagers closer to those of verbalisers. The case studies in Chapter 4 support the notion that these cognitive styles may indicate the ways students mentally store and process ideas.

To cater for both cognitive styles, key features should be pointed out verbally (as already suggested) and discussed conceptually, as well as shown visually. For example, the idea that solids vibrate at room temperature should be pointed out in the animation of solid sodium chloride. Students can then be asked to consider the conceptual question “Is there any point at which movement completely stops?” and the idea of absolute zero introduced. The conceptual approach should enhance the understanding of features in the animations for all learners.

**Establish “Animation Literacy”**

“Animation literacy” refers to an understanding of the conventions used in animations. This includes the portrayal of atoms, ions, molecules and electrons, colour coding, artistic license *etc.*, as well as the recognition of particular chemical species, such as water molecules.
To interpret the VisChem animations successfully, students need to be aware of these conventions, so the conventions must be explicitly taught to students when first viewing the animations. Recognition of ions might, for example, increase the number of students aware of the fact that ions, not atoms, make up ionic solids, enabling students to “read” a feature from the animations that is not visually obvious.

Furthermore, to ensure that students know the chemical identity of the particles in the animations, a key should always be provided with the animation and each feature of the key be described to students at the outset. There are also VisChem animations of discrete ions, atoms and molecules available, which should be shown to students before they view more complex animations. As mentioned previously, the effectiveness of these animations could be improved by temporarily superimposing a key onto the animation. It is expected that this would improve animation literacy among students and enhance their ability to learn from the animations by reducing the “split-attention effect” that arises when the key is separated from the animation. In this way, the cognitive load would be reduced.

Failure to provide the appropriate groundwork may lead to a limited understanding of the animation among students, especially those students with poor prior knowledge. This was evident in one third-year student’s (L2) inability to interpret an animation of an aqueous solution of sodium chloride (see Chapter 2, Section 2.4.3.3).

Laying the appropriate groundwork is particularly important for animations that might otherwise be ambiguous. In the studies in this thesis, students had developed some animation literacy by the time they were shown an animation of silver chloride precipitating. The resemblance of the silver ion to the previously shown sodium ion (from animations of sodium chloride) inhibited the students’ ability to interpret this animation. Therefore, for this animation in particular, an effort should be made to compare the representation of the silver ion with one of a sodium ion, and the differences pointed out.

Repetition of each animation is important for establishing animation literacy, and for enhancing students’ understanding of an animation. Repetition in one sitting allows students to first come to grips with the components of an animation, to make sense of what the animation is showing in a global sense, then finally to examine the specific details of the animations.
Minimise Cognitive Load

In Chapter 3, visuospatial working-memory capacity was shown to correlate with the sophistication of students’ mental models. Working memory plays a key role in learning from animations, according to the model of perception. Therefore, to enhance the learning of all students, the animations should be presented to minimise cognitive load. Working memory requirements will be especially high if students are still struggling with chemistry content, are unfamiliar with the animations, are expected to relate the information from a number of sources, and use all of this new knowledge in transfer situations.

As students become more familiar with the conventions in the animations, the working memory requirements decrease and students can concentrate more on the content of the animations. Similarly, as students become more aware of the relevant chemical concepts, their ability to interpret the animations will improve. Repetition of animations is, therefore, also an essential factor in reducing the WM requirements. Another technique is to start with simple animations and progress to more complex ones. Simple animations contain less conventions and ideas and, therefore, require less WM capacity. Starting with simple animations helps students to develop animation literacy before they are shown more complex animations. In Chapter 4, students with low levels of prior knowledge preferred models, diagrams and animations (Chapter 4) that were simple and “easy to visualise”. Showing complex animations too soon may lead to discouragement of students and their rejection of animation as a learning medium.

As mentioned above, the use of “removable” labelling (see page 469), can further reduce the cognitive load by removing the split-attention effect (Cooper, 1997; Mayer & Moreno, 1998) between the key and an animation or between the animation and other representations of key features.

It has been suggested in previous research that a verbal narration is preferable to written text as an accompaniment to an animation, because both verbal and visual material can be encoded simultaneously. Therefore, a verbal narration can minimise the working memory requirements (Mousavi, Low & Sweller, 1995).
It is also recommended that students not be overexposed to animations within a short period of time. Being shown too many animations at once might lead to information overload and poor learning outcomes. In the first-year study in Chapter 2, a video of all the water animations was shown in one sitting. Although the video is short (~ 10 mins), it contains many ideas. It is suspected that this method of delivery might have reduced the effectiveness of the animations. If the VisChem videos are used, it is recommended that the instructor allows time between the animations for reflection and discussion, or deals with each animation again separately after showing the video.

**Use Animation as Feedback**

The results of Chapter 2 indicate that students felt that the animations helped to reinforce or consolidate ideas that they already knew or of which were unsure. Therefore, animations were able to help improve students’ confidence in their mental models. One third-year student (L7) commented that “the main benefit of animations is that…they confirm an impression that you get from reading a book”. Animations can, therefore, play a role in providing feedback to students on their self-generated images and ideas. Feedback has been shown to be an extremely important component of learning, as discussed by Sleet (1998).

The proposed model of perception does not yet take into account the role of confidence and feedback in the development of students’ mental models. The modified model would take into account the emotional aspects of learning, controlled by the amygdala (Squire & Kandel, 1999).

**Use Student Drawings as a Learning Strategy with Animations**

Student drawings are a means by which students can express their mental models, generated in the WM and/or stored in the LTM.

On several occasions throughout these studies, students commented that drawing their own diagrams of the molecular level helped to develop their images (for example, see Chapter 4, Section 4.8.1.5). Encouraging students to produce their own diagrams should be done before and after viewing animations: before to elucidate prior understanding and after to allow modification. Students should be encouraged to check their drawings for all the relevant key features.
When asked to produce molecular-level diagrams of similar substances, students learn that the ideas are relevant to other situations and are not restricted to the substances shown in the animations.

Furthermore, drawing molecular-level representations allows students to rehearse the material presented in animations, and provides them with a means of expressing their recollection of those animations.

It should be noted that drawing is a skill and students need to be taught the appropriate methods with which to represent molecular-level structures and processes, including the conventions for drawing movement, etc. Some students will also be more comfortable or better at expressing their ideas in words, so students should be encouraged to provide annotations on their drawings or an accompanying description.

**Repeat Animations**

Repetition of animations in a single sitting is recommended in the “best practice” protocol, and was adopted in the instruction described in this thesis. Repetition is important for a number of reasons:

- It allows students to come to grips with the different components of the animations, *i.e.*, to learn the key before having to make sense of the processes occurring in the animation.
- It allows students to examine the animations for both global and local features separately.
- It enhances a student’s ability to discriminate the features in animations, as explained by Squire and Kandel:

  “‘Perceptual learning’ refers to an improvement in the ability to discriminate simple perceptual attributes, such as tones or line orientations, simply as the result of performing the discrimination repeatedly.” (Squire & Kandel, 1999, p. 164)

- Working memory requirements are reduced because the students become more familiar with the stimulus and because they don’t need to absorb everything at once. Therefore, the likelihood of effective learning is increased.
• It improves the likelihood that the student will store an image of the animation in the LTM (Squire & Kandel, 1999).

Third-year chemistry students recommended that the use of animations be continued beyond first-year chemistry (Chapter 2, Section 2.4.3). The fact that some students’ images of simple molecular-level substances and processes were still poor at this level indicates that this is an appropriate suggestion. For two interviewed students, exposure to animations helped to demonstrate the incorrect features of their mental models, leading them to produce improved representations. In some cases, viewing animations sparked the recollection of key features.

Repetition of animations over time is, therefore, also important.

• It improves the ability to “read” animations.
• It can provide students with a reminder or reinforcement of the information.
• It allows students to use any new understanding to more fully interpret the animation, and hence improve their mental models.
• It can encourage students to build on previous understanding by noticing that the ideas from the animation are relevant in a new context.

One concern with this recommendation is that some students may find repetition of the animations over time demotivating. Milheim (1993) warns against the overuse of animations, suggesting that it may be distracting to students. High ability students or those with high prior knowledge, in particular, may feel that the animations are a waste of time. Hewson (2002), who also studied the effectiveness of VisChem animations as a learning medium, revealed that high-ability students did not see the benefit of viewing animations when the “real information is in the text”. One high achieving first-year chemistry student from the 2000 study presented in Chapter 2 felt that seeing animations once was enough.

I actually found the animations a bit boring after a while because it was okay, we've seen that, I don't have to see it again. (Student 6)

The longitudinal study presented in Chapter 2 indicates that students vividly recall animations. Therefore, one method for addressing the problem of demotivation might be to encourage students to recall images of animations when they are deemed relevant to a new
topic. The animations can then be used as a feedback mechanism to allow students to confirm their existing model and the modification(s) made. Recall can be prompted using still shots of animations. These can be provided in lecture notes to cue the recollection of animations at relevant points in the text.

**Discuss “Scientific Modelling”**

There is some concern expressed in the literature that students might interpret molecular-level animations as “real” depictions of substances and processes, which will consequently inhibit the development of more abstract models of the molecular world. This thesis presented some evidence that animations might restrict students’ modelling ability insofar as students see animations as depicting what the molecular world looks like. There was no evidence to suggest, however, that students in this study interpreted the animations as exact replicas of the molecular level. In fact, students in the case studies were generally able to recognise the correspondences and non-correspondences in an animation of a water molecule. Moreover, the animations did not appear to restrict further development of mental models in chemistry. Indeed, some third-year students demonstrated that they had built on their mental models since seeing the animations in first-year chemistry. First-year students also accepted that they would be exposed to other models as their chemistry education progressed, and that their understanding was appropriate to their level of development.

Modelling ability appears, however, to be influenced by prior knowledge, so this effect of animations is likely to be of more concern with younger, less educated students.

To reduce any negative effects of exposure to animations on the student’s modelling ability, it is recommended that:

- Discussion of modelling be incorporated into the curriculum. This could include a discussion of the nature of a scientific model as opposed to a physical model, the way in which a scientific model is developed over time, the fact that a model can never be proven correct and examples of the development of specific theories.
Multiple models be used and evaluated in the instruction. Dominant use of a particular model might produce a skewed effect on students’ mental model. Some students might feel that one model is a better representation simply because the instructor uses it more often, and hence might consider features of this model “real”. In this research, overuse of the ball-and-stick model of solid sodium chloride appeared to have a negative effect on students’ mental models. For students to adopt the appropriate ideas from different models, there should be discussion of the strengths and limitations of each model, as well as reasons for employing more than one model to explain a concept (Davies, 1991; Harrison & Treagust, 1996; Oversby, 1999; Jones et al., 2001).

Models be used for testing ideas and predicting or solving problems, not simply for representing the molecular world (Treagust et al., 2000). Grosslight et al. (1991) suggest “…it is important to provide students with experiences using models to solve intellectual problems. In this way students would have the opportunity to learn that a model can be used as a tool of inquiry and that it is not simply a package of facts about the world that needs to be memorised.” (p. 820)

5.1.2.1. Summary

The recommendations emphasise that effective use of animations requires the support of accompanying instruction. Effort should be made to encourage students not only to memorise ideas from the animations but also to see the value in their mental images as tools with which to evaluate, interpret, predict, explain and ponder various aspects of chemistry.

The following is an outline of one possible approach to presenting the animations in a classroom situation, taking into account these recommendations. The outline is strikingly similar to the “best practice” protocol (Appendix F) which is largely based on practical experience with using animations. Therefore, the results of this study tend to confirm the perceptions of effective teaching using the VisChem animations. Additional recommendations emerging from the research, not addressed in the “best practice” protocol, are presented in italics.
1. Find out students’ prior knowledge (drawing, brainstorming, etc.).
2. Teach or revise concepts relevant to the animations.
3. Explain the conventions used in the animations – show animations of single atoms, ions and molecules; discuss artistic license and scientific modelling.
4. Use an experimental observation, macroscopic phenomenon, chemical equation or otherwise, as a stimulus. Allow students to predict what they would observe in an animation of the molecular level by drawing a representation (alternatives such as role plays are also possible).
5. Provide a key to the chemical identities in the animation, showing animated and/or non-animated depictions of each particle.
6. Show the animation once or twice, reiterating the chemical identities and conventions in a verbal narrative.
7. Allow students to discuss the animation in light of their original representation (class or group discussion, question time) and to make any modifications to their representations.
8. Show the animation again, at least twice, as feedback to the modified drawings produced in step 7. In a verbal narration, point out the global features and the details, explain the underlying concepts and draw attention to the common misconceptions.
9. Ask students to check their drawings, adding or changing features where required.
10. Ask students to consider how their representations relate to the original stimulus.
11. Propose direct and applied transfer problems for students to solve in groups.

Many of the recommendations outlined in this section can be summarised by the following statement on how human memory operates.

“Whether or not something that is perceived will be remembered later is determined by a number of factors, the most important of which operate around the time of learning: the number of times the event or fact is repeated, its importance, the extent to which we can organise it and relate it to knowledge that we already have and the extent to which we rehearse the material after it has first been presented.”

(Squire & Kandel, 1999, p. 71) (emphases mine)
5.2. Summary of Contributions

In a report prepared for the 2001 Gordon Research Conference on Science Education and Visualisation, Jones et al. (2001) stated “We know very little about how to use animation effectively in instruction. The proper role of animations in chemistry education should be treated as an issue in cognitive, educational, and curricular research. As animation is brought increasingly into the curriculum, its effects on students should be carefully researched.” (p. 11)

The report also featured a series of fruitful research questions relating to visualisation in science. Among them were the following:

- “How do individual differences such as gender, learning style, culture, etc., affect the ability to learn from visualisations?”
- “How do student mental models of matter change as a function of interaction with molecular visualisations?”
- “How do student-generated visualisations develop and change as students learn scientific concepts?”

Hewson (2002) proposed in his doctoral thesis on the effectiveness of the VisChem animations, that future research on animations might concentrate on “how human cognition can better perceive and process such dense information efficiently” (p. 200).

Research in this thesis adds to the limited body of knowledge on how to use animation effectively in instruction. The research has begun to answer the first question above by examining some of the individual factors that affect a student’s ability to develop mental models with the aid of animations. Case studies in mental model development revealed how four students’ mental models changed as a result of exposure to animations and other chemistry instruction, thus providing insight into questions 2 and 3. The proposed model of perception begins to answer how individuals perceive and process complex visual displays, thus providing a framework, based in neuroscience, from which to design and deliver effective instructional materials that consider the workings of human cognition.
Original and confirmatory contributions made by this research to current literature in the field are summarised below. This thesis has provided:

- An examination of the effectiveness of the VisChem animations to help students develop mental models, including both the immediate and long-term effects;
- An extension and confirmation of recommendations for the effective use of animations in general;
- The proposal of an original model of perceptual processes involved in interpreting animations, based on evidence from neuroscience;
- Identification of factors affecting mental model development using the above model: although disembedding ability and study style have been identified as contributing to student success in science, they have not previously been identified as specifically affecting the development of scientific mental models;
- An extension of the current literature on student misconceptions in the topic areas of precipitation and concentration, including the proposal of an alternative conceptual framework for understanding precipitation;
- Confirmation of misconceptions in the topics of structure and bonding, chemical formulae and equations, and chemical equilibrium;
- An exploration of factors affecting modelling ability, including the use of animations in teaching and prior knowledge;
- Elucidation of the role of prior knowledge in students’ critical evaluations of scientific diagrams and animations;
- The design of a questionnaire, using novel critical-analysis-style questions, to reveal students’ mental models.

5.3. Future Research

The possibilities for further research in this field that emerge from this thesis are numerous. Some of the more pertinent avenues for research are discussed in this section.

One of the key concerns regarding the research presented in this thesis is whether or not the results can be extrapolated to other student bodies or to alternative modes of presenting animations. The studies were conducted with small sample sizes, predominantly with first-year chemistry students, at a single university. These studies on the effectiveness of
animations require replication and extension, and the inclusion of factors affecting mental model development, using larger sample sizes. Furthermore, the effectiveness of animations should be examined in other bodies of students, including highly academic students and high-school and primary-level students. Further studies should be conducted to examine the effectiveness of the VisChem animations when incorporated into multimedia settings, in individual and cooperative learning environments. Effectiveness studies with different methodologies, such as a pre/post-test design with controlled intervening instruction, would serve to further validate the findings. It is expected that the recommendations given in Section 5.1.2, for presenting animations, will be useful guidelines in all learning environments, but such a hypothesis requires rigorous testing.

Based on the research presented here, the proposed model of visual perception appears to explain why some students develop scientifically acceptable mental models more readily than others. Further research is required to fully establish this as a useful model in educational practice. Supporting research may consist of:

- The design and testing of teaching materials or methodologies based on the proposed perceptual model;
- Neurological and physiological experiments, including eye-movement tracking, arousal and brain scanning, to examine students’ processing of animations and to validate the measures of cognitive processing;
- Further quantitative studies to examine the effects of relevant factors on students’ ability to learn from animations.
More specific studies might concentrate on:

- Establishing the link between disembedding ability and the development of students’ mental models through further quantitative studies;
- Examining how disembedding ability operates to enhance the development of students’ mental models by conducting further case studies or using neurological experiments, controlling for prior knowledge and study style.
- Confirming the influence of visuospatial working memory on students’ ability to learn from animations, develop mental models and transfer mental models to new situations;
- Exploring differences in the way verbalisers and imagers process, store and use chemical information;
- Examining the effects of cognitive style combinations (for example: wholist-imagers) on students’ ability to learn from animations; and
- Substantiating the negative effects of animations on modelling ability, and looking at ways of minimising these effects.
The Development of Students' Mental Models of Chemical Substances and Processes at the Molecular Level

APPENDICES

Rebecca Marie Dalton

BSc. (Hons), Grad. Dip. Ed.

A thesis submitted in fulfilment of the requirements for the award of the degree

DOCTOR OF PHILOSOPHY

From

University of Western Sydney

2003
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Appendix A: Questionnaires and Associated Documents

A.0. Pre-test/Post-test 2000
## A.1. Marking Scheme for Pre-test and Post-test

<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image [numbers in brackets refer to the relevant question in the post-questionnaire]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MOLECULAR SUBSTANCES - general</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| Molecules in a liquid are closely crowded | The molecules in a liquid are closely packed, small amounts of space arise due to the molecules colliding | There is considerable space between molecules in a liquid | Hill, 1988 | Multiple choice and explanation | (3) **Spacing of molecules in a liquid**  
Representation 1 and explanation such as:  
Incompressible or  
Similar density to solid or  
"not much room for them to move" or closely packed  
OR  
An acceptable explanation such as:  
In representation 1 - molecules are too closely packed to allow for movement in 3 dimensions and in representation 2 - molecules too far apart, liquids are incompressible  
with choice of representation 1, 2 or no representation adequate  
OR  
Representation 1 (no explanation) with selection confidence greater than or equal to 3 (assume uninformed guess is worth 0).  
AND/OR |
<p>| The relative distances of s:l:g are 1: 1: 17 | The relative distances of s:l:g are 1: 2-3: 6-7 | The relative distances of s:l:g are approx 1: 2: 3-4 | Andersson, 1990 | | |
| There is little difference between the densities of the liquid and gaseous states of a substance | There is considerable space between molecules in a liquid | Hill, 1988 | | | |</p>
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| Molecules in a gas are widely spaced | The relative distances of  $s:l:g$ are 1:1:17                                   | The relative distances of  $s:l:g$ are 1:2-3; 6-7   | Andersson, 1990 | Multiple choice and explanation               | (4) Spacing of molecules in a gas  
Representation 3 and explanation such as:  
Easily compressible or  
Lowest density/ furthest apart or  
"most room for them to move" or  
greatest amount of kinetic energy  
OR  
An acceptable explanation such as:  
representation 2 or 3 may be adequate depending on the pressure or  
The molecules should be even further apart than is shown in representation 3  
with choice of representation 2, 3 or no representation adequate  
OR  
Representation 3 (no explanation) with selection confidence greater than or equal to 3.  
AND/OR  
(7) States of water  
Statement alluding to the extreme distance between the water molecules in the gaseous state without contradiction with answer to Question 4. |


<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| Molecules do not change size from solid to liquid to gas | Molecules of the same substance are identical (disregarding isotopes) regardless of the state the substance is in; only the arrangement and energy of these particles differs. | Molecules of the same substance have different properties in different phases (eg: shape, size, mass) | Nakhleh, 1992  
Griffiths and Preston, 1992  
Haidar and Abraham, 1991  
Pereira and Pestana, 1991 | Multiple choice and explanation | (5) **Relative size of the molecules in the three states**  
Choice of Set 3 and explanation such as:  
The distance between molecules changes or  
The energy of the molecules changes or  
The packing of the molecules changes or  
The strength of the intermolecular forces changes  
Chemical identity of the molecule doesn't change OR  
Choice of Set 3 and explanation such as:  
The size of the molecules doesn't change AND  
Selection confidence greater than or equal to 3 OR  
Choice of Set 3 and selection confidence greater than or equal to 3 |
| The molecular level is multi-particulate | Students often think in terms of single units | Ben-Zvi et al, 1987 | Student-generated illustration and description of particle level | (7) **States of water**  
Diagrams of water that include more than one particle |
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Molecular substances contain discrete particles in the solid, liquid and gas states</td>
<td>Melting and boiling of molecular compounds are processes in which intermolecular forces between discrete molecules are broken.</td>
<td>Compounds consist of mixtures of their constituent elements Melting and boiling of molecular compounds are processes in which covalent bonds within molecules (intramolecular bonds) are broken.</td>
<td>Garnett, 1998 Sleet, 1993</td>
<td>Multiple Choice and explanation Student-generated illustration and description of particle level</td>
<td>(6) Model number 5 Choice of any model of a water molecule apart from number 5 AND (7) States of water Use of this model (or other suitable model) without alteration for all 3 states of matter - solid, liquid and gaseous water all contain discrete H₂O molecules (use of circles is NOT adequate for mark)</td>
</tr>
<tr>
<td>There is empty space between the molecules</td>
<td>Matter is continuous There is no empty space; matter (eg: air, water) may be seen to fill the spaces between particles in other substances</td>
<td>Andersson, 1990 Andersson, 1990 Garnett, 1998 Novick and Nussbaum, 1981 Griffiths and Preston, 1992</td>
<td>Andersson, 1990 Garnett, 1998</td>
<td>Student-generated illustration and description of particle level Description</td>
<td>(7) States of water No indication that there is something between the molecules eg: air particles AND (8) Is there anything between the particles? A statement suggesting that there is &quot;nothing&quot;, &quot;empty space&quot; or just intermolecular bonds between molecules OR The answer &quot;no&quot; with confidence greater than or equal to 3</td>
</tr>
<tr>
<td>Key Feature</td>
<td>Scientific Idea</td>
<td>Misconception</td>
<td>Reference</td>
<td>Probe</td>
<td>Evidence of correct mental image</td>
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<tr>
<td><strong>SOLID</strong></td>
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<tr>
<td>Structured lattice</td>
<td></td>
<td>There is no particular arrangement of particles in the solid state</td>
<td>Pilot study, 1999</td>
<td>Student-generated illustration and description of particle level</td>
<td>7(iii) <strong>Ice at the particle level</strong>&lt;br&gt;The diagram shows water molecules arranged neatly in rows or a cubic or hexagonal-type lattice structure AND&lt;br&gt;The description states that there is a structured arrangement of water molecules OR&lt;br&gt;The diagram unambiguously shows a deliberate attempt to represent structure eg: molecules are situated at the corners of a faint or dotted cube</td>
</tr>
<tr>
<td>Vibrate in fixed positions</td>
<td></td>
<td>Molecules in the solid state do not move</td>
<td>Pilot study, 1999</td>
<td>Student-generated illustration and description of particle level</td>
<td>7(iii) <strong>Ice at the particle level</strong>&lt;br&gt;Either the diagram indicates movement OR&lt;br&gt;The description states that the molecules vibrate/move slightly</td>
</tr>
<tr>
<td>Significant intermolecular attractions</td>
<td>Hydrogen Bonding exists between the water molecules in ice</td>
<td>Covalent bonding exists between H and O of different molecules in water Water molecules contain hydrogen bonded atoms</td>
<td>Pilot study, 1999</td>
<td>Student-generated illustration and description of particle level</td>
<td>7(iii) <strong>Ice at the particle level</strong>&lt;br&gt;Either the diagram indicates H-bonding via the use of dotted lines connecting H and O of different molecules OR&lt;br&gt;The description notes the presence of H-bonding (or polar/dipole-dipole) and the diagram does not contradict this (diagram shows correct alignment of molecules and H-bonding between molecules, not within) OR</td>
</tr>
<tr>
<td>Key Feature</td>
<td>Scientific Idea</td>
<td>Misconception</td>
<td>Reference</td>
<td>Probe</td>
<td>Evidence of correct mental image</td>
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</table>
|             |                 |               |           |       | (8) **Is there anything between the particles?**  
Student states that there is H-bonding, dipole-dipole or polar bonding between the water molecules in a solid  
OR  
(3), (4) **Spacing of molecules**  
Students state that intermolecular forces are strongest between molecules in a solid |
| LIQUID      |                 |               |           |       |                                  |
| Movement    |                 | Matter is static | Andersson, 1990 | Student-generated illustration and description of particle level | 7(i) **Liquid water at the particle level**  
Either the diagram indicates movement  
OR  
The description states that the molecules move  
OR  
(3), (4) **Spacing of molecules**  
There is often a connection made between spacing and movement, a mention of movement here should be recognised as knowledge of key feature |
| Collisions  |                 | Particles do not interact with one another | Pilot study, 1999 | Student-generated illustration and description of particle level | 7(i) **Liquid water at the particle level**  
The description states that molecules collide or bump into each other or the walls of the container |
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| Significant intermolecular         | Hydrogen bonding exists between the water molecules in liquid water             | Particles do not interact with one another                                    | Pilot study, 1999| Student-generated illustration and description of particle level       | 7(i) Liquid water at the particle level  
| attractions                        |                                                                                 | Covalent bonding exists between H and O of different molecules in water        |                 |                                                                        | Either the diagram indicates H-bonding via the use of dotted lines connecting H and O of different molecules  
|                                    |                                                                                 |                                                                                |                 |                                                                        | OR                                                                                               |
|                                    |                                                                                 |                                                                                |                 |                                                                        | The description notes the presence of H-bonding (or polar/dipole-dipole) and the diagram does not contradict this (diagram shows correct alignment of molecules and H-bonding between molecules, not within)  
|                                    |                                                                                 |                                                                                |                 |                                                                        | OR                                                                                               |
|                                    |                                                                                 |                                                                                |                 |                                                                        | (8) Is there anything between the particles?  
|                                    |                                                                                 |                                                                                |                 |                                                                        | Student states that there is H-bonding, dipole-dipole or polar bonding between the water molecules in a liquid  
|                                    |                                                                                 |                                                                                |                 |                                                                        | OR                                                                                               |
|                                    |                                                                                 |                                                                                |                 |                                                                        | (3), (4) Spacing of molecules  
|                                    |                                                                                 |                                                                                |                 |                                                                        | Students state that intermolecular forces are weaker in a liquid than a solid or stronger in a liquid than in a gas  
|                                    |                                                                                 |                                                                                |                 |                                                                        |                                                                                                  |
| **GAS**                            |                                                                                 |                                                                                |                 |                                                                        | 7(ii) Gaseous water at the particle level  
|                                    |                                                                                 |                                                                                |                 |                                                                        | Either the diagram indicates movement  
|                                    |                                                                                 |                                                                                |                 |                                                                        | OR                                                                                               |
|                                    |                                                                                 |                                                                                |                 |                                                                        | The description states that the molecules move  
<p>|                                    |                                                                                 |                                                                                |                 |                                                                        | OR                                                                                               |
| Movement (translational, vibrational and rotational) |                                                                                 |                                                                                |                 |                                                                        |                                                                                                  |</p>
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
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<td>(3), (4) Spacing of molecules</td>
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<td>There is often a connection made</td>
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<td>between spacing and movement, a</td>
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<td>mention of movement here should</td>
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<td>be recognised as knowledge of key</td>
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<td>feature</td>
</tr>
<tr>
<td>Collisions</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>7(ii) <strong>Gaseous water at the particle level</strong></td>
</tr>
<tr>
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<td>The description states that</td>
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<td>molecules occasionally collide</td>
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<td>or bump into each other or the</td>
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<td></td>
<td></td>
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<td>walls of the container</td>
</tr>
</tbody>
</table>

**SPECIFIC FEATURES**

**Water:**

- Greater spacing in solid than liquid due to H-bonding
  - Water molecules in ice are close-packed, leaving no space between them
  - Molecules in liquid water are further apart than in ice
  - Pilot study, 1999
  - Pilot study, 1999
  - Student-generated illustration and description of particle level
  - 7 (iii) **Particle level diagram of ice**
  - The description states that the density of ice is less than that of water so the molecules are further apart (or there is more space between them)

- Water molecules can react with each other to form hydronium ions and hydroxide ions
  - Student-generated illustration and description of particle level
  - 7 (i) **Particle level diagram of liquid water**
  - The description states that there are a very small number of hydronium and hydroxide ions present in liquid water.

**Water molecule:**

- Correct model
  - Students show preference for different models - popular ones include ball and stick, space-filling, symbolic
  - Pilot study, 1999
  - Pereira and Pestana, 1991
  - Harrison and Treagust, 1996
  - Multiple choice
  - (6) **Select a model for water**
  - Selection of representation 1, 2 and/or 3
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bent</td>
<td></td>
<td>Reports of bond angles vary widely and may change for different states</td>
<td>Pilot study, 1999</td>
<td>Explanation</td>
<td><strong>Models 1, 2, 3</strong>&lt;br&gt;It is stated in the explanation for choice of model that water molecules have a bent shape</td>
</tr>
<tr>
<td>Overlapping electron clouds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Model 2</strong>&lt;br&gt;It is stated in the explanation for choice of model that bonds are overlapping orbitals, not “sticks”</td>
</tr>
<tr>
<td>Different sized atoms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td><strong>Model 2</strong>&lt;br&gt;It is stated in the explanation for choice of model that oxygen atoms are larger than hydrogen atoms</td>
</tr>
</tbody>
</table>

**IONIC SOLIDS**

<p>| Correct model                   |                 |                                                                                | Multiple choice                |                | <strong>(9) Structure of sodium chloride lattice</strong>&lt;br&gt;Selection of model 3 as that which best describes solid sodium chloride (with confidence greater than 3 if no explanation given) |
| Ions not molecules              | Ionic solid consist of alternating oppositely charged ions electrostatically attracted. The forces of attraction are of equal intensity throughout the lattice | An ionic bond exists between the ions in the formula unit only, these “ionic molecules” are attracted to other ionic molecules by “just forces” | Taber, 1994, Pilot study, 1999 | Criticism of incorrect representations | <strong>(9) Structure of sodium chloride lattice</strong>&lt;br&gt;The criticism of diagram 2 or 4 states that there should be separate ions not molecules&lt;br&gt;OR&lt;br&gt;The explanation for choice of representation implies that an ionic solid contains 2 distinct/separate types of particles – cations and anions (eg: in 2 dimensions each sodium ion is surrounded by 4 chloride ions) |</p>
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ions not atoms</td>
<td></td>
<td></td>
<td></td>
<td>Criticism of incorrect representations</td>
<td>(9) Structure of sodium chloride lattice</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OR</td>
<td>The criticism of diagram 1 states that ionic solids contain ions not atoms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OR</td>
<td>The explanation for choice of representation states that an ionic solid contains charged particles</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>are electrostatically attracted</td>
<td></td>
</tr>
<tr>
<td>Structured</td>
<td>Ionic solids pack themselves in loose, random arrangements (MgO)</td>
<td>Lee, 1999</td>
<td></td>
<td>Criticism of incorrect representations</td>
<td>(9) Structure of sodium chloride lattice</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OR</td>
<td>The criticism of diagram 4 states that ionic solids are structured</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OR</td>
<td>The explanation for choice of representation states that an ionic solid are structured</td>
</tr>
<tr>
<td>Closely packed</td>
<td>The particles in a solid are loosely packed</td>
<td>Lee, 1999</td>
<td></td>
<td>Criticism of incorrect representations</td>
<td>(9) Structure of sodium chloride lattice</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OR</td>
<td>The criticism of diagram 1, 2 or 4 states that ionic solids are closely packed and/or the ions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>should be touching</td>
<td>The explanation for choice of representation states that an ionic solid is closely packed</td>
</tr>
<tr>
<td>Vibrations in fixed positions</td>
<td>The ions in a solid ionic lattice are static</td>
<td>Pilot study, 1999</td>
<td>Description</td>
<td>(10) Heating an ionic crystal</td>
<td>The description states that &quot;vibrations increase&quot; rather than &quot;ions start to vibrate&quot;</td>
</tr>
<tr>
<td>Key Feature</td>
<td>Scientific Idea</td>
<td>Misconception</td>
<td>Reference</td>
<td>Probe</td>
<td>Evidence of correct mental image</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>---------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
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<td>---------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>IONIC SOLUTIONS</td>
<td></td>
<td></td>
<td></td>
<td>(11) Representations of aqueous sodium chloride</td>
<td>Student allocates the highest mark to Model 3, therefore indicating it is the best representation of an aqueous solution of sodium chloride (with confidence greater than 3 if no explanation)</td>
</tr>
<tr>
<td>Correct model</td>
<td></td>
<td></td>
<td></td>
<td>(11) Representations of aqueous sodium chloride</td>
<td>Feedback for representations 1, 2 or 4 states that there should be more water molecules present OR Feedback for representation 2 or 5 states that the solute is over-represented OR Comment on representation 3 states that there is a satisfactory ratio of ions to water molecules</td>
</tr>
<tr>
<td>High water to salt ratio</td>
<td>There are 55 water molecules per formula unit of NaCl in a 1 M solution.</td>
<td>The concentration of solute particles in solutions is over-represented</td>
<td>Hill, 1988</td>
<td>Criticism of incorrect representations</td>
<td></td>
</tr>
<tr>
<td>Key Feature</td>
<td>Scientific Idea</td>
<td>Misconception</td>
<td>Reference</td>
<td>Probe</td>
<td>Evidence of correct mental image</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------</td>
<td>-----------</td>
<td>--------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Closely crowded   | There is very little space between the molecules in a liquid                      | There is considerable space between molecules in a liquid                     | Hill, 1988| Criticism of incorrect representations    | (11) **Representations of aqueous sodium chloride** Feedback for representations 1,2 or 4 states that there is too much space between the particles for a liquid state  
OR  
Comment on representation 3 states that the particles are closely crowded  
(no mark if contradiction eg: too much space in 1 but not enough space in 3)  
OR  
Feedback for representations 1,2 or 4 states that there should be many more water molecules present  
(no mark if contradiction eg: more water in 1 but not enough space in 3) |
|                   |                                                                                  |                                                                                |           |                                            |                                                                                                |
| Hydration of ions | Water molecules hydrate each ion                                                  | In dissolving, each ‘NaCl unit’ (ions or molecule) sticks to a single water molecule | Pilot study, 1999| Criticism of incorrect representations    | (11) **Representations of aqueous sodium chloride** Feedback for representation 1 states that there should be water molecules surrounding each ion  
OR  
Feedback for representation 2, 4 or 5 states water molecules should surround the ions  
OR  
Comment on representation 3 states that water molecules are hydrating the ions  
 OR  
Feedback for representation 1,2 or 4 states that there should be many more water molecules present  
(no mark if contradiction eg: more water in 1 but not enough space in 3) |
<p>| | | | | | |
|                   |                                                                                  |                                                                                |           |                                            |                                                                                                |</p>
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| There is an electrostatic attraction between water molecules and ions     | The hydrating water molecules are orientated according to polarity, towards the ions (oxygen points towards cations, hydrogen points towards anions) | In aqueous NaCl there is no interaction of solute particles with water molecules | Pilot study, 1999         | Criticism of incorrect representations                 | (11) Representations of aqueous sodium chloride  
Feedback for representation 1 states that the water molecules are correctly oriented towards the ions  
OR  
Feedback for representation 2, 4 or 5 states that water molecules should orient themselves towards the ions according to polarity  
OR  
Comment on representation 3 states that water molecules are correctly oriented towards the ions |}
| The solution is electrically neutral                                      |                                                                                |                                                                               |                            |                                                         | (11) Representations of aqueous sodium chloride  
Feedback for representation 5 states that there are too many sodium ions present, the ratio of sodium to chloride ions should be 1:1  
OR  
Comment on representation 3 (and/or 1, 2, 4) states that the ratio of sodium ions to chloride ions is correct |}
| Ions not molecules                                                        |                                                                                | An aqueous solution of sodium chloride contains sodium chloride molecules     | Pilot study, 1999         | Criticism of incorrect representations                 | (11) Representations of aqueous sodium chloride  
Feedback for representation 2 states that there should be separate ions or formula units not molecules  
OR  
Comment on representation 1, 3, 4 or 5 states that an ionic solution contains 2 separate types of particles  
OR  

<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Scientific Idea</th>
<th>Misconception</th>
<th>Reference</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ions not atoms</strong></td>
<td></td>
<td></td>
<td></td>
<td>Criticism of incorrect representations</td>
<td>(11) Representations of aqueous sodium chloride</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Feedback for representation 2 states that ionic solutions contain ions not atoms</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Comment on representation 1, 3, 4 or 5 states that an ionic solution contains 2 types of particles -</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>cations and anions</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>OR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Some comment made with regard to charges/polarity electrostatic attraction etc on NaCl</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>that suggests student realises the particles are charged</td>
</tr>
<tr>
<td><strong>Dynamic</strong></td>
<td>Matter is static</td>
<td></td>
<td>Andersson, 1990</td>
<td>Criticism of incorrect representations</td>
<td>(11) Representations of aqueous sodium chloride</td>
</tr>
<tr>
<td>(movement,</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Any comment referring to movement, collisions or water molecule exchange for hydrated ions</td>
</tr>
<tr>
<td>collisions,</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>water exchange</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>etc)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## A.2. Tally Sheet for Pre-test and Post-test Key Features

<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Pre-test</th>
<th>Post-test</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MOLECULAR SUBSTANCES - general</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecules in a liquid are closely crowded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecules in a gas are widely spaced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecules do not change size from solid to liquid to gas</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The molecular level is multi-particulate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecular substances contain discrete particles in the solid, liquid and gas states</td>
<td></td>
<td></td>
</tr>
<tr>
<td>There is empty space between the molecules</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SOLID</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structured lattice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrate in fixed positions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant intermolecular attractions</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LIQUID</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collisions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant intermolecular attractions</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GAS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement (translational, vibrational and rotational)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collisions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SUBTOTAL:**
### SPECIFIC FEATURES

<table>
<thead>
<tr>
<th>Water:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater spacing in solid than liquid due to H-bonding</td>
<td></td>
</tr>
<tr>
<td>Water molecules can react with each other to form hydronium ions and hydroxide ions</td>
<td></td>
</tr>
</tbody>
</table>

**Water molecule:**
- Correct model
- Bent
- Overlapping orbitals
- Different sized atoms

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**IONIC SOLIDS**
- Correct model
- Ions not molecules
- Ions not atoms
- Structured
- Closely packed
- Vibrations in fixed positions

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### IONIC SOLUTIONS

Correct model

<table>
<thead>
<tr>
<th>High water to salt ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Closely crowded</td>
</tr>
<tr>
<td>Hydration of ions</td>
</tr>
<tr>
<td>There is an electrostatic attraction between water molecules and ions</td>
</tr>
<tr>
<td>The solution is electrically neutral</td>
</tr>
<tr>
<td>Ions not molecules</td>
</tr>
<tr>
<td>Ions not atoms</td>
</tr>
<tr>
<td>Dynamic (movement, collisions, water exchange etc)</td>
</tr>
</tbody>
</table>

**subSUBTOTAL:**

**SUBTOTAL (ionic substances):**

**TOTAL:**

**CHANGE:**
A.3. Transfer Test
## A.4. Marking Scheme for the Transfer Test

<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Relevant animations</th>
<th>Relevant Question(s) from Post-test</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
<tbody>
<tr>
<td>MOLECULAR SUBSTANCES - general</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecules in a liquid are closely crowded</td>
<td>Liquid water</td>
<td>3; 7 (i)</td>
<td>Particle level diagram and description</td>
<td>Direct Transfer (1 mark is allocated per key feature) TOTAL: 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecules in a gas are widely spaced</td>
<td>Gaseous water</td>
<td>4; 7</td>
<td>Particle level diagram and description</td>
<td>4(ii) Iodine in the gaseous state</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mention of wide spacing in the gaseous state and clear representation in diagram OR Mention that the molecules are more widely spaced in the gas than in the liquid OR The molecules in the diagram of the gas are clearly further apart than those in the liquid</td>
</tr>
<tr>
<td>Molecules do not change size from solid to liquid to gas</td>
<td>Ice melting; liquid water evaporating</td>
<td></td>
<td></td>
<td>Not tested</td>
</tr>
<tr>
<td>Key Feature</td>
<td>Relevant animations</td>
<td>Relevant Question(s) from Post-test</td>
<td>Probe</td>
<td>Evidence of correct mental image</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>--------------------</td>
<td>-------------------------------------</td>
<td>--------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>The molecular level is multi-particulate</td>
<td>Solid, liquid gaseous water; solid, aqueous sodium chloride etc</td>
<td>7</td>
<td>Particle level diagrams and descriptions</td>
<td><strong>4. States of iodine</strong>&lt;br&gt;Representations of iodine in the 3 states ALL contain more than one particle</td>
</tr>
<tr>
<td>Molecular substances contain identically structured particles in the solid, liquid and gas states</td>
<td>Solid, liquid gaseous water</td>
<td>6; 7</td>
<td>Particle level diagrams and descriptions</td>
<td><strong>4. States of iodine</strong>&lt;br&gt;The diatomic iodine molecule is conserved during phase changes and discrete particles are drawn each time</td>
</tr>
<tr>
<td>There is empty space between the molecules</td>
<td></td>
<td></td>
<td></td>
<td><strong>Not tested</strong></td>
</tr>
<tr>
<td><strong>SOLID</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structured lattice</td>
<td>Ice</td>
<td>7 (iii)</td>
<td>Particle level diagram and description</td>
<td><strong>4(i) Iodine in the solid state</strong>&lt;br&gt;Mention of ordered structure (regular pattern) in the solid state and representation in diagram (if given) OR&lt;br&gt;The diagram unambiguously shows a deliberate attempt to represent structure eg: molecules are situated at the corners of a faint or dotted cube</td>
</tr>
<tr>
<td>Vibrate in fixed positions</td>
<td>Ice</td>
<td>7 (iii)</td>
<td>Particle level diagram and description</td>
<td><strong>4(i) Iodine in the solid state</strong>&lt;br&gt;Mention of vibration or very little movement in the solid state and/or clear representation in diagram</td>
</tr>
<tr>
<td>Key Feature</td>
<td>Relevant animations</td>
<td>Relevant Question(s) from Post-test</td>
<td>Probe</td>
<td>Evidence of correct mental image</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>--------------------</td>
<td>------------------------------------</td>
<td>--------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
</tbody>
</table>
| Significant intermolecular attractions         | Ice                | 7 (iii)                            | Particle level diagram and description     | 4(i) Iodine in the solid state  
Mention of dispersion or intermolecular forces in the solid state and/or clear representation in diagram |
| Closely packed                                  |                     |                                    |                                            | 4(i) Iodine in the solid state  
Mention of close-packing in the solid state and/or clear representation in diagram               |
| **LIQUID**                                      |                    |                                    |                                            |                                                                                                  |
| Movement                                        | Liquid water        | 7 (i)                              | Particle level diagram and description     | 4(ii) Iodine in the liquid state  
Mention of appropriate movement in the liquid state (eg: tumbling/rolling) and/or clear representation in diagram |
| Collisions                                      | Liquid water        | 7 (i)                              | Particle level diagram and description     | 4(ii) Iodine in the liquid state  
Mention of collisions in the liquid state and/or clear representation in diagram                  |
| Significant intermolecular attractions         | Liquid water        | 7 (i), 8                           | Particle level diagram and description     | 4(ii) Iodine in the liquid state  
Mention of dispersion forces or intermolecular forces in the liquid state and/or clear representation in diagram |
| **GAS**                                         |                    |                                    |                                            |                                                                                                  |
| Movement (translational, vibrational and rotational) | Gaseous water     | 7 (ii)                             | Particle level diagram and description     | 4(iii) Iodine in the gaseous state  
Mention of movement in the gaseous state and/or clear representation in diagram                  |
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Relevant animations</th>
<th>Relevant Question(s) from Post-test</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| Collisions                   | Gaseous water      | 7 (ii)                             | Particle level diagram and description     | 4(iii) Iodine in the gaseous state  
Mention of occasional collisions in the gaseous state and/or clear representation in diagram |
| Minimal attractive forces    | Gaseous water      | 4; 7 (ii)                          | Particle level diagram and description     | 4(iii) Iodine in the gaseous state  
Mention of minimal attractive forces in the gaseous state                                       |

**IONIC SOLIDS**

| Correct ion ratio           | Solid sodium chloride | 9                                  | 1. Particle level drawing and description  
3. Critique of representation given | 1. Solid potassium bromide  
Mention of 1:1 ratio and/or clear representation in diagram  
OR  
The formula given is KBr | 3. Precipitation of copper(II) hydroxide  
Mention that the copper to hydroxide ratio, in the ionic lattice formed, should be 1:2 |
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Relevant animations</th>
<th>Relevant Question(s) from Post-test</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| Ions not molecules  | Solid sodium chloride | 9                                  | 1. Particle level drawing and description  
3. Critique of representation given | 1. **Solid potassium bromide**  
Mention of separate ions, formula units or continuous lattice and/or clear representation in diagram (eg: ball and stick representation)  
OR  
Correct space-filling representation with no mention of "molecules", sharing of electrons or bonding between one cation and one anion, for example.  
3. **Precipitation of copper(II) hydroxide**  
Mention that the copper and hydroxide ions are ions, not molecules in the ionic lattice formed |
| Ions not atoms      | Solid sodium chloride | 9                                  | 1. Particle level drawing and description | 1. **Solid potassium bromide**  
Student selects ions from the key for use in their diagram  
OR  
Reference is made to "charged atoms" attracting |
| Structured          | Solid sodium chloride | 9                                  | 1. Particle level drawing and description  
3. Critique of representation given | 1. **Solid potassium bromide**  
Mention of structured lattice and/or clear representation in diagram  
3. **Precipitation of copper(II) hydroxide**  
Mention that the copper hydroxide lattice formed should be structured  
OR  
Mention that the copper hydroxide forms an ionic lattice |
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Relevant animations</th>
<th>Relevant Question(s) from Post-test</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| Closely packed               | Solid sodium chloride | 9                                   | 1. Particle level drawing and description                             | 1. Solid potassium bromide  
Mention of close-packing and/or clear representation in diagram |
|                              |                     |                                     | 3. Critique of representation given                                  | 3. Precipitation of copper(II) hydroxide  
Mention that the copper hydroxide lattice formed should be close-packed |
| Vibrations in fixed positions| Solid sodium chloride | 10                                  | Particle level drawing and description                               | 1. Solid potassium bromide  
Mention of vibrations and/or clear representation in diagram |
| Alternating ions             | Solid sodium chloride | 9                                   | Particle level drawing and description                               | 1. Solid potassium bromide  
Mention of alternating positive and negative ions and/or clear representation in diagram |
| IONIC SOLUTIONS              |                     |                                     |                                                                      |                                                                                  |
| Contains water               | Aqueous solutions of sodium chloride, copper nitrate, silver nitrate | 11                                  | Particle level drawing and critique of representation given          | 2. Aqueous solution of barium chloride  
Mention that the diagram should show water molecules and/or clear representation in diagram |
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Relevant animations</th>
<th>Relevant Question(s) from Post-test</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| High water to salt ratio | Aqueous solutions of sodium chloride, copper nitrate, silver nitrate                 | 11                                  | 2. Particle level drawing and critique of representation given       | 2. Aqueous solution of barium chloride  
Mention that there are a lot of water molecules compared to ions and/or clear representation in diagram (1 or 2 hydrated formula units with additional unattached water molecules, or equivalent ratio of water molecules to formula units without hydration) |
|                      |                                                                                     |                                     | 3. Critique of representation given                                 | 3. Precipitation of copper hydroxide  
Mention that more water molecules are needed                                                    |
|                      |                                                                                     |                                     | 7. Particle level drawings and descriptions                          | 7(i) aqueous solution of hydrochloric acid  
7(iii) mixture after partial reaction of sodium hydroxide and hydrochloric acid  
Mention that there are a lot of water molecules compared to ions and/or clear representation in diagrams |
| Closely crowded       | Aqueous solutions of sodium chloride, copper nitrate, silver nitrate                 | 11                                  | 2. Particle level drawing and critique of representation given       | 2. Aqueous solution of barium chloride  
Mention of close crowding of molecules/ions in the solution and/or clear representation in diagram (representation shows that the distance between particles is less than the size of the particles) |
|                      |                                                                                     |                                     | 3. Critique of representation given                                 | 3. Precipitation of copper hydroxide  
Mention that there is too much empty space in the diagram given OR  
Mention that more water molecules are needed                                                  |
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Relevant animations</th>
<th>Relevant Question(s) from Post-test</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| Hydration of ions    | Aqueous solutions of sodium chloride, copper nitrate, silver nitrate, keys showing hydrated ions, above solutions with background water molecules removed | 11                                  | 2. Particle level drawing and critique of representation given  
3. Critique of representation given  
7. Particle level drawings and descriptions | 7(i) aqueous solution of hydrochloric acid  
7(iii) mixture after partial reaction of sodium hydroxide and hydrochloric acid  
Mention of close crowding of molecules/ions in the solution and/or clear representation in diagrams (representations show that the distance between particles is less than the size of the particles) |

2. Aqueous solution of barium chloride  
Mention that ions are surrounded by water molecules and/or clear representation in diagram  
3. Precipitation of copper hydroxide  
Mention that spectator ions should be surrounded by water molecules  
7(i) aqueous solution of hydrochloric acid  
7(iii) mixture after partial reaction of sodium hydroxide and hydrochloric acid  
Mention that ions are surrounded by water molecules and/or clear representation in diagrams |
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Relevant animations</th>
<th>Relevant Question(s) from Post-test</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| There is an electrostatic attraction between water molecules and ions | Aqueous solutions of sodium chloride, copper nitrate, silver nitrate, keys showing hydrated ions, above solutions with background water molecules removed | 11                                  | 2. Particle level drawing and critique of representation given       | 2. Aqueous solution of barium chloride  
Mention that water molecules orient themselves around ions according to polarity and/or water molecules correctly aligned in diagram |
|                                                 |                                                                                      |                                     | 3. Critique of representation given                                  | 3. Precipitation of copper hydroxide  
Mention that water molecules orient themselves around spectator ions according to polarity |
|                                                 |                                                                                      |                                     | 7. Particle level drawings and descriptions                          | 7(i) aqueous solution of hydrochloric acid  
Mention that water molecules orient themselves around ions according to polarity and/or water molecules correctly aligned in diagrams |
|                                                 |                                                                                      |                                     |                                                                      | 7(iii) mixture after partial reaction of sodium hydroxide and hydrochloric acid  
Mention that water molecules orient themselves around ions according to polarity and/or water molecules correctly aligned in diagrams |
| The solution is electrically neutral           | Aqueous solutions of sodium chloride, copper nitrate, silver nitrate                  | 11                                  | 2. Particle level drawing and critique of representation given       | 2. Aqueous solution of barium chloride  
Mention that ions (barium:chloride) are in a 1:2 ratio and/or clear representation in diagram (marked INCORRECT if charges on the ions are incorrect but CORRECT if atoms are used instead of ions (no charges )) |
|                                                 |                                                                                      |                                     | 7. Particle level drawings and descriptions                          | 7(i) aqueous solution of hydrochloric acid  
Mention that ions (hydronium:chloride) are in a 1:1 ratio and/or clear representation in diagram |
|                                                 |                                                                                      |                                     |                                                                      | 7(iii) mixture after partial reaction of sodium hydroxide and hydrochloric acid  
Depiction should demonstrate electrical neutrality (equal numbers of positive and negative charges) |
<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Relevant animations</th>
<th>Relevant Question(s) from Post-test</th>
<th>Probe</th>
<th>Evidence of correct mental image</th>
</tr>
</thead>
</table>
| Ions not molecules                      | Aqueous solutions of sodium chloride, copper nitrate, silver nitrate                  | 11                                  | 2. Particle level drawing and critique of representation given       | 2. *Aqueous solution of barium chloride*  
Mention that barium and chloride are separate in aqueous solution and/or clear representation in diagram  
7(i) aqueous solution of hydrochloric acid  
7(iii) mixture after partial reaction of sodium hydroxide and hydrochloric acid  
Mention that ions are separate in aqueous solution and/or clear representation in diagrams |
| Ions not atoms                          | Sodium chloride dissolving, aqueous solutions of sodium chloride, copper nitrate, silver nitrate | 11                                  | 2. Particle level drawing and critique of representation given       | 2. *Aqueous solution of barium chloride*  
Mention that barium chloride is ionic and hence its solution will contained barium (2+) and chloride (-) ions  
AND/OR  
The representation shows Barium and Chloride with positive and negative charges respectively (marked correct even if charges incorrect) |
| Dynamic (movement, collisions, water exchange etc) | Aqueous solutions of sodium chloride, copper nitrate, silver nitrate                  | 11                                  | 2. Particle level drawing and critique of representation given       | 2. *Aqueous solution of barium chloride*  
Mention of movement, collisions or dynamic exchange of water molecules and/or clear representation in diagram are indicators that the student recognises the system as a dynamic one  
7(i) aqueous solution of hydrochloric acid  
7(iii) mixture after partial reaction of sodium hydroxide and hydrochloric acid  
Mention of movement, collisions or dynamic exchange of water molecules and/or clear representation in diagram are indicators that the student recognises the system as dynamic |
<table>
<thead>
<tr>
<th>Topic</th>
<th>Relevant Animations</th>
<th>Probe</th>
<th>Questions / Answers</th>
<th>Marking Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>IONIC EQUATIONS</td>
<td>Aqueous solutions of sodium chloride, copper nitrate, silver nitrate, Solid sodium chloride, Silver chloride precipitation</td>
<td>Selection of most appropriate equation with reasoning</td>
<td>3. Reaction between copper(II) nitrate and potassium hydroxide at the particle level</td>
<td>1 mark for selection of equation (2)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Write the complete ionic equation</td>
<td>Net ionic equation shows:&lt;</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Hydrated ions rather than &quot;molecules&quot;</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Participatory species only (or omission of spectator ions)</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>7. titration between hydrochloric acid and sodium hydroxide</td>
<td>0 marks</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Complete ionic equation (hydrogen or hydronium ion)</td>
<td>2 marks (OR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Net ionic equation</td>
<td>1 mark (OR)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Full &quot;molecular&quot; equation</td>
<td>0 marks</td>
</tr>
</tbody>
</table>
<pre><code>                                                                                                                                                                                                                                  |                                                                     |                                                                                                                                                                                                                                                                                                                                                                                                                                           | TOTAL: 5                                                                                                                                                                                                                       |
</code></pre>
<table>
<thead>
<tr>
<th>Topic</th>
<th>Relevant Animations</th>
<th>Probe</th>
<th>Questions / Answers</th>
<th>Marking Scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>CONCENTRATION</td>
<td>Evaporation of liquid water, Aqueous solutions</td>
<td>Particle level drawing and description</td>
<td>6(i). Changes in a solution after some evaporation</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Drawing of a more concentrated solution</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Comment on the fact that the solution is more concentrated or that there is more sugar per unit volume or that the sugar molecules are closer together</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The amount of sugar in the entire beaker is the same before and after evaporation</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>6(ii) Changes in a solution after some spillage</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Drawing showing that the concentration remains the same</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The amount of sugar is reduced after spillage</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>TOTAL: 5</td>
<td></td>
</tr>
<tr>
<td>REACTIONS</td>
<td>Aqueous solutions, ammonia with water acid-base reaction, silver chloride precipitation</td>
<td>Particle level drawing and description</td>
<td>7. Titration between hydrochloric acid and sodium hydroxide</td>
<td>1 mark for each correct feature in description or diagram</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(iii) Reaction products</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Some hydronium ions still present</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>The chloride to sodium ion ratio is greater than one</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>More water molecules present</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Description</td>
<td>(iv) Reason for titre volume change</td>
<td>1 mark</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Comment on the fact that the hydronium ion concentration has decreased due to the reaction and therefore more solution from the burette is required to neutralise the NaOH in the flask</td>
<td>TOTAL: 4</td>
</tr>
<tr>
<td>Topic</td>
<td>Relevant Animations</td>
<td>Probe</td>
<td>Questions / Answers</td>
<td>Marking Scheme</td>
</tr>
<tr>
<td>---------------</td>
<td>---------------------</td>
<td>--------------------------------------------</td>
<td>--------------------------------------------------------------------------------------</td>
<td>----------------</td>
</tr>
<tr>
<td>DISSOLVED GAS</td>
<td>Aqueous solutions</td>
<td>Particle level diagram and description</td>
<td>8. Oxygen bubbled through water</td>
<td>1 mark per key feature to a maximum of 3</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Very few oxygen molecules</td>
<td>Demonstrated in just diagram or diagram and description</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>No particular arrangement of water molecules or justifiable reason why there might be an alignment</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Oxygen dispersed among the water molecules</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Many water molecules closely packed</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Demonstrated in diagram and description</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>TOTAL: 3</td>
</tr>
</tbody>
</table>
## A.5. Tally Sheet for the Transfer Test

<table>
<thead>
<tr>
<th>Key Feature</th>
<th>Direct transfer</th>
<th>Applied transfer</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MOLECULAR SUBSTANCES – general</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecules in a liquid are closely crowded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecules in a gas are widely spaced</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The molecular level is multi-particulate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Molecular substances contain identically structured particles in the solid,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>liquid and gas states</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SOLID</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structured lattice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrate in fixed positions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant intermolecular attractions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Close-packed structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>LIQUID</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collisions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Significant intermolecular attractions</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>GAS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Movement (translational, vibrational and rotational)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collisions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimal attractive forces</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>SUBTOTAL:</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>IONIC SOLIDS</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>Correct ion ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Separate ions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Structured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closely packed</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vibrations in fixed positions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alternating ions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SUBTOTAL:**

<table>
<thead>
<tr>
<th><strong>IONIC SOLUTIONS</strong></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Contains water</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High water to salt ratio</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Closely crowded</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydration of ions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>There is an electrostatic attraction between water molecules and ions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>The solution is electrically neutral</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Separate ions</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic (movement, collisions, water exchange etc)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**SUBTOTAL:**

**TOTAL:**
<table>
<thead>
<tr>
<th>Topic</th>
<th>Questions / Answers</th>
<th>Tally</th>
</tr>
</thead>
<tbody>
<tr>
<td>IONIC EQUATIONS</td>
<td>3. Reaction between copper(II) nitrate and potassium hydroxide at the particle level</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Net ionic equation shows: (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>hydrated ions rather than &quot;molecules&quot; (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>participatory species only (or omission of spectator ions) (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7. titration between hydrochloric acid and sodium hydroxide</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Complete ionic equation (hydrogen or hydronium ion) (2)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Net ionic equation (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full &quot;molecular&quot; equation (0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>SUBTOTAL:</strong></td>
<td></td>
</tr>
<tr>
<td>CONCENTRATION</td>
<td>6(i). Changes in a solution after some evaporation</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drawing of a more concentrated solution (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Comment on the fact that the solution is more concentrated or that there is more sugar per unit volume or that the sugar molecules are closer together (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The amount of sugar in the entire beaker is the same before and after evaporation (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6(ii) Changes in a solution after some spillage</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Drawing showing that the concentration remains the same (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>The amount of sugar is reduced after spillage (1)</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>SUBTOTAL:</strong></td>
<td></td>
</tr>
</tbody>
</table>
### REACTIONS

7. titration between hydrochloric acid and sodium hydroxide

#### (iii) Reaction products (1 mark each)
- Some hydronium ions still present
- The chloride to sodium ion ratio is greater than one
- More water molecules present

#### (iv) Reason for titre volume change (1)
Comment on the fact that the hydronium ion concentration has decreased due to the reaction and therefore more solution from the burette is required to neutralise the NaOH in the flask

<table>
<thead>
<tr>
<th>SUBTOTAL:</th>
<th></th>
</tr>
</thead>
</table>

### DISSOLVED GAS

8. oxygen bubbled through water (1 mark each)

- Very few oxygen molecules
- No particular arrangement of water molecules (in just diagram or description)
- Oxygen dispersed among the water molecules (in just diagram or description)
- Many water molecules closely packed

<table>
<thead>
<tr>
<th>SUBTOTAL:</th>
<th></th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>TOTAL:</th>
<th></th>
</tr>
</thead>
</table>
A.6. Modified Questions on Pre-test/Post-test 2001

<table>
<thead>
<tr>
<th>Question 1</th>
<th>Question 2</th>
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</thead>
<tbody>
<tr>
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</table>

<table>
<thead>
<tr>
<th>Question 3</th>
<th>Question 4</th>
</tr>
</thead>
<tbody>
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</table>

<table>
<thead>
<tr>
<th>Question 5</th>
<th>Question 6</th>
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</thead>
<tbody>
<tr>
<td></td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Question 7</th>
<th>Question 8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
</tbody>
</table>
A.7. Additional Question in Post-test 2001
A.8. Basic Skills Questions 2001
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A.10. Images Questionnaire and Attitude Survey 2000
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B.2. VVIQ Overhead Transparency
B.3. Chemistry Study Processes Questionnaire (CSPQ)
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B.5. Sample Items from Figural Intersection Test (FIT)
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Appendix C: Interview Materials

C.0. First Year Interview Protocol (2000)

I’d like to thank you again for taking the time to participate in my study. As was stated in the earlier questionnaires we are looking at ways to improve learning strategies in chemistry. Your input will help advance research in this area and hopefully benefit many students in the future.

I’d like to talk to you today about some of your responses from the diagnostic questionnaire and post-questionnaire and the most recent survey, which I will refer to as the transfer questionnaire. Our discussion today will concentrate mostly on factors that you feel have affected the way you think about chemistry.

Here are copies of your responses to the three questionnaires. Do you remember filling this out?

Firstly, when you filled in these questionnaires, what did you take the term "particle level" to mean?

In general, do you think that your images of the particle world have improved since starting this course? Why, why not? What aspects of the course do you think influenced this?

INDIVIDUALISED QUESTIONING – Post-test

Do you think that your mental image of ___ has changed since the beginning of the year? In what way? Can you identify any particular learning strategies that influenced these changes?

The vividness of your image has improved. Can you identify any particular learning strategies that influenced this change?

The confidence in your answer has increased. Can you identify any particular learning strategies that influenced this change?

INDIVIDUALISED QUESTIONING – Transfer Test

If animations were mentioned in the previous section:

You mentioned on a number of occasions that the animations shown to you in lectures helped you to answer questions on the post-questionnaire. We’re going to have a look at the Transfer questionnaire now. I want you to tell me if you think the animations helped you to answer any of the questions in this questionnaire, and if not what learning strategies did help?

If animations were not mentioned in the previous section:
We’re going to have a look at the Transfer questionnaire now. I want you to tell me what learning strategies helped you to answer these questions?

**STIMULATED ANIMATION RECALL**

I’m now going to show you one or more of the animations from your lectures again [NaCl(s), NaCl (aq), AgCl ppt]. I’ll let you watch it through once and then I’ll play it again. The second time, I want you to describe to me what the animation is trying to show. Let me know if you want me to stop the animation at certain points.

Do you think that any of these animations relate to any of the questions in either of these questionnaires? Which are related to which? How?

*Give interpretation of animations at student's request.*

Finally, I would like you to try and recall the way you think about or study chemistry for example in lectures, tutorials, labs or just when you are attempting a chemistry problem. In particular do you recall being aware of having a mental picture or image of the particulate level of matter when you are thinking about chemistry. Indicate on this scale here how often you feel that you imagine the particulate level of matter when you are thinking about chemistry.

See if you can list all the topics that you think about in terms of the particulate nature of matter and describe this thinking in these areas.

Now before we finish, is there anything you would like to ask about my study or about these questionnaires?

Thank you for your participation in my study.

---

**Imagery Rating Scale**

How often do you imagine the particle level of matter when you are thinking about chemistry?

<table>
<thead>
<tr>
<th>Rarely</th>
<th>Almost always</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

[Introduction]

It's been a while since you filled in this questionnaire so you might like to just review your responses. Are there any more points you would like to add to any of the images? (Provide a RED pen if they ask to modify something.)

I just want to ask you a couple of questions about your responses to this questionnaire.

INDIVIDUALISED QUESTIONING ON “PROBLEM” QUESTION(S)

How do you think you might have originally developed these images?

Try to think back to when you were first filling in the questionnaire. At any stage, did you recall images of animations you viewed in first year? Tell me what you remember about the animations that sprung to mind.

I’m now going to show you one (a couple) of the animations (ice melting, sodium chloride dissolving, precipitation)

SHOW RELEVANT ANIMATION (Student asked to describe what each animation is showing.)

Do you wish to modify any of your representations?

SHOW ANIMATION AGAIN AND POINT OUT KEY FEATURES (Animation repeated as often as the student desires. Key features not pointed out.)

Would you now make any modifications to your representations?

---

1 Modifications made to the protocol in 2000 are given in italics.

Research Questions:

• Have student's mental models of substances and reactions started to change by week 4 of their first year university course? In what way?
• What has influenced these changes?
• How developed is students' understanding of the use of models in chemistry?

[Introduction]

Basic Skills (Approx. 10 mins)

Firstly, could you describe the differences you perceive there to be between atoms, ions and molecules?

Question 6 (in post-test):
So according to these definitions, what would this formula represent?
Can you describe to me how you interpret this formula?

Question 7 (in post-test):
Explain how you derived the formula for this representation

I want to show you an equation now. Tell me what it means to you and see if you can draw me a representation of the reactants and products of the reaction.

[on separate card….. 4 NH₃(g) + 5 O₂(g) → 4 NO(g) + 6H₂O(g) ]

Images - all other questions in post-test (Approx. 30 mins)

The rest of this questionnaire documents your images of some chemical substances and processes, before doing any university chemistry. We are going to go through some of the questions in this questionnaire and I am going to ask you
• to explain your original idea
• discuss whether this idea has changed at all, and how it has changed
• identify and describe factors which have influenced any changes

Could you please describe what you were thinking when you answered this question?

Do you still have the same idea?
[If not] How has your idea changed? [questioning relating to understanding of the new image eg: Does the student understand why the water molecules orient themselves towards the ions?] What do you think influenced these changes? (ask for description)

[If so] Has anything you have done in chemistry so far confirmed your idea about this?

Question 11 (in post-test):
Explain why you selected this model of a water molecule. Do you like any others? What don't you like about the other models? Here are some more models of water molecules. What do you think of these models?

**Modelling Ability** (Approx. 10 mins)

[Use animation of one water molecule]

Do you think anyone has actually seen an atom or molecule? How would they see it?
Do you think that a water molecule would actually look like that? Colour? Hard spheres?
What is it made of?
Is there anything inside there?
How similar do you think this animation is to the way scientists imagine atoms and molecules?

Research Questions:

- Have student's mental models of substances and reactions developed further since week 4/5/6 of their first year university course? In what way?
- What has influenced some of these changes?

Follow up (20 mins)

Firstly today I'd like to ask you about some of the things you didn't seem too sure about last time you were here.

[devise for each student]

What do you think has helped you to further develop this idea since I talked to you last?

Solutions (10 mins)

I want to show you a bottle that I borrowed from the laboratory (aqueous solution of H$_2$SO$_4$). Okay, have a read of the label. You used a similar solution of H$_2$SO$_4$ in your last lab. Now I want you to give me your interpretation of what you think is in the bottle by describing what you would see if you zoomed down to the level of ions, atoms and molecules.

If we add this to a solution of sodium hydroxide. Watch what happens. Nothing? Did anything happen at the particle level?

This is the reaction that occurs. It is the same reaction that you carried out in your first titration last week.

\[
\text{H}_2\text{SO}_4\ (aq) + 2\text{NaOH}\ (aq) \rightarrow \text{Na}_2\text{SO}_4\ (aq) + 2\text{H}_2\text{O}\ (l)
\]

Describe what you think might be happening in the solution at a particle level, as the sodium hydroxide is added.

Draw and describe the products of this reaction.

Precipitation (15 mins)

I want to show you another equation. Tell me what it means to you. Are you able to draw me a representation of the reactants and products from this equation? (allow student draw if they wish) If not, what information do you need?

[on separate card….. \(2\text{KCl} + \text{Pb(NO}_3\text{)}_2 \rightarrow \text{PbCl}_2 + 2\text{KNO}_3\)]
Now what if I add the states...does your representation change?

\[ 2\text{KCl(aq)} + \text{Pb(NO}_3\text{)_2(aq)} \rightarrow \text{PbCl}_2(s) + 2\text{KNO}_3(aq) \]

Okay, this is the reaction that you were shown last time you were here (\(4 \text{NH}_3(g) + 5 \text{O}_2(g) \rightarrow 4 \text{NO(g)} + 6\text{H}_2\text{O(g)}\)) and the representations you drew for me. Do you still agree with your answer? What changes (if any) would you make? What do you think are the most important differences between these two reactions?

I want to show you a third equation. Tell me what it means to you and see if you can draw me a representation of the reactants and products of the reaction.

\[ 2\text{K}^+(aq) + 2\text{Cl}^{-}(aq) + \text{Pb}^{2+}(aq) + 2\text{NO}_3^{-}(aq) \rightarrow \text{PbCl}_2(s) + 2\text{K}^+(aq) + 2\text{NO}_3^{-}(aq) \]

All of these equations represent the same reaction. Which do you think best represents what is actually happening at the particle level and why?

**Complexation** (10 mins)

The following reactions were studied during lab sessions:

\[ \text{Cu}^{2+}(aq) + 2\text{OH}^{-}(aq) \rightarrow \text{Cu(OH)}_2(s) \quad [1] \]

\[ \text{Cu(OH)}_2(s) + 4\text{NH}_3(aq) \rightarrow \text{Cu(NH}_3)_4^{2+}(aq) + 2\text{OH}^{-}(aq) \quad [2] \]

What would you observe in each reaction?

Draw a representation for the products in reaction 1. Describe your representation as you are drawing it.

Describe what you think happens to this solid as ammonia is added. How do you think you came up with this idea?

Draw a representation for the products in reaction 2. Describe your representation as you are drawing it.

The above equations can be written in a different way:

\[ \text{Cu(H}_2\text{O)}_6^{2+}(aq) + 2\text{OH}^{-}(aq) \rightarrow \text{Cu(OH)}_2(s) + 6\text{H}_2\text{O(l)} \quad [1] \]

\[ \text{Cu(OH)}_2(s) + 4\text{NH}_3(aq) \rightarrow \text{Cu(NH}_3)_4(H\text{H}_2\text{O)}_2^{2+}(aq) + 2\text{OH}^{-}(aq) \quad [2] \]

Do you wish to modify your drawing based on seeing this equation?

Which do you think best represents what is actually happening at the particle level and why?

Aims:

To further examine the development, sophistication and usefulness of a selection of students' mental models and to assess the modelling abilities of these students. Specifically:

- To determine the cause of any changes in ideas from last interview to the post-test
- To determine students’ ability to critically evaluate textbook diagrams and poor animations
- To determine students’ level of modelling ability

Part 1: Individualised questioning (10 mins)

Questions will ask about any changes that have occurred between last interview and post-test; any "holes" in previous interviews.

Response to extra "movement" question: If you were watching a video or animation of what was going on here, would you see anything else happen? For liquid water you mentioned that the particles move. Does a similar thing happen here? Why do you think that idea didn't spring immediately to mind? Can you picture this in your head? Is the image moving at all?

[If student still believes there is no movement in solid, after discussing NaCl being heated] Say we have some salt sitting on the kitchen bench. In the morning it is 10 degrees. Are the ions in the solid moving? Now during the day the temperature rises to 25 degrees. Are the any changes at the molecular level? At what point do the ions start vibrating? When do they stop? What if the temperature was 5 degrees one morning? …..etc

Part 2: Applications of models (with demos, 10 mins) - explaining phenomena

I'm going to open this bottle of nail polish remover. The ingredients on the bottle say that it is made of ethyl acetate. Let me know when you can smell the nail polish remover. Why do you think some liquids smell? Can you explain it at a molecular level? What do you think reaches your nose in order for you to be able to smell it?

Here I have two white solids (lead(II) nitrate and potassium iodide). I'm going to add a small amount of each solid to either end of this glass container. What do you think will happen? [perform experiment] Explain to me everything you think is happening at a molecular level.

Part 3: Modelling ability 1 (10 mins) - multiple representations, uses of models, correspondences and non-correspondences

During our last interview you were unsure as to what this model of a water molecule was trying to show. Do you have any ideas about that now?
The following are all representations of solid NaCl. Which do you think is the best representation? Why? What do you think of some of these other models? Why do you think we have these different representations?
(diagrams page, ball and stick model)

Part 4: Critical Thinking Skills (10 mins)

Here are some diagrams I have photocopied from textbooks. Tell me what you think of each of them. Do you think they need to be improved? How would you improve them?
Do you think students might develop any misleading/incorrect ideas from them?

Here is an animation of sodium chloride dissolving in water (not VisChem). What do you think of it? Do you think it needs to be improved? Do you think students might develop any misleading/incorrect ideas from it?

Do you think there are any limitations to the use of diagrams for representing the molecular world?

Part 5: Modelling Ability 2 - correspondences and non-correctances, uses of models, applicability of models, reasons for modelling

Here is an animation you may or may not be familiar with. (aqueous solution of potassium fluoride). Do you know what it is trying to represent? [prompt to answer]
How close do you think this animation is to what the molecular world of an aqueous solution of potassium fluoride would actually be like?
How do you think representations of solutions at the molecular level were first developed?
Why were they developed?
What do you think is the purpose of producing animations to represent these ideas?
Why do you think your lecturer wants you to learn this?
Do you think these images are of any use to you?
Do you think that this animation is applicable to all aqueous ionic solutions?
What might convince you otherwise?
Do you think that scientists’ ideas about ionic solutions have been developed further or changed since this representation was proposed?
Why might this come about?
Do you think that all scientists would agree that this was a good representation of an ionic aqueous solution?
Do you think there are any other models of aqueous ionic solutions that scientists use?
Can you give an example?

\[ \text{NaCl (s)} \]

Aims:

- To further examine students' ability to form mental images of chemical phenomena by examining how they imagine redox reactions, equilibrium reactions and acid-base reactions
- To test students' ability to identify correspondences and non-correspondences in analogies of chemical equilibrium
- To determine students' recall of VisChem animations shown during Semester 1
- To determine students' ability to interpret a VisChem redox animation not seen before

Part 1: Equilibrium Reactions (20 mins)

Imaging

What is an equilibrium reaction?
Explain how the forward and reverse reactions can both occur.
Imagine you are watching an animation of this reaction:

\[ \text{ClNO}_2(\text{g}) + \text{NO}_2(\text{g}) \rightleftharpoons \text{ClNO}_3(\text{g}) + \text{NO}_2(\text{g}) \]

The equilibrium constant, \( K \), of this reaction at 25 \(^\circ\)C is \( 1.3 \times 10^4 \)

This is an elementary reaction – the equation also represents the mechanism. Describe the processes you imagine occur at the molecular level at equilibrium. Draw a representation of what you might see if you were able to pause or take a snapshot of this process.

Imagine now that you add some NO(g) to the reaction vessel. What do you think will happen? Why? Describe the molecular level processes that cause this reaction to shift to produce more products.

Modelling

I'm going to show you some analogies that I have taken from textbooks, web-sites and other instructional material. All of the analogies are used to help describe the process of chemical equilibrium. As with all analogies, they have features that are like the phenomena we are trying to describe and features that are not like the phenomena we are trying to describe.

For each analogy I want you to describe the advantages (What's right with it?) and limitations (What's wrong with it?).
Tell me whether or not you like the analogy, whether you think it needs to be improved and how you would improve it?

**SHOW ANALOGY**

Do you think students might develop any misleading/incorrect ideas from this analogy?

- Equilibrium is like substituting players in a game of soccer. For every new player substituted onto the field, an old player must leave. There is no change in the number of players on the field, even though their identities are different. There is no requirement that the number of players on the field and on the bench be equal (and usually they are not equal).

http://www.sciencepage.org/anleq.htm#subs

- Chemical equilibrium is like a juggling - balls go up at the same time as balls are returned, such that the number of balls in the air or in the hands always remains the same.


- Equilibrium is like males and females dancing alone and in pairs. Some men and women are dancing together, others are dancing alone. Every time one couple splits and begins dancing separately, another couple begins dancing together. A male must find a female partner and persuade her to dance before they can dance together.


Which would you prefer to use if you were teaching about equilibrium? Why?

**Part 2: Acid/Base Reactions** (15 mins)

*Imaging*

Imagine you are able to zoom down to the molecular level and watch this reaction at equilibrium. What would you see?

Boric acid can be structurally represented as B(OH)$_3$(aq).

The equilibrium constant, $K_a$, of this reaction at 25 °C is $5.8 \times 10^{-10}$

$$\begin{align*}
\text{H}_3\text{BO}_3\text{(aq)} & \rightleftharpoons \text{H}_2\text{BO}_3^-\text{(aq)} + \text{H}^+(\text{aq})
\end{align*}$$

Draw a representation of a solution of boric acid.

This is another equation for the same reaction. Would you like to make any changes to your representation?
\[ \text{H}_3\text{BO}_3(aq) + \text{H}_2\text{O}(aq) \rightleftharpoons \text{H}_2\text{BO}_3^-(aq) + \text{H}_3\text{O}^+(aq) \]

Now imagine that we had a more concentrated solution of \( \text{H}_3\text{BO}_3(aq) \) than you have represented here. What changes would you make? Draw a representation of the concentrated solution.

**Part 3: Redox Reactions** (10 - 15 mins)

*Imaging*

I have here some solid copper and an aqueous solution of silver nitrate. Draw diagrams of each of these substances at a molecular level.

I'm now going to show you a reaction between this piece of Copper metal and this solution of Silver Nitrate.

What do you predict will happen?

[perform experiment]

Can you explain, using drawings to help, what is happening at the molecular/ionic level?

Draw diagrams of the products of this reaction.

**Part 4: Stimulated animation recall** (15 mins)

I'm now going to show you some of the animations from your lectures again. I'll let you watch it through once and then I'll play it again. The second time, I want you to point out all the important features that the animation is trying to show. Let me know if you want me to stop the animation at certain points.

[Melting of Ice, Evaporation of water, NaCl dissolving, NaCl solution, AgCl ppt]

Is there any reason why you did not point out the fact that [insert key feature]?

**Part 5: Animation Interpretation** (5 mins)

Here is an animation you will not be familiar with (Redox: solid copper with aqueous solution of silver nitrate). Tell me what you think it is trying to represent. I'll play through it as many times as you like and you can make comments about what you are seeing as we go.
Appendix D: Animation Quotes

D.0. FIRST YEAR INTERVIEWS (2000)

D.1. THIRD YEAR ATTITUDE SURVEY (1999, 2000)
Appendix D: Animation Quotes

D.0. First Year Interviews (2000)

The following is a complete list of edited supporting quotes for the influence of VisChem animations on key features from the post-test and questions on the transfer test. Absence of certain key features indicates a lack of interview evidence. Key features 18 – 20 (features of a water molecule) have been excluded due to the fact that they were discussed in relation to modelling and not VisChem animations.

1. Molecules in a liquid are closely crowded

Reinforced

Interviewer: With those projector images, can you actually picture those in your head?

Student 7: Yeah

Interviewer: You can picture liquid water in your head?

Student 7: Yeah

Interviewer: …Do you think you would have pictured those in your head when you were answering these questions?

Student 7: Yeah

Interviewer: Can you describe to me sort of what you can see?

Student 7: Well, I don't know like great big spheres with little tiny spheres with the mickey mouse shape and its bent and it's bouncing around.... Say liquid water, say and it's bouncing around and some are connected or some have more hydrogens or less hydrogens than the others… they're crowded but some are connected and some aren't, they don't have that much energy but they have some energy.

Interviewer: I think with your water ones, I think your representations are probably fairly similar. Okay, you've probably included more detail in this one, you've got here that the molecules are close together. Here you've said that the molecules are close together and free to move, and you've also got improved confidence and improved vividness. What do you think may have caused that improvement?

Student 10: Well that was definitely the video cause in the video it shows the molecules are moving but they're still close together.
2. Molecules in a gas are widely spaced

*Learnt*

Student 11: …He had a lot of computer animations, which actually helped a lot. I think the example he used was water ...and so he showed the little beaker...I don't know. It helped a lot, him showing the actual physical pictures and everything.

Interviewer: Okay so that gave you move of an idea about how far apart the molecules were

Student 11: Mm

Interviewer: Alright, similar sort of situation here…

Student 11: And I did exactly the same thing again [mumbles]

Interviewer: So once again you've got a change in your response. What do you think might have influenced that change?

Student 11: Probably the same thing; the pictures that he showed us. He actually went over it quite a lot.

Interviewer: Pictures?

Student 11: The little diagrams on the computer... We did a lot of them.

*Reinforced*

Interviewer: Your description has got a little more detailed…and your confidence in your explanation has gone right up too. Do you remember how that might have come about?

Student 10: It was basically revising over the work, those videos again, they showed like, H2O particles and the video showed it moving around, rotating, vibrating.

3. Molecules do not change size from solid to liquid to gas

*Learnt*

Student 3: [The lecturer] sort of demonstrated through the videos and all that it maybe isn’t different.

Interviewer: Okay, the videos, can you talk a little more about that?

Student 3: Visual images.

Interviewer: Okay, what sort of visual images.

Student 3: Oh gosh, the particles, the atoms, what they do in different states…so like we get to see what actually happens at every state.

Interviewer: and what does happen?
Student 3: Solid they’re all packed together, sort of rigidly, I think that’s the word, and then liquid they vibrate and they sort of they move but like not as much as gases. Gases then they start floating up.

Interviewer: So how does that help you to understand that the size of the molecules doesn’t change within each state?

Student 3: Cause nothing happens to the actual molecule apart from movement.

Interviewer: Okay, at the beginning of the year you were unsure … as to the size of the different molecules in each state and your confidence has improved dramatically and your answer has changed…okay any idea what influenced this change?

Student 9: Just the same. Lectures.

Interviewer: Can you think of any examples where you were shown something similar that … changed your idea about it?

Student 9: Well, the water, the water on the computer screen.

Interviewer: Yeah?

Student 9: Yeah, how it was solid then liquid then gas and the molecules stay the same.

Interviewer: Okay … so the molecules stay the same. What actually changes in each when we change states then?

Student 9: Just the distance, the distance between the molecules.

Reinforced

Interviewer: This is the size of the molecules in the different states and your confidence has gone up slightly. Maybe one notch. Do you feel as if your confidence … in that idea had improved?

Student 1: Yeah

Interviewer: Yeah? What do you think has helped with that?

Student 1: What was the question? …Well that one it was more sort of a logical guess … but that one I actually knew. Like we’d done it, we’d covered it in lectures.

Interviewer: Okay when you say you’d covered it in lectures, how was that approached in lectures?

Student 1: …Just that the difference between the states of matter, like solid, liquid and gas it didn’t affect the size of the molecule, only how they were bonded together.

Interviewer: Okay, and was that just told to you?

Student 1: There were the videos, they were good where it went from like solid just vibrating and then they started rolling around and then they broke off. That was really good actually, that video.
Interviewer: Okay, what was that video portraying?

Student 1: The changes of state.

Interviewer: Of anything in particular?

Student 1: I think it was water.

Interviewer: Okay, and how did that video help you with the idea that the molecules didn’t change size?

Student 1: Well they were still the same molecule.

4. The molecular level is multi-particulate

Reinforced

Interviewer: So if you brought up the animation of liquid water in your head describe to me what you actually see.

Student 13: Well I just see … lots of water molecules.

5. Molecular substances contain discrete particles in the solid, liquid and gas states

Learnt

Interviewer: Do you think that your mental images of liquids or liquid water specifically has changed at all since the beginning of the year?

Student 12: Yeah, I would’ve always done it like that before, now I always do it like that. That’s mainly because of the videos that [the lecturer] showed us of the water going round. I always put the hydrogens on now cause just, I don’t know.

Interviewer: Okay, so you’re mental image before contained maybe just balls or circles.

Student 12: Yeah, very shallow yeah. This one actually contains the molecule.

Interviewer: Okay, do you picture those, [the lecturer’s] videos in your head when you answer this now?

Student 12: Yeah, there’s a lot of stuff now, yeah.

Interviewer: Do you think that’s actually improved the vividness of your mental image?

Student 12: Yes, I would say it has, yes.

Interviewer: Okay, do you remember particular things that were done in lectures or shown to you or whatever that made you realise that water doesn't consist of these two separate particles?
Student 13: The animations… The computer animations and well not just with the water molecules but when they're going from solid to liquid or whatever or vice-versa

6. There is empty space between the molecules

Learnt

Interviewer: Your idea is obviously different now…. You said no there’s nothing, everything remains the same except the ability to move around. How do you think you developed that sort of an idea?

Student 14: Obviously from the animations, how obviously they show that that was frozen and as the temperature rises they become more mobile and when it gets to the gaseous stage it’s just wooshka everywhere.

Interviewer: In those animations, is there anything between the molecules?

Student 14: No

Interviewer: What do you see?

Student 14: Just nothing. It just showed them and that was it.

Reinforced

Interviewer: slight improved confidence. You obviously had very high confidence before in what was between the particles… Do you think anything helped you consolidate that idea that there is only empty space between the particles?

Student 2: The images, these visual images that are used, they describe not only the particles but because they can be seen vibrating they describe also the small amount of space which is between the particles.

7. Structured lattice

Learnt

Interviewer: Okay, you've mentioned vibrating here but you haven't mentioned any movement in the solid here and I would also suggest that maybe your representations here for solid, for the ice were slightly different… Do you think that that image has changed at all…?

Student 4: Yeah, that again would have come from those animations.

Interviewer: Okay, so if you had to picture maybe the animation of ice in your head…could you describe that to me?

Student 4: Yeah, I can see it, there are molecules stacked up in rows and all tight together and vibrate....

Interviewer: Okay, just like it says there. Okay, when you were answering this…post questionnaire, with these water questions, do you think at any stage you imagined those animations in your head to answer this question?
Student 4: Definitely.

Interviewer: You can’t remember any particular things in lectures that showed you that idea?

Student 14: Only those little animation things that he had going but that’s all I remember of it.

Interviewer: Okay, well, do you think they gave you that sort of an image or do you think it was probably more just something [the lecturer] said?

Student 14: Just more how he explained it then he showed an image of it…sort of backing himself up a bit.

Interviewer: Yeah, okay… Can you think of that image that he backed himself up with?

Student 14: Yeah.

Interviewer: Can you picture that in your head?

Student 14: Yeah, all the molecules in a line, they’re all aligned and sort of vibrating a tiny bit…

8. Vibrate in fixed positions

Learnt

Interviewer: What about this “free to vibrate within their fixed positions”? Is that an image that you had originally?

Student 1: I don’t think so…

Interviewer: You’re not sure?

Student 1: No, I’m not sure but I think I would have mentioned it if I’d been confident of it. I might have maybe thought it but not…

Interviewer: So you don’t remember anything in particular…?

Student 1: Nup.

Interviewer: …Do you think that anything in particular helped you to improve the vividness of this image?

Student 1: Again that was directly from, that is my recall of that video.

Interviewer: Okay the video animation?

Student 1: Yep, from solid to liquid to gas.
Interviewer: Okay, you've mentioned vibrating here but you haven't mentioned any movement in the solid here and I would also suggest that maybe your representations here for solid, for the ice were slightly different. Do you think that that image has changed at all or you?

Student 4: Yeah, that again would have come from those animations.

Interviewer: Okay, so if you had to picture maybe the animation of ice in your head… Could you describe that to me?

Student 4: Yeah, I can see it, there are molecules stacked up in rows and all tight together and vibrate....

Interviewer: Okay, just like it says there. Okay, when you were answering this…post questionnaire, with these water questions, do you think at any stage you imagined those animations in your head to answer this question?

Student 4: Definitely.

Interviewer: Here you've mentioned pretty much spacing and hydrogen bonding. Here you mentioned spacing and movement and no bonding… okay so you've got a similar number but you've got different things. Do you think that that the image of movement is a new thing that you’ve added to your image…?

Student 5: Yeah, I think so…what [the lecturer] did in the lectures with the computer animation things. That really helped I guess. I never well you know, specifically with the solid, I guess I never knew that they still moved a little bit.

Interviewer: Okay, so the vibrations in ice?

Student 5: Yeah.

Interviewer: Yep. Do you think that when you answered these questions, that you might have pictured in your head those animations that [the lecturer] showed you?

Student 5: Yeah probably, yeah.

Interviewer: Do you think that your model of water in the different states has changed at all since the beginning of the year?

Student 7: Yeah, a bit.

Interviewer: What do you think might have influenced that change?

Student 7: … Just looking at water, states on the projector…

Interviewer: …Do you remember anything else that, just about your images of liquid, gas or solid water…that have specifically changed? …You said your images might have changed little bit, can you tell me what those changes are? …

Student 7: … ice would vibrate a bit and I never really considered that.
Interviewer: Okay, when you say very little movement of molecules, what do you mean by that?...

Student 10: Yeah they move. I know there's three types of movement…there's rotational, vibrational and there's translational or something…so they sort of just vibrate but they stay really close together...

Interviewer: And did you have that image before you saw the animation?

Student 10: No, no.

Interviewer: Okay, the other difference here is that you've noted here that there's vibrating in a fixed lattice and you didn’t mention that before. I was wondering if that was a new image?

Student 12: Yeah, that’s from the videos again.

Interviewer: Okay, the video of ice?

Student 12: Oh, all them ones he showed us of water.

Interviewer: …Can you describe to me what your mental image of that video looks like? Like is it similar to what you've drawn here?

Student 12: Yeah, I think so. I don’t think we ever saw it like this, like a hexagon. It was always in…just in a square lattice and they vibrated in one place.

Interviewer: You've developed some sort of idea of the structure of the particular molecules… Do you recall an animation of ice at the particle level?

Student 13: Yes, I do.

Interviewer: Yep, and what do you see when you picture that in your head?

Student 13: Well there's more of them, they're all packed in tightly.

Interviewer: Okay.

Student 13: And they struggle to move around at all.

Interviewer: When you say they struggle to move at all, what does that...?

Student 13: Well they're bouncing around off each other. There's hardly any room to move at all.

Interviewer: Okay, but there's some sort of movement then?

Student 13: A little bit, yeah.

Interviewer: Do you think the idea that there's some movement in the solid state has come from…do you think that came from the animations?

Student 13: Yeah
Interviewer: You can’t remember any particular things in lectures that showed you that idea?

Student 14: Only those little animation things that he had going but that’s all I remember of it.

Interviewer: Okay, well, do you think they gave you that sort of an image or do you think it was probably more just something [the lecturer] said?

Student 14: Just more how he explained it then he showed an image of it…sort of backing himself up a bit.

Interviewer: Yeah, okay… Can you think of that image that he backed himself up with?

Student 14: Yeah.

Interviewer: Can you picture that in your head?

Student 14: Yeah, all the molecules in a line, they’re all aligned and sort of vibrating a tiny bit…

10. Movement in liquid water

Learnt

Student 3: [The lecturer] sort of demonstrated through the videos and all that it maybe isn’t different.

Interviewer: Okay, the videos, can you talk a little more about that?

Student 3: Visual images

Interviewer: Okay, what sort of visual images.

Student 3: …The particles, the atoms, what they do in different states…so like we get to see what actually happens at every state.

Interviewer: And what does happen?

Student 3: Solid they’re all packed together, sort of rigidly, I think that’s the word, and then liquid they vibrate and they sort of they move but like not as much as gases.

Interviewer: You've probably included more detail in this one. You’ve got here that the molecules are close together. Here you've said that the molecules are close together and free to move, and you've also got improved confidence and improved vividness. What do you think may have caused that improvement?

Student 10: Well that was definitely the video cause in the video it shows the molecules are moving.

Reinforced
Student 1: …We’ve been using those, that representation a lot in the lectures and like I just said like I can picture that in my head. You sort of look at that and if you didn’t know that $\text{H}_2\text{O}$ was water or even if it was a molecule you’d sort of look at it and say that doesn’t look like anything but that looks like a beaker full of water molecules, you know.

Interviewer: Okay, what do you think helped you to be able to picture it in that way?

Student 1: Like what things were done in the lectures?

Interviewer: Yeah.

Student 1: Well all the pictures and the video…like the pictures are good and that but videos are better because it shows a moving description of it rather than just this then that. It shows the transitional period between…

Interviewer: Do you think that you picture those images in your head when you go to draw something like this?

Student 1: Well, I must do because…I drew that so that’s obviously how I picture it.

Interviewer: And do you think that those visual images were responsible for the increase in the vividness of your image?

Student 1: Yeah, yeah.

Interviewer: Can you identify any particular learning strategies, teaching strategies that may have contributed to increasing your visual images or your confidence in this question?

Student 2: Well the overheads, the videos of the water molecules bumping around.

Interviewer: …Do you think that when you were answering these questions you brought up a mental image of water?

Student 2: Oh yes, definitely.

Interviewer: And could you describe that mental image to me? Say for the liquid water.

Student 2: Well on the screen, in colour, all the molecules of water are all gently bumping around, [muffled] Repeated twice or three times, sometimes they are they [muffled] Across sometimes

Interviewer: So you're talking about the animations?

Student 2: The animations yes.

Interviewer: Okay and you would say to me, when you were actually answering this question you actually pictured the animation in your head?

Student 2: Yes.

Interviewer: Do you feel that your image is more vivid now then it was at the beginning of the year?

Student 7: Yeah, I suppose, yeah.
Interviewer: Yeah? … What do you think might have helped?

Student 7: Like I keep on saying, the projector thing.

Interviewer: … Can you actually picture those in your head?

Student 7: Yeah.

Interviewer: You can picture like liquid water in your head?

Student 7: Yeah.

Interviewer: … Do you think you would have pictured those in your head when you were answering these questions?

Student 7: Yeah.

Interviewer: Can you describe to me sort of what you can see?

Student 7: Well, I don't know like great big spheres with little tiny spheres with the mickey mouse shape and its bent and it's bouncing around…. Say liquid water, say and it's bouncing around and some are connected or some have more hydrogens or less hydrogens than the others… They're crowded but some are connected and some aren't. They don't have that much energy but they have some energy.

Interviewer: Yeah

Student 7: Just moving around each other.

Interviewer: … So if you brought up the animation of liquid water in your head describe to me what you actually see.

Student 13: Well I just see the, lots of water molecules… They'll be floating around a little bit.

Interviewer: You’ve obviously got some sort of a mental image that’s fairly strong now….

Student 14: It’s the way the molecules like, flying around, colliding with each other, instead of obviously being like, they’re not aligned any more… unlike the solid one.

Interviewer: … How do you know?

Student 14: Cause they’re moving… cause that’s liquid so it’s… they’re colliding into each other.

Interviewer: So you’re picturing them colliding and moving … Is that an image that you developed yourself?

Student 14: No.

Interviewer: Well where did you steal it from?

Student 14: From him, I guess.
11. Collisions in liquid water

**Learnt**

*Interviewer:* Okay, what exactly did you steal it from?

*Student 14:* From those animations again…

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**Reinforced**

*Interviewer:* … You’ve obviously got some sort of a mental image that’s fairly strong now….

*Student 14:* It’s the way the molecules like, flying around, colliding with each other, instead of obviously being like, they’re not aligned any more…unlike the solid one.

*Interviewer:* …How do you know?

*Student 14:* Cause they’re moving… cause that’s liquid so … they’re colliding into each other.

*Interviewer:* So you’re picturing them colliding and moving … Is that an image that you developed yourself?

*Student 14:* No

*Interviewer:* Well where did you steal it from?

*Student 14:* From him, I guess.

*Interviewer:* Okay, what exactly did you steal it from?

*Student 14:* From those animations again…

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13. Movement in gas (translational, vibrational and rotational)

**Learnt**

*Interviewer:* Okay, the videos, can you talk a little more about that?

*Student 3:* Visual images

*Interviewer:* Okay, what sort of visual images?
Student 3: The particles, the atoms, what they do in different states...so like we get to see what actually happens at every state.

Interviewer: And what does happen?

Student 3: Solid they’re all packed together, sort of rigidly, I think that’s the word, and then liquid they vibrate and they sort of they move but like not as much as gases. Gases then they start floating up.

Interviewer: Here you’ve mentioned distance and movement and collisions with the glass, big improvement in vividness and confidence.

Student 10: …Yeah, cause we got most of this out of the video like just showing the gaseous state.

Interviewer: How do you think you developed this image of the water molecules coming away and then coming back down again?

Student 14: Well that was the animations again.

Reinforced

Student 1: Exactly like in the video that’s how I, that’s how I remember. It was like those molecules …in the water state, some of them are going up but it’s not enough to make a real difference so if they’ve got more energy then they’re able to like…you just see one or two of them going off and the more moving to gas you know that the more have got energy to go and I just see them pretty much moving from there to there.
14. Collisions in gas

**Learnt**

*Interviewer:* Here you've mentioned distance and movement and collisions with the glass, big improvement in vividness and confidence.

*Student 10:* …Yeah, cause we got most of this out of the video like just showing the gaseous state.

16. Water molecules can react with each other to form hydronium ions and hydroxide ions

**Reinforced**

*Student 7:* Like I keep on saying, the projector thing…

*Interviewer:* …Can you describe to me sort of what you can see?

*Student 7:* Well, I don't know like…great big spheres with little tiny spheres with the mickey mouse shape and its bent and it's bouncing around…. Say liquid water, say it's bouncing around and some are connected…or some have more hydrogens or less hydrogens than the others, they're like really… They're crowded but some are connected and some aren't. They don't have that much energy but they have some energy.

17. Correct model of water molecule

**Learnt**

*Interviewer:* Okay, do you remember particular things that were done in lectures or shown to you…that made you realise that water doesn't consist of these two separate particles?

*Student 13:* The animations.

**Reinforced**

*Interviewer:* Okay, now obviously here you’ve drawn your representation using a different representation to the one you chose on the previous page. What do you think might have influenced that decision?

*Student 1:* Well we’ve been using those, that representation a lot in the lectures and like I just said like I can picture that in my head. You sort of look at that and if you didn’t know that H₂O was water or even if it was a molecule you’d sort of look at it and say that doesn’t look like anything but that looks like a beaker full of water molecules, you know.

*Interviewer:* Okay. What do you think helped you to be able to picture it in that way?

*Student 1:* Like what things were done in the lectures?

*Interviewer:* Yeah.
Student 1: Well all the pictures and the video... like the pictures are good and that but videos are better because it shows a moving description of it rather than just this then that. Interviewer: Do you think anything else influenced your choice of molecule?

Interviewer: You've selected the same model before and after instruction... Can you tell me why you selected that model over the others?

Student 4: I think that would have probably because we watched those computerised animations... They looked like that.

Interviewer: You said that this one was the one that was pushed in lectures. Can you sort of expand how it was pushed?

Student 6: Well every visual representation that was graphic had that diagram, so on the overheads, the animations were three dimensional, when we did solutions in water, we always did a circle with a little mickey mouse head.

Interviewer: This is your choice of model of water... Okay you've chosen a different representation to the one you chose in the beginning. What do you think might have influenced your change in choice?

Student 7: Well actually, I think it's because at the other time I did this it was either 1 or 2, I just chose that one cause it's stick figure and the other was ball and model figure. I probably chose that one later, 2, number two later because...I see it one all the time and on those...3D model things that they showed on the projector.

Interviewer: Oh, the animations?

Student 7: Yeah.

Student 9: I don’t know.

Interviewer: Nothing in lectures or labs or anything that you sort of thought...

Student 9: Well in lectures that's the representation that was used in the videos.

Interviewer: Did that influence your choice?

Student 9: Pretty much.
23. Ions not atoms

**Animation Interpretation**

*Student 5:* There’s two different atoms or ions there, so I’d say one’s probably a positive, one’s a negative.

24. Structured

**Reinforced**

*Interviewer:* And sorry, what was the other thing you mentioned might have helped here?

*Student 2:* The overhead, the visual images.

*Interviewer:* Okay, the visual images. Could you possibly describe those for me?

*Student 2:* Well they’re respectively ??? More three-dimensional, with different colours, and being an array in the cubic fashion enables you to picture clearly as to what the situation is.

*Interviewer:* Yep, and do you remember what the animation was actually of?

*Student 2:* Animation? Sodium chloride.

*Interviewer:* How would you describe your image now?

*Student 9:* Now I know that they are all touching different molecules and it's a regular pattern.

*Interviewer:* Yeah? A regular pattern of what?

*Student 9:* of the sodium and the chloride.

*Interviewer:* Ions, atoms?

*Student 9:* ions, ions….

*Interviewer:* What do you think helped you to develop that stronger image of sodium chloride at the particle level?

*Student 9:* Just seeing it all the time in the lectures just…

*Interviewer:* Seeing it, you mean?

*Student 9:* Pretty much by seeing it you know, it's easier to visualise.

*Interviewer:* Okay, but seeing it where?
Student 9: … On the computer animations.

Animation Interpretation

Student 5: Okay, it looks like there’s an ionic lattice. The molecules or the ions I should say, are vibrating very slowly. It’s a solid cause it’s in a solid formation.

Student 8: That’s the ionic lattice and they’re vibrating. Yep they’re in the lattice. They’re close together…

Student 10: I don't know what molecules they are but they're green and white and white's smaller and for every one green there's four whites around the molecules, so it's in a sort of lattice.

Student 14: How they’re sort of aligned and not all over the shop.

25. Closely packed

Animation Interpretation

Student 8: That’s the ionic lattice and they’re vibrating. Yep they’re in the lattice. They’re close together…

Student 13: Well, they're all packed in together at the moment.

26. Vibrations in fixed positions

Learnt

Interviewer: Can you describe the video?

Student 1: Well, like that picture of the ice cube, there was the cube and they had the molecules in it and they were just sitting there like that and then they started vibrating more and then they could just go like that.

Interviewer: Moving past one another? … The subtle difference between these two responses is that originally you wrote “the molecules begin to vibrate quickly” and here you’ve got “they start to vibrate more rapidly”… Do you think that there’s a change in idea there?

Student 1: Well that makes sense cause remember earlier on in this first one where I had to draw the representation of the solid…the second one I said they were vibrating in their fixed positions and in this one I didn’t and I don’t think I had a concept of that.
Interviewer: Okay so you’ve developed the image that solids vibrate at room temperature.

Student 1: Yep

Interviewer: And do you think that you transferred the idea from the ice to sodium chloride?

Student 1: Yep

Interviewer: Okay, well when you look at this answer you’ve got more vibrations as the bonds become weaker. What sort of a mental image do you get of that, if any?

Student 5: Well again, the computer animation things are very helpful. One of the ones, the one that I can remember which was the melting of some sort of ionic substance had more or less just increase in kinetic … they were just moving a lot faster and then they broke off and I guess that’s the sort of image I got in my head when I was answering that one. I don’t think we had those sort of things when we were at school so I don’t remember ever learning that.

Interviewer: When you say more vibrations… are there vibrations then, before you start heating?

Student 5: Yeah.

Interviewer: …Okay, if you bring up a mental image now of sodium chloride, does your image have ions vibrating?

Student 5: Yes.

Interviewer: And do you think that that is an additional feature of your image…

Student 5: Yeah, I think so, I think my understanding of a solid back in high school was more that it was just completely still so.

Interviewer: Do you think that your mental model or mental image of sodium chloride solid has changed at all since the beginning of the year?

Student 7: … even though if they're really solid they vibrate a bit as molecules

Interviewer: …How do you think you developed that image or that idea?

Student 7: Well, I’d say … from the head projector you know.

Interviewer: …So can you remember a particular video projection…

Student 7: Yeah it had green and silver little bits and you sort of zoomed across it and you saw it and

Interviewer: And the ions were vibrating?

Student 7: Yeah, just a little bit.
Interviewer: Computer animations again? Did you get anything else out of the computer animations. Like is there anything that that diagram doesn't show that you got from the computer animations?

Student 9: Yeah. They're constantly moving. They're vibrating.

Interviewer: Okay, so we take some of that sodium chloride now…and we heat it up. …What sort of changes do you imagine happening at the particle level, if any?

Student 13: Well they start to vibrate a bit more than usual.

Interviewer: …So now you're telling me that as you add more heat, the particles start to vibrate more?

Student 13: Yeah.

Interviewer: How do you think you developed that sort of an image?

Student 13: Well I think go back to computer animations again.

Interviewer: Mm hmm

Student 13: Cause that's one thing I tended to look at a lot and it got stuck in my head a fair bit as well.

Interviewer: …Can you identify a particular animation that helped you with this sort of an image?

Student 13: …I think there was one with sodium chloride getting heated up like the question said and they started vibrating a lot more...

Reinforced

Interviewer: Can you please identify the differences between this drawing here and the animation? You already mentioned it is three-dimensional, are there any other differences?

Student 2: The animation is more realistic because on account it’s three dimensional and…flat drawings don’t have that advantage.

Interviewer: Okay

Student 2: And also the animations can be made to vibrate which gives again the image, the idea of three-dimensionality.
**Animation Interpretation**

*Student 5:* Okay, it looks like there’s an ionic lattice, the molecules or the ions I should say, are vibrating very slowly.

*Interviewer:* Okay, anything else happening in there?

*Student 10:* They're vibrating.

*Student 11:* One of the things we learnt was that…atoms are never…still, they're always moving.

*Interviewer:* Anything else you wanted to point out?

*Student 14:* Just how they’re vibrating. They’re not totally stationary.

*Interviewer:* …Okay, earlier when you were telling me about that questionnaire there, you said that it only started vibrating as you heated it up.

*Student 14:* Well, it vibrates more.

*Interviewer:* Okay.

*Student 14:* Yeah.

*Interviewer:* Okay, so at room temperature would it be vibrating?

*Student 14:* Yeah

28. High water to salt ratio

**Learned**

*Student 2:* The only ones I would bring up in memory would be the animation images. They're the ones that you bring up mentally.

*Interviewer:* And do you think that you thought about those when you were answering this question?

*Student 2:* Mm yes.

*Interviewer:* …So what would be the differences between the animations or your mental picture and this drawing?
Student 2: The animation has the advantage of three dimension...However, bearing that in mind, that there has the details...that is namely there's a lot of water molecules...

Interviewer: So do you think that your mental image of sodium chloride in water has changed at all since the beginning of the year?

Student 11: This is like more of the animations that we got from [lecturer] that were fairly identical to these actually.

Interviewer: Okay.

Student 11: ...Judging by my what I’ve actually written, probably just the number and the fact that they're actually I think the term is hydrated, yeah water molecules actually stick to them...which obviously I didn't realise in the beginning and then the number of water molecules would be much greater.

Interviewer: And do you think you got those images from the animations?

Student 11: Mm [in agreement]

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**Animation Interpretation**

Interviewer: ...Solution of sugar question...how is that one relevant?

Student 3: Because it basically shows you that there’s lots of water.

Interviewer: Okay, so it’s like a ratio of water to solute thing?

Student 10: There's heaps of water molecules and they're everywhere

Student 12: ...The ratio of ions to water molecules is very low.

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29. Closely crowded

**Animation Interpretation**

Student 5: It’s fairly obvious that it’s liquid water cause it’s moving around...molecules sliding all over the place fairly close.

Student 7: Yeah, you can sort of see like the water molecules that are sticking to it...And they’re like crowding around each other.
30. Hydration of ions

**Learnt**

*Interviewer:* Can you describe to me the animation that may have helped you with this one?

*Student 7:* You know with the water molecules stuck to the ions and they were like spinning it around…and they didn't show the other water molecules.

*Interviewer:* Can you bring up a picture of what’s going on in the video you remember?

*Student 8:* They had sodium chloride in a big lattice and the water molecules moving in and as like the water molecules move in the sodium chloride they just start separating and then the chloride’s surrounded by water and the sodium’s surrounded by water so there’s no connection. Like they’re not together. So that’s how I pictured it.

*Student 10:* …like on the video like, he'd show the polarity and how … water molecules, would stick to the chloride, and like the picture would rotate cause like it's a 3D video.

*Interviewer:* So do you think that your mental image of sodium chloride in water has changed at all since the beginning of the year?

*Student 11:* This is like more of the animations that we got from [the lecturer] that were fairly identical to these actually.

*Interviewer:* Okay

*Student 11:* Judging by my what I’ve actually written, probably just the number and the fact that they're actually I think the term is hydrated. Yeah, water molecules actually stick to them.

*Student 13:* Sodium chloride in water…chloride is a negative ion but then it's surrounded by water molecules with the positive end of the water molecules.

*Interviewer:* Mm hmm. How do you know that?

*Student 13:* Well, I learnt that during the year, first semester.

*Interviewer:* How did you learn it?

*Student 13:* Going to lectures and the animations again.

**Reinforced**

*Student 2:* The only ones I would bring up in memory would be the animation images. They're the ones that you bring up mentally
Interviewer: And do you think that you thought about those when you were answering this question?

Student 2: Mm yes.

Interviewer: Yeah, okay and so what would be the differences between the animations or your mental picture and this drawing?

Student 2: The animation has the advantage of three dimension…However, bearing that in mind, that there has … the important details. That is namely, there’s a lot of water molecules and each ion is buffered, surrounded by water molecules, according to polarity…

Animation Interpretation

Student 1: Whatever that green ion is, it's surrounded by the water molecules…and there’s the other half of whatever the ion solution is and that's surrounded by six water molecules as well.

Student 3: That’s hydrated. I know that, surrounded by six water molecules.

Student 5: Okay, you’ve got an ion there which is being surrounded by the water molecules in solution. There’s another ion, moving round. Like I said before, there’s a few interactions between ions and water molecules.

Student 7: Yeah, you can sort of see like the water molecules that are sticking to it.

Interviewer: … I’ll just play it again. Is there anything else you want to point out?

Student 7: Yeah, the way they’re sticking to each other. There’s about six. You can see that better on a 3D animation …

Student 8: It becomes [an] aqueous solution and the…sodium chloride, they separate and are surrounded by water molecules, six water molecules.

Student 10: There's heaps of water molecules and they're everywhere…there's six of them, six water molecules surrounding them…

Student 11: Hydrated ions dodging round.

Student 12: There’s two ions, and one’ll come up later… That’s obviously a negative ion, the green one because … the hydrogens of the water molecules are facing towards it… That must make the other one positive.
Interviewer: Okay

Student 12: But yeah, some waters are attaching and other ones are attracting to it but generally it always has six around it.

Interviewer: Okay, so the ones that are around it are changing?

Student 12: Yeah, yep, some come off and others reattach to it.

Student 13: It's sodium ions and chloride ions, surrounded by water.

Interviewer: Yep. Which ones are the sodium and which are the chloride?

Student 13: …The sodium's the white one… The green's the chloride…

Interviewer: …How do you know that that's the chloride?

Student 13: The chlorine? Because it's surrounded by the hydrogen part of the water, which is the positive ion.

Interviewer: Okay and what about the other one? What charge does that one have?

Student 13: That’s got a positive charge.

Interviewer: And how do we know that?

Student 13: It’s surrounded by the negative… side of the water, oxygen.

31. There is an electrostatic attraction between water molecules and ions

Learnt

Interviewer: Do you want to give me an idea of what you were thinking when you answered this and whether or not any particular learning strategies or teaching strategies helped you to answer this particular question?

Student 4: …I’d have to say the animations again

Interviewer: Okay, do you think when you answered this question that you actually … pictured… an animation in your head?

Student 4: Yeah.

Interviewer: …Can you describe to me if there are any other differences between this picture here and the mental image that you are bringing up of there of sodium chloride and water?

Student 4: Yeah, this one looks a bit crowded now but um…it also looks to be the best one out of the lot of them still.

Interviewer: Okay, and what makes it better?


Student 4: The dipoles… It’s showing the reaction and what they do.

Interviewer: Do you think that your model of water in the different states has changed at all since the beginning of the year?

Student 7: Yeah, a bit.

Interviewer: What do you think might have influenced that change?

Student 7: …Just looking at water states on the projector

Interviewer: Yeah.

Student 7: …I couldn’t really remember being taught that you know, ions attracted to water, water attracted ions.

Interviewer: What particular features of the lectures do you think helped you to develop that sort of an image of sodium chloride in water?

Student 9: Computer animations again.

Interviewer: Yeah, do you reckon you could describe to me what goes on in the computer animation?

Student 9: Yeah well the water molecules are at the positive poles are attracted to the chlorine ions and the negative poles are attracted to the sodium ions.

Student 10: On the video like, he'd show the polarity and how … water molecules, would stick to the chloride, and like the picture would rotate cause like it's a 3D video.

Student 13: Sodium chloride in water…chloride is a negative ion but then it's surrounded by water molecules with the positive end of the water molecules.

Interviewer: How do you know that?

Student 13: Well, I learnt that during the year, first semester

Interviewer: How did you learn it?

Student 13: Going to lectures and the animations again.

Reinforced

Student 2: The animation has the advantage of three dimension… However, bearing that in mind, that there has … the important details, that is namely … each ion is buffered, surrounded by water molecules according to
polarity…

**Animation Interpretation**

*Student 3:* Na’s positive so then it’s got to have the O next to it. The water molecules, how they attach to the ion itself… Chloride is a Cl minus therefore the positive H ions are attached to it.

*Student 4:* Okay, this one shows water being poured onto a sodium chloride crystals and any second now you’ll see how the dipole forces on the water molecules pull apart the crystal…

*Student 5:* Okay, you’ve got an ion there, which is being surrounded by the water molecules in solution. There’s another ion. Moving round. Like I said before, there’s a few interactions between ions and water molecules. Looks like one of them was a positive ion and another one was a negative.

*Interviewer:* Which one’s which?

*Student 5:* Okay, the green one there is a positive, no it’s negative, negative ion yep.

*Interviewer:* Why is it negative?

*Student 5:* Because of the polarised water molecules. The hydrogen end is the positive end and they’re all pointing towards the molecule so…this grey one that comes up must be a positive, yep it’s a positive, cause all the negative ends, the oxygen are pointing towards it.

*Interviewer:* Okay. I’ll just play it again. Is there anything else you want to point out?

*Student 7:* Yeah, the way they’re sticking to each other. There’s about six, you can see that better on a 3D animation and the, the red side’s connected, that’s the oxygen side, is connected to the sodium while the other sides connected to the chlorine because of the negativity.

*Student 10:* …for the grey one, it’s like the red part of the molecule hydrating…the oxygen surrounding it.

*Interviewer:* And why does it do that?

*Student 10:* …the oxygen’s attracted to the positive polarity …

*Student 12:* There’s two ions, and one’ll come up later… That’s obviously a negative ion, the green one because the … hydrogens of the water molecules are facing towards it…That must make the other one positive.

*Interviewer:* Which ones are the sodium and which are the chloride?

*Student 13:* …The sodium’s the white one…the green’s the chloride…
Interviewer: Yep, how do you know that? How do you know that that's the chloride?

Student 13: The chlorine? Because it's surrounded by the hydrogen part of the water, which is the positive ion.

Interviewer: Okay and what about the other one? What charge does that one have?

Student 13: That's got a positive charge…It's surrounded by the negative … side of the water, oxygen.

Interviewer: Do you notice anything, anything else?

Student 14: Yeah, how the hydrogens are going, like pulling towards the green one, so that means the green one’s a negative one, so that’d be the chloride ion.

32. The solution is electrically neutral

Learnt

Interviewer: What particular features of the lectures do you think helped you to develop that sort of an image of sodium chloride in water?

Student 9: Computer animations again.

Interviewer: Yeah, do you reckon you could describe to me what goes on in the computer animation?

Student 9: Yeah well the water molecules are at the positive poles are attracted to the chlorine ions and the negative poles are attracted to the sodium ions…and there’s an even number of each.
Animation Interpretation

Student 12: There’s two ions, and one’ll come up later… That’s obviously a negative ion, the green one because … the hydrogens of the water molecules are facing towards it… That must make the other one positive.

33. Ions not molecules

Learnt

Interviewer: Can you bring up a picture of what’s going on in the video you remember?

Student 8: They had sodium chloride in a big lattice and the water molecules moving in and as like the water molecules move in the sodium chloride they just start like separating and then like the chloride’s surrounded by water and the sodium’s surrounded by water so there’s no connection like they’re not together so that’s how I pictured it.

Interviewer: Do you think that your mental image of sodium chloride dissolved in water has changed at all?

Student 14: Yeah

Interviewer: What aspects?

Student 14: …They break up. The water separates the chloride and the sodium ions apart…

Interviewer: …Okay, and how did you develop that sort of an image?

Student 14: From the lectures. From the animations.

Reinforced

Student 2: The animation has the advantage of three dimension…However, bearing that in mind, that there has the details…that is …the fact that individual ions are borne off…

Animation Interpretation

Student 1: They come together because they do have an attractive force…like a positive and a negative charge but the forces of the water molecules pulling them away is greater than the force keeping them together.

Student 3: Okay, they were passing by each other and their attraction to connect sort of happened but it wasn’t strong enough so then they stayed ions.
Students:

Student 4: Okay, this one shows water being poured onto a sodium chloride crystals and any second now you'll see how the dipole forces on the water molecules pull apart the crystal... one ion at a time and potentially there's enough water there... the whole crystal will be broken up.

Student 4: ... That's sodium chloride solution and you'll see for a moment there a sodium and a chloride ion come into contact and there's still some attraction between them but the water again pulls them apart and they go their separate ways.

Student 7: ... The water's pulling it all apart... so it turns into a solution.

Student 8: It becomes an aqueous solution and the sodium chloride they separate and are surrounded by water molecules, six water molecules.

Student 10: ... You sort of remember these things because [the lecturer] would talk you through them but then you think yeah, why don't they stay together? ... Why don't they form a solid? But like he'd say there's heaps of water molecules around them.

Student 12: There's two ions, and one'll come up later. That's obviously a negative ion, the green one because... the hydrogens of the water molecules are facing towards it... That must make the other one positive.

Interviewer: Okay, so what's this one trying to show?

Student 13: It's sodium ions and chloride ions, surrounded by water.

Student 14: The green one's the sodium, small one's the chloride or...

Interviewer: And how do you know that?

Student 14: Hopefully I just remembered it.

Interviewer: Okay, can you tell from the animation?

Student 14: Maybe because they're separated... I'm not really sure.

Student 13: Sodium chloride in water, well you see chloride is a negative ion but then it's surrounded by water molecules with the positive end of the water molecules.
Interviewer: How do you know that?

Student 13: Well, I learnt that during the year, first semester…going to lectures and the animations again.

Animation Interpretation

Student 1: They come together because they do have an attractive force…like a positive and a negative charge but the forces of the water molecules pulling them away is greater than the force keeping them together.

Student 3: Na’s positive so then it’s got to have the O next to it. The water molecules, how they attach to the ion itself… Chloride is a Cl minus therefore the positive H ions are attached to it.

Student 5: Looks like one of them was a positive ion and another one was a negative.

Interviewer: Which one’s which?

Student 5: Okay, the green one there is a positive, no it’s negative, negative ion yep.

Interviewer: Why is it negative?

Student 5: Because of the polarised water molecules, the hydrogen end is the positive end and they’re all pointing towards the molecule so…this grey one that comes up must be a positive, yep it’s a positive, cause all the negative ends, the oxygen are pointing towards it.

Student 12: …That’s obviously a negative ion, the green one because … the hydrogens of the water molecules are facing towards it… That must make the other one positive.

Interviewer: Which ones are the sodium and which are the chloride?

Student 13: …The sodium's the white one…the green's the chloride…

Interviewer: Yep, how do you know that? How do you know that that's the chloride?

Student 13: The chlorine? Because it's surrounded by the hydrogen part of the water, which is the positive ion.

Interviewer: Okay and what about the other one? What charge does that one have?

Student 13: That's got a positive charge…It's surrounded by the negative … side of the water, oxygen.

Interviewer: Do you notice anything else?
Appendix D

Student 14: Yeah, how the hydrogens are … pulling towards the green one, so that means the green one’s a negative one, so that’d be the chloride ion.

35. Dynamic (movement, collisions, water exchange etc)

Learnt

Interviewer: What particular features of the lectures do you think helped you to develop that sort of an image of sodium chloride in water?

Student 9: Computer animations again.

Interviewer: Yeah? Do you reckon you could describe to me what goes on in the computer animation?

Student 9: …they're all moving everywhere.

Interviewer: Okay, now if you can you bring up a mental image of the animation in your head? …Are there any differences between what you're picturing in your head and what's illustrated here?

Student 13: Only that they're moving around a little bit...

Animation Interpretation

Student 1: …The water molecules just cruise around.

Interviewer: Okay, so tell me what’s going on…What’s it a representation of?

Student 3: Water molecules floating around and they are hydrating the ions.

Student 5: Okay, you’ve got an ion there, which is being surrounded by the water molecules in solution. There’s another ion. Moving round…It’s fairly obvious that it’s liquid water cause it’s moving around … molecules sliding all over the place...

Student 7: They’re like in a liquid state and they want to bounce around.

Student 10: There's heaps of water molecules and they're everywhere, no specific pattern and they're rotating and they're moving
Student 11: It's all moving and everything, then sometimes they're going to sort of bounce into each other…

Student 12: Some waters are attaching and other ones are attracting to it but generally it always has six around it.

Interviewer: Okay, so the ones that are around it are changing?

Student 12: Yeah…Some come off and others reattach to it.

Direct transfer

MOLECULAR SUBSTANCE: IODINE

Application of Water Animations

Student 5: Yeah, I’d say this probably was helped by the animations. I’m not sure if I’m correct or anything. I don’t really know how iodine acts. The first thing I got in my head was that iodine…sublimes so I was going hang on liquid, I didn’t know how to draw that but I think probably got helped straight away from the... animations, I’d say. The fact that it sublimes, I knew that from high school. I just, that was one of the ones that we just learnt in class…I did know vanderwaals forces as well, I knew that from high school so.

Interviewer: Okay, so what features did you get from the animations, do you think?

Student 5: I guess, I don’t know, maybe the orientation, I don’t know. I just think again it just gives you a clearer image. I mean, maybe it’s something you understand, that it just, it becomes a solid, but maybe you don’t understand…how it interacts... I suppose a lot of it probably came from knowledge that I had already but …maybe some of it was knowledge and some of it came from the actual the animation that I’d used to get an image.

Interviewer: These were the states of iodine… Any particular animations help you to answer these?

Student 7: Yeah, like the ice one, the picture of the water molecules as ice…the one with liquid water would help you with that one I suppose

Interviewer: Iodine in the three states, any animations influence that question…?

Student 9: The water ones. The water ones influenced it.

Interviewer: This is iodine in the solid, liquid and gaseous states. Any particular animations spring to mind when you were answering these questions…?
Student 11: Probably the same animations from before… The ones about the solid, liquid gas, yeah… the same animations again, it was just because this was a slightly different, I mean we hadn’t actually learnt about something like this specifically which was probably why again I wasn’t terribly confident about my answer.

Interviewer: Okay, so you were applying your ideas from the water molecules videos…?

Student 11: Mm hmm

Interviewer: So do you think that the water animations influenced these ideas?

Student 13: Yeah, they did again.

Interviewer: And so, would you say that when you answering this you’d actually bring up, try and bring up some sort of a mental image of those animations in your head?

Student 13: Yep.

Interviewer: And perhaps apply those ideas to something else? Can you explain why you feel that the animations were relevant to this question?

Student 13: Well, as I say they helped with that mental picture…that helps me work out the answer. Before I saw those, I couldn’t really get a picture in my head.

Interviewer: So you’ve got a tightly packed organised structure there with very slight movement. What do you think influenced…that representation of the solid there?

Student 14: How he explained how solids are; that they’re all aligned and still vibrating a tiny bit but they’re not moving anywhere.

Interviewer: So it was just things that he verbally said in the lectures?

Student 14: And the diagrams, the water so I sort of related it back to that.

Interviewer: The water?

Student 14: The animation one

Interviewer: Okay, so you think that the structure is probably similar to that of ice? Structure and vibrating?

Student 14: Yeah, that’s what I thought at the time, yeah.

Interviewer: Okay. Now describe what happens as you melt the iodine to form liquid iodine.

Student 14: How the thingys break up and form separate ones and they start moving around more and it’s getting all liquidish.

Interviewer: Okay, and where did you get, how did you form that sort of an idea?

Student 14: From the animations
Appendix D

IONIC SOLID: POTASSIUM BROMIDE

**Application of Solid Sodium Chloride Animation**

*Interviewer:* Do you think any particular learning strategies helped you to develop that image of...this type of a solid?

*Student 1:* ...The videos got the idea across of like the alternating, actually not so much the alternating that way but

*Interviewer:* Three dimension

*Student 1:* Yeah, that it went back that way as well...and if you took one, no matter where you looked around it, that the surrounding one would be the opposite charge.

*Interviewer:* You've mentioned that a lot of your images have been influenced by these overhead projections, these animations, I was just wondering if for any of the questions in this questionnaire whether you brought up any images of the animations and which animations?

*Student 2:* The lattice-work animation...

*Interviewer:* Okay, so that's what you imagined for this one...the sodium chloride lattice I assume?

*Student 2:* Yes.

*Interviewer:* So potassium bromide, do you think that any of the animations helped you to answer that question?

*Student 7:* ...I already knew basically what it looked like but if any projection helped it would have been the zoom in of the ionic solid; sodium chloride.

*Interviewer:* Okay, so you feel that the animation of sodium chloride was at least relevant to this question?

*Student 7:* Yeah

*Interviewer:* Do you think that you might have actually brought that image up into your head when you were answering it?

*Student 7:* Oh yeah.

*Interviewer:* You don't have to say yes, I mean...

*Student 7:* Well yeah, [when I] think about what the ionic solid would look like...it just pops up in my head.

*Interviewer:* Did any of the animations come to mind when you were looking at solid potassium bromide?

*Student 9:* Yeah, just that it needs to be in a regular pattern.

*Interviewer:* Okay, which animation?
Student 9: The sodium chloride.

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IONIC SOLUTION: AQUEOUS SOLUTION OF BARIUM CHLORIDE

Application of Animations Related to Aqueous Sodium Chloride

Interviewer: I was just wondering if for any of the questions in this questionnaire whether you brought up any images of the animations and which animations?

Student 2: The lattice-work animation, brought up the dissolving animations there.

Interviewer: Do you want to describe to me the dissolving animation?

Student 2: There you'd have the solid lattice of barium chloride, water molecules pouring down, water molecules working their way around ions, the barium or chlorine ions, they're wobbling around and they kind of randomly float off…one by one.

Student 5: ...I probably think the animations might have helped in the sense that I did know there was ions in water but perhaps the water molecules themselves, I didn’t have a complete understanding of how they, in water acted. I knew about the polar bonds, how they joined to the ions but maybe the rest of them how they … almost exchange as they move through the water… one of these might sort of float away, another one’ll join and things like that so I guess it was clear understanding of the mechanics of it I suppose as it moves through.

Interviewer: Any particular animation help you with this?

Student 7: …The one with the little water molecules attracted to the ions.

Student 11: The second one was definitely an animation. We saw a lot of those animations actually…

Interviewer: Okay, so which particular animation do you think is relevant to this question?

Student 11: Oh, the same animation... It actually showed virtually the same thing only it would have been sodium chloride maybe… as well as the animations, [the lecturer] drew that about 50 times, that exact same thing, this is going to be in your test.

Interviewer: Do you think his drawings of it influenced your image more than the animations?

Student 11: No, I don't think so. The animations because they were animated they made me sort of pay more attention because it was sort of moving and gives you a better image whereas when he drew it on the board it sort of gave us an idea of what we had to draw in the exam.

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Applied transfer
Appendix D

PRECIPITATION OF COPPER HYDROXIDE

Application of Aqueous Sodium Chloride Animations

Interviewer: Do you think that when you were answering that question you thought about animations?

Student 9: …Yeah, well just all the ions floating around in the water and the water being attracted to them.

Student 10: …The polarities are just from the books and the lecture notes and stuff, the water polarity and how it sort of is attracted to ions…that came from the video too, how like there's heaps of water molecules around ions.

Interviewer: Do you think for the image…that the sodium chloride in water animation is relevant?

Student 11: Yeah, I do actually because I mean, from what I’ve said is wrong with it, to my way of thinking there's not enough water molecules because if you think about how much water you'll need there should be a lot more water molecules and they should actually be hydrating ions rather than just be free and that's the same principle that I got from the animations.

Application of Precipitation of Silver Chloride Animation

Student 5: I’d say, yes, the animations do help … I think this second one would have been probably helped be the animations and also from school. Like I said we did know that but they aren’t surrounded, those potassium and nitrate aren’t surrounded by water and they should be… they should be forming a lattice rather than just free floating molecules … I’d say that was definitely helped by the animations.

Interviewer: Okay, which particular animation?

Student 5: The one that I mentioned before where you saw them joining two and then four

Interviewer: Precipitation

Student 5: Yep. I think that was probably was really helpful because I wouldn’t have understand the interactions, like you said before. From school I wouldn’t have understood that because … I just knew that suddenly it became a solid. I didn’t know how. So I think that probably helped a lot.

AQUEOUS SOLUTION OF HYDROCHLORIC ACID

Application of Aqueous Sodium Chloride Animations

Interviewer: This is your depiction of hydrochloric acid solution … Any particular animations that you thought of when you were drawing this?

Student 4: …They're all pretty much the same after a while aren't they? They're all sort of waters bouncing around and everything’s dissociated…

Interviewer: So you were applying the same ideas...
Student 4: Yeah, I think so yeah

Interviewer: This is your representation now of hydrochloric acid solution. Anything in particular help you form that sort of an image?

Student 5: … maybe ions… in solution which I saw in one of the animations...

Interviewer: Okay, so this is your representation of a solution of hydrochloric acid? … Do you think that any of the animations helped you with that question?

Student 7: Sodium chloride one with the water molecules stuck to it.

Interviewer: Any animations spring to mind when you were doing that…?

Student 9: The salt one again.

Interviewer: Okay, once again I’m interested in whether or not you brought up any particular animations into your head when you were thinking about this and if not what were you thinking?

Student 11: That probably would have been once again the same one. The same animation.
PRODUCTS OF REACTION BETWEEN AQUEOUS SOLUTIONS OF HYDROCHLORIC ACID AND SODIUM HYDROXIDE

Application of Aqueous Sodium Chloride Animations

Interviewer: An aqueous solution of sodium chloride? … When you were drawing that do you think any mental images came into your head?

Student 4: The one I've drawn, pretty much.

Interviewer: Okay, what do you think influenced that image…? …

Student 4: Yeah, I don't know...yeah those fantastic animations.

Interviewer: Do you think that any of the animations helped you with that question?

Student 7: Sodium chloride one with the water molecules stuck to it

Interviewer: …and the products of that reaction after we accidentally put some sodium hydroxide in there?

Student 7: Yeah, probably about the same thing.

The following is the complete list of responses given by third year students in the Attitudes Survey, relating to the benefits of VisChem animations.

**Improved Visualisation**

“helped to imagine molecules (basic), see more clearly”

“imagining how reactions take place/understanding why”

“helped in imagining what the concepts in chemistry were about”

“understand and image reaction in everyday life”

“Helped to visualise in the exam.”

"the animations give a guide that can be applied in other situations, it's the visualising and thinking about them which made them most useful”

“…did enable broader thought as I had the actual images in my mind I could substitute other molecules for and play in my mind.”

“created a visual image in mind”

“Helps visualise a certain element or molecules behaviour in various conditions.”

“helped in developing visual images”

“got a better idea of how molecules look and interact with each other”

“helps me visualise interactions between molecules”

“Observation via visual aids made it easier to picture out the events during chemical reaction”

“it added colour to my images and more clarity”

“I could visualise what lectures were trying to communicate”

**Assisted with Idea of Movement and Interactions**

"helps me visualise interactions between molecules”

"They helped me visualise interactions of different molecules”

“the interactions around in air and water or the surrounding are explained in a visual manner”

"everything is moving”

“science of positive and negative”
“chemistry is the interaction of molecules and transfer of electrons”

“the world seems static at times, but now I understand reactions and molecules are always on the move ie. equilibrium”

“everything is a result on transfer of energy”

“to know a solid material, in essence, from a molecular point of view, is constantly vibrating”

“it is a constantly moving environment”

“how things react and bond together.”

“the way molecules react in their different states”

“Better able to think of eg a glass of water as a mobile mass of constant motion rather than a glass of water on a cupboard, still.”

“the way they attached to other molecules to form compounds”

“I was able to understand how the atoms interacted at the levels that one could never see in the naked eye or microscope”

“got a better idea of how molecules look and interact with each other”

“helps me visualise interactions between molecules”

**Improved Understanding**

“things started to make sense, and we can give a clear explanation”

"made a better visual understanding of the structures (as if they are tangible)”

“not only made lectures interesting but a better visual understanding of chem”

“animations gave better understanding”

“the way the molecules are not ball and stick molecule and electron cloud theory”

“gave an understanding of molecules better than just ball and stick model”

“increased my ability to understand concepts – linking pictures/diagrams to information presented.”

“understanding reactions on a micro scale at the molecular level”

“imagining how reactions take place/understanding why”

“views of atoms were better understood”

“understand and image reaction in everyday life”

“Strengthened my basic understanding which is what I had to build on”
“I was able to understand how the atoms interacted at the levels that one could never see in the naked eye or microscope”

“to understand and able to interpret some aspects at the molecular level”

Made Learning Easier

“made work easier to understand, than just with text-books or overheads”

“made it easier to perceive a molecule at an atomic level”

“easier and better way of presenting ideas”

“They made things a lot easier in the sense, you could see exactly what happened.”

“made it easier to learn 1st year”

“grasping of concepts visually as I learn quicker visually”

“gave a better conceptual image of different molecular species and enable easy understanding”

“visualising made chemistry easier”

Interpretation of Macroscopic Phenomena

“you can imagine the molecules, atoms, structures, on a molecular level instead of just a macro level”

“things aren’t always as you see them”

“when I see ice, I picture static water molecule not being allowed much movement”

“see thing in 2 ways normal and molecular”

“it allowed me to picture processes”

“make you visualise something which you cannot always see”

“It makes you think what is happening in that test-tube, beaker etc. Not just what you see.”

“nothing looks the same anymore”

“Gives you an idea of what to expect, how it works, during experiments”

“Better able to think of eg a glass of water as a mobile mass of constant motion rather than a glass of water on a cupboard, still.”

Aroused Interest/Curiosity

“increased interest in chemistry”

“I wonder was is actually going on”
"made it [chemistry] more interesting, meaningful"

"they helped inspire my imagination of what is happening at the scale of atoms and molecules."

“not only made lectures interesting but a better visual understanding of chem’”

“helped shake those daunting boring images of chemistry texts of the 70s”

**Improved 3D Thinking**

"helped to visualise at the molecular/atomic level, in 3D"

“helped in developing visual images…especially 3d models ie lattices”

“animations helped me think in a 3-dimensional way with all molecules”

“it was the 1st time I started seeing molecules as 3-d structures”

**Good Foundation for Further Study**

“Understanding of 1st yr Chem ideas and concepts made a good foundation for years that followed.”

“helped to have a vivid basis to build further ideas on”

“Strengthened my basic understanding which is what I had to build on”

“any new ideas that were taught to me, I’d have a better understanding on why it was happening”

**Application**

"the animations give a guide that can be applied in other situations, it’s the visualising and thinking about them which made them most useful”

“…did enable broader thought as I had the actual images in my mind I could substitute other molecules for and play in my mind.”

**Improved Ability to Draw Molecules**

“They helped me to draw molecules”
Appendix D: Animation Quotes

D.0.  FIRST YEAR INTERVIEWS (2000)

D.1.  THIRD YEAR ATTITUDE SURVEY (1999, 2000)
Appendix D: Animation Quotes

D.0. First Year Interviews (2000)

The following is a complete list of edited supporting quotes for the influence of VisChem animations on key features from the post-test and questions on the transfer test. Absence of certain key features indicates a lack of interview evidence. Key features 18 – 20 (features of a water molecule) have been excluded due to the fact that they were discussed in relation to modelling and not VisChem animations.

1. Molecules in a liquid are closely crowded

Reinforced

Interviewer: With those projector images, can you actually picture those in your head?

Student 7: Yeah

Interviewer: You can picture liquid water in your head?

Student 7: Yeah

Interviewer: …Do you think you would have pictured those in your head when you were answering these questions?

Student 7: Yeah

Interviewer: Can you describe to me sort of what you can see?

Student 7: Well, I don't know like great big spheres with little tiny spheres with the mickey mouse shape and its bent and it's bouncing around.... Say liquid water, say and it's bouncing around and some are connected or some have more hydrogens or less hydrogens than the others… they're crowded but some are connected and some aren't, they don't have that much energy but they have some energy.

Interviewer: I think with your water ones, I think your representations are probably fairly similar. Okay, you've probably included more detail in this one, you've got here that the molecules are close together. Here you've said that the molecules are close together and free to move, and you've also got improved confidence and improved vividness. What do you think may have caused that improvement?

Student 10: Well that was definitely the video cause in the video it shows the molecules are moving but they're still close together.
2. Molecules in a gas are widely spaced

*Learnt*

Student 11: …He had a lot of computer animations, which actually helped a lot. I think the example he used was water …and so he showed the little beaker…I don't know. It helped a lot, him showing the actual physical pictures and everything.

Interviewer: Okay so that gave you move of an idea about how far apart the molecules were

Student 11: Mm

Interviewer: Alright, similar sort of situation here…

Student 11: And I did exactly the same thing again [mumbles]

Interviewer: So once again you've got a change in your response. What do you think might have influenced that change?

Student 11: Probably the same thing; the pictures that he showed us. He actually went over it quite a lot.

Interviewer: Pictures?

Student 11: The little diagrams on the computer… We did a lot of them.

*Reinforced*

Interviewer: Your description has got a little more detailed…and your confidence in your explanation has gone right up too. Do you remember how that might have come about?

Student 10: It was basically revising over the work, those videos again, they showed like, H₂O particles and the video showed it moving around, rotating, vibrating.

3. Molecules do not change size from solid to liquid to gas

*Learnt*

Student 3: [The lecturer] sort of demonstrated through the videos and all that it maybe isn’t different.

Interviewer: Okay, the videos, can you talk a little more about that?

Student 3: Visual images.

Interviewer: Okay, what sort of visual images.

Student 3: Oh gosh, the particles, the atoms, what they do in different states…so like we get to see what actually happens at every state.

Interviewer: and what does happen?
**Student 3:** Solid they’re all packed together, sort of rigidly, I think that’s the word, and then liquid they vibrate and they sort of they move but like not as much as gases. Gases then they start floating up.

**Interviewer:** So how does that help you to understand that the size of the molecules doesn’t change within each state?

**Student 3:** Cause nothing happens to the actual molecule apart from movement.

**Interviewer:** Okay, at the beginning of the year you were unsure … as to the size of the different molecules in each state and your confidence has improved dramatically and your answer has changed…okay any idea what influenced this change?

**Student 9:** Just the same. Lectures.

**Interviewer:** Can you think of any examples where you were shown something similar that … changed your idea about it?

**Student 9:** Well, the water, the water on the computer screen.

**Interviewer:** Yeah?

**Student 9:** Yeah, how it was solid then liquid then gas and the molecules stay the same.

**Interviewer:** Okay … so the molecules stay the same. What actually changes in each when we change states then?

**Student 9:** Just the distance, the distance between the molecules.

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**Reinforced**

**Interviewer:** This is the size of the molecules in the different states and your confidence has gone up slightly. Maybe one notch. Do you feel as if your confidence … in that idea had improved?

**Student 1:** Yeah

**Interviewer:** Yeah? What do you think has helped with that?

**Student 1:** What was the question? …Well that one it was more sort of a logical guess … but that one I actually knew. Like we’d done it, we’d covered it in lectures.

**Interviewer:** Okay when you say you’d covered it in lectures, how was that approached in lectures?

**Student 1:** …Just that the difference between the states of matter, like solid, liquid and gas it didn’t affect the size of the molecule, only how they were bonded together.

**Interviewer:** Okay, and was that just told to you?

**Student 1:** There were the videos, they were good where it went from like solid just vibrating and then they started rolling around and then they broke off. That was really good actually, that video.
Interviewer: Okay, what was that video portraying?

Student 1: The changes of state.

Interviewer: Of anything in particular?

Student 1: I think it was water.

Interviewer: Okay, and how did that video help you with the idea that the molecules didn’t change size?

Student 1: Well they were still the same molecule.

4. The molecular level is multi-particulate

Reinforced

Interviewer: So if you brought up the animation of liquid water in your head describe to me what you actually see.

Student 13: Well I just see … lots of water molecules.

5. Molecular substances contain discrete particles in the solid, liquid and gas states

Learnt

Interviewer: Do you think that your mental images of liquids or liquid water specifically has changed at all since the beginning of the year?

Student 12: Yeah, I would’ve always done it like that before, now I always do it like that. That’s mainly because of the videos that [the lecturer] showed us of the water going round. I always put the hydrogens on now cause just, I don’t know.

Interviewer: Okay, so you’re mental image before contained maybe just balls or circles.

Student 12: Yeah, very shallow yeah. This one actually contains the molecule.

Interviewer: Okay, do you picture those, [the lecturer’s] videos in your head when you answer this now?

Student 12: Yeah, there’s a lot of stuff now, yeah.

Interviewer: Do you think that’s actually improved the vividness of your mental image?

Student 12: Yes, I would say it has, yes.

Interviewer: Okay, do you remember particular things that were done in lectures or shown to you or whatever that made you realise that water doesn't consist of these two separate particles?
Student 13: The animations… The computer animations and well not just with the water molecules but when they're going from solid to liquid or whatever or vice-versa

6. There is empty space between the molecules

Learnt

Interviewer: Your idea is obviously different now…. You said no there’s nothing, everything remains the same except the ability to move around. How do you think you developed that sort of an idea?

Student 14: Obviously from the animations, how obviously they show that that was frozen and as the temperature rises they become more mobile and when it gets to the gaseous stage it’s just wooshka everywhere.

Interviewer: In those animations, is there anything between the molecules?

Student 14: No

Interviewer: What do you see?

Student 14: Just nothing. It just showed them and that was it.

Reinforced

Interviewer: slight improved confidence. You obviously had very high confidence before in what was between the particles… Do you think anything helped you consolidate that idea that there is only empty space between the particles?

Student 2: The images, these visual images that are used, they describe not only the particles but because they can be seen vibrating they describe also the small amount of space which is between the particles.

7. Structured lattice

Learnt

Interviewer: Okay, you've mentioned vibrating here but you haven't mentioned any movement in the solid here and I would also suggest that maybe your representations here for solid, for the ice were slightly different… Do you think that that image has changed at all…?

Student 4: Yeah, that again would have come from those animations.

Interviewer: Okay, so if you had to picture maybe the animation of ice in your head…could you describe that to me?

Student 4: Yeah, I can see it, there are molecules stacked up in rows and all tight together and vibrate....

Interviewer: Okay, just like it says there. Okay, when you were answering this…post questionnaire, with these water questions, do you think at any stage you imagined those animations in your head to answer this question?
**Student 4:** Definitely.

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**Interviewer:** You can’t remember any particular things in lectures that showed you that idea?

**Student 14:** Only those little animation things that he had going but that’s all I remember of it.

**Interviewer:** Okay, well, do you think they gave you that sort of an image or do you think it was probably more just something [the lecturer] said?

**Student 14:** Just more how he explained it then he showed an image of it…sort of backing himself up a bit.

**Interviewer:** Yeah, okay… Can you think of that image that he backed himself up with?

**Student 14:** Yeah.

**Interviewer:** Can you picture that in your head?

**Student 14:** Yeah, all the molecules in a line, they’re all aligned and sort of vibrating a tiny bit…

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8. Vibrate in fixed positions

**Learnt**

**Interviewer:** What about this “free to vibrate within their fixed positions”? Is that an image that you had originally?

**Student 1:** I don’t think so…

**Interviewer:** You’re not sure?

**Student 1:** No, I’m not sure but I think I would have mentioned it if I’d been confident of it. I might have maybe thought it but not…

**Interviewer:** So you don’t remember anything in particular…?

**Student 1:** Nup.

**Interviewer:** …Do you think that anything in particular helped you to improve the vividness of this image?

**Student 1:** Again that was directly from, that is my recall of that video.

**Interviewer:** Okay the video animation?

**Student 1:** Yep, from solid to liquid to gas.
**Interviewer:** Okay, you've mentioned vibrating here but you haven't mentioned any movement in the solid here and I would also suggest that maybe your representations here for solid, for the ice were slightly different. Do you think that that image has changed at all or you?

**Student 4:** Yeah, that again would have come from those animations.

**Interviewer:** Okay, so if you had to picture maybe the animation of ice in your head… Could you describe that to me?

**Student 4:** Yeah, I can see it, there are molecules stacked up in rows and all tight together and vibrate....

**Interviewer:** Okay, just like it says there. Okay, when you were answering this…post questionnaire, with these water questions, do you think at any stage you imagined those animations in your head to answer this question?

**Student 4:** Definitely.

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**Interviewer:** Here you've mentioned pretty much spacing and hydrogen bonding. Here you mentioned spacing and movement and no bonding…okay so you've got a similar number but you've got different things. Do you think that that the image of movement is a new thing that you've added to your image…?

**Student 5:** Yeah, I think so…what [the lecturer] did in the lectures with the computer animation things. That really helped I guess. I never well you know, specifically with the solid, I guess I never knew that they still moved a little bit.

**Interviewer:** Okay, so the vibrations in ice?

**Student 5:** Yeah.

**Interviewer:** Yep. Do you think that when you answered these questions, that you might have pictured in your head those animations that [the lecturer] showed you?

**Student 5:** Yeah probably, yeah.

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**Interviewer:** Do you think that your model of water in the different states has changed at all since the beginning of the year?

**Student 7:** Yeah, a bit.

**Interviewer:** What do you think might have influenced that change?

**Student 7:** … Just looking at water, states on the projector…

**Interviewer:** …Do you remember anything else that, just about your images of liquid, gas or solid water…that have specifically changed? …You said your images might have changed little bit, can you tell me what those changes are? …

**Student 7:** … ice would vibrate a bit and I never really considered that.
Interviewer: Okay, when you say very little movement of molecules, what do you mean by that? ...

Student 10: Yeah they move. I know there's three types of movement…there's rotational, vibrational and there's translational or something…so they sort of just vibrate but they stay really close together…

Interviewer: And did you have that image before you saw the animation?

Student 10: No, no.

Interviewer: Okay, the other difference here is that you’ve noted here that there’s vibrating in a fixed lattice and you didn’t mention that before. I was wondering if that was a new image?

Student 12: Yeah, that’s from the videos again.

Interviewer: Okay, the video of ice?

Student 12: Oh, all them ones he showed us of water.

Interviewer: …Can you describe to me what your mental image of that video looks like? Like is it similar to what you’ve drawn here?

Student 12: Yeah, I think so. I don’t think we ever saw it like this, like a hexagon. It was always in…just in a square lattice and they vibrated in one place.

Interviewer: You've developed some sort of idea of the structure of the particular molecules… Do you recall an animation of ice at the particle level?

Student 13: Yes, I do.

Interviewer: Yep, and what do you see when you picture that in your head?

Student 13: Well there's more of them, they're all packed in tightly.

Interviewer: Okay.

Student 13: And they struggle to move around at all.

Interviewer: When you say they struggle to move at all, what does that...?

Student 13: Well they're bouncing around off each other. There's hardly any room to move at all.

Interviewer: Okay, but there's some sort of movement then?

Student 13: A little bit, yeah.

Interviewer: Do you think the idea that there's some movement in the solid state has come from…do you think that came from the animations?

Student 13: Yeah
Interviewer: You can’t remember any particular things in lectures that showed you that idea?

Student 14: Only those little animation things that he had going but that’s all I remember of it.

Interviewer: Okay, well, do you think they gave you that sort of an image or do you think it was probably more just something [the lecturer] said?

Student 14: Just more how he explained it then he showed an image of it…sort of backing himself up a bit.

Interviewer: Yeah, okay… Can you think of that image that he backed himself up with?

Student 14: Yeah.

Interviewer: Can you picture that in your head?

Student 14: Yeah, all the molecules in a line, they’re all aligned and sort of vibrating a tiny bit…

10. Movement in liquid water

Learnt

Student 3: [The lecturer] sort of demonstrated through the videos and all that it maybe isn’t different.

Interviewer: Okay, the videos, can you talk a little more about that?

Student 3: Visual images

Interviewer: Okay, what sort of visual images.

Student 3: …The particles, the atoms, what they do in different states…so like we get to see what actually happens at every state.

Interviewer: And what does happen?

Student 3: Solid they’re all packed together, sort of rigidly, I think that’s the word, and then liquid they vibrate and they sort of they move but like not as much as gases.

Interviewer: You've probably included more detail in this one. You've got here that the molecules are close together. Here you've said that the molecules are close together and free to move, and you've also got improved confidence and improved vividness. What do you think may have caused that improvement?

Student 10: Well that was definitely the video cause in the video it shows the molecules are moving.

Reinforced
Student 1: …We’ve been using those, that representation a lot in the lectures and like I just said like I can picture that in my head. You sort of look at that and if you didn’t know that H\textsubscript{2}O was water or even if it was a molecule you’d sort of look at it and say that doesn’t look like anything but that looks like a beaker full of water molecules, you know.

Interviewer: Okay, what do you think helped you to be able to picture it in that way?

Student 1: Like what things were done in the lectures?

Interviewer: Yeah.

Student 1: Well all the pictures and the video…like the pictures are good and that but videos are better because it shows a moving description of it rather than just this then that. It shows the transitional period between…

Interviewer: Do you think that you picture those images in your head when you go to draw something like this?

Student 1: Well, I must do because…I drew that so that’s obviously how I picture it.

Interviewer: And do you think that those visual images were responsible for the increase in the vividness of your image?

Student 1: Yeah, yeah.

Interviewer: Can you identify any particular learning strategies, teaching strategies that may have contributed to increasing your visual images or your confidence in this question?

Student 2: Well the overheads, the videos of the water molecules bumping around.

Interviewer: …Do you think that when you were answering these questions you brought up a mental image of water?

Student 2: Oh yes, definitely.

Interviewer: And could you describe that mental image to me? Say for the liquid water.

Student 2: Well on the screen, in colour, all the molecules of water are all gently bumping around, [muffled] Repeated twice or three times, sometimes they are they [muffled] Across sometimes

Interviewer: So you’re talking about the animations?

Student 2: The animations yes.

Interviewer: Okay and you would say to me, when you were actually answering this question you actually pictured the animation in your head?

Student 2: Yes.

Interviewer: Do you feel that your image is more vivid now then it was at the beginning of the year?

Student 7: Yeah, I suppose, yeah.
Interviewer:  Yeah? … What do you think might have helped?

Student 7:  Like I keep on saying, the projector thing.

Interviewer:  …Can you actually picture those in your head?

Student 7:  Yeah.

Interviewer:  You can picture like liquid water in your head?

Student 7:  Yeah.

Interviewer:  …Do you think you would have pictured those in your head when you were answering these questions?

Student 7:  Yeah.

Interviewer:  Can you describe to me sort of what you can see?

Student 7:  Well, I don't know like great big spheres with little tiny spheres with the mickey mouse shape and its bent and it's bouncing around…. Say liquid water, say and it's bouncing around and some are connected or some have more hydrogens or less hydrogens than the others… They're crowded but some are connected and some aren't. They don't have that much energy but they have some energy.

Interviewer:  Yeah

Student 7:  Just moving around each other.

Interviewer:  …So if you brought up the animation of liquid water in your head describe to me what you actually see.

Student 13:  Well I just see the, lots of water molecules… They'll be floating around a little bit.

Interviewer:  You've obviously got some sort of a mental image that's fairly strong now….

Student 14:  It's the way the molecules like, flying around, colliding with each other, instead of obviously being like, they're not aligned any more…unlike the solid one.

Interviewer:  …How do you know?

Student 14:  Cause they're moving…cause that's liquid so it's… they're colliding into each other.

Interviewer:  So you're picturing them colliding and moving … Is that an image that you developed yourself?

Student 14:  No.

Interviewer:  Well where did you steal it from?

Student 14:  From him, I guess.
Interviewer: Okay, what exactly did you steal it from?

Student 14: From those animations again…

11. Collisions in liquid water

Learnt

Interviewer: … You’ve obviously got some sort of a mental image that’s fairly strong now….

Student 14: It’s the way the molecules like, flying around, colliding with each other, instead of obviously being like, they’re not aligned any more… unlike the solid one.

Interviewer: … How do you know?

Student 14: Cause they’re moving… cause that’s liquid so … they’re colliding into each other.

Interviewer: So you’re picturing them colliding and moving … Is that an image that you developed yourself?

Student 14: No

Interviewer: Well where did you steal it from?

Student 14: From him, I guess.

Interviewer: Okay, what exactly did you steal it from?

Student 14: From those animations again…

Reinforced

Interviewer: Can you identify any particular learning strategies, teaching strategies that may have contributed to increasing your visual images or your confidence in this question?

Student 2: Well the overheads. The videos of the water molecules bumping around.

13. Movement in gas (translational, vibrational and rotational)

Learnt

Interviewer: Okay, the videos, can you talk a little more about that?

Student 3: Visual images

Interviewer: Okay, what sort of visual images?
Student 3: The particles, the atoms, what they do in different states…so like we get to see what actually happens at every state.

Interviewer: And what does happen?

Student 3: Solid they’re all packed together, sort of rigidly, I think that’s the word, and then liquid they vibrate and they sort of they move but like not as much as gases. Gases then they start floating up.

Interviewer: Here you’ve mentioned distance and movement and collisions with the glass, big improvement in vividness and confidence.

Student 10: …Yeah, cause we got most of this out of the video like just showing the gaseous state.

Interviewer: How do you think you developed this image of the water molecules coming away and then coming back down again?

Student 14: Well that was the animations again.

Reinforced

Student 1: Exactly like in the video that’s how I, that’s how I remember. It was like those molecules …in the water state, some of them are going up but it’s not enough to make a real difference so if they’ve got more energy then they’re able to like…you just see one or two of them going off and the more moving to gas you know that the more have got energy to go and I just see them pretty much moving from there to there.
14. Collisions in gas

_Learnt_

_Interviewer:_ Here you've mentioned distance and movement and collisions with the glass, big improvement in vividness and confidence.

_Student 10:_ …Yeah, cause we got most of this out of the video like just showing the gaseous state.

16. Water molecules can react with each other to form hydronium ions and hydroxide ions

_Reinforced_

_Student 7:_ Like I keep on saying, the projector thing…

_Interviewer:_ …Can you describe to me sort of what you can see?

_Student 7:_ Well, I don't know like…great big spheres with little tiny spheres with the mickey mouse shape and its bent and it's bouncing around… Say liquid water, say and it's bouncing around and some are connected…or some have more hydrogens or less hydrogens than the others, they're like really… They're crowded but some are connected and some aren't. They don't have that much energy but they have some energy.

17. Correct model of water molecule

_Learnt_

_Interviewer:_ Okay, do you remember particular things that were done in lectures or shown to you…that made you realise that water doesn't consist of these two separate particles?

_Student 13:_ The animations.

_Reinforced_

_Interviewer:_ Okay, now obviously here you’ve drawn your representation using a different representation to the one you chose on the previous page. What do you think might have influenced that decision?

_Student 1:_ Well we’ve been using those, that representation a lot in the lectures and like I just said like I can picture that in my head. You sort of look at that and if you didn’t know that H₂O was water or even if it was a molecule you’d sort of look at it and say that doesn’t look like anything but that looks like a beaker full of water molecules, you know.

_Interviewer:_ Okay. What do you think helped you to be able to picture it in that way?

_Student 1:_ Like what things were done in the lectures?

_Interviewer:_ Yeah.
Student 1: Well all the pictures and the video... like the pictures are good and that but videos are better because it shows a moving description of it rather than just this then that. Interviewer: Do you think anything else influenced your choice of molecule?

Interviewer: You've selected the same model before and after instruction... Can you tell me why you selected that model over the others?

Student 4: I think that would have probably because we watched those computerised animations... They looked like that.

Interviewer: You said that this one was the one that was pushed in lectures. Can you sort of expand how it was pushed?

Student 6: Well every visual representation that was graphic had that diagram, so on the overheads, the animations were three dimensional, when we did solutions in water, we always did a circle with a little mickey mouse head.

Interviewer: This is your choice of model of water... Okay you've chosen a different representation to the one you chose in the beginning. What do you think might have influenced your change in choice?

Student 7: Well actually, I think it's because at the other time I did this it was either 1 or 2, I just chose that one cause it's stick figure and the other was ball and model figure. I probably chose that one later, 2, number two later because...I see it one all the time and on those...3D model things that they showed on the projector.

Interviewer: Oh, the animations?

Student 7: Yeah.

Student 9: I don't know.

Interviewer: Nothing in lectures or labs or anything that you sort of thought...

Student 9: Well in lectures that's the representation that was used in the videos.

Interviewer: Did that influence your choice?

Student 9: Pretty much.
23. Ions not atoms

*Animation Interpretation*

Student 5: There’s two different atoms or ions there, so I’d say one’s probably a positive, one’s a negative.

24. Structured

*Reinforced*

Interviewer: And sorry, what was the other thing you mentioned might have helped here?

Student 2: The overhead, the visual images.

Interviewer: Okay, the visual images. Could you possibly describe those for me?

Student 2: Well they're respectively ???. More three-dimensional, with different colours, and being an array in the cubic fashion enables you to picture clearly as to what the situation is.

Interviewer: Yep, and do you remember what the animation was actually of?

Student 2: Animation? Sodium chloride.

Interviewer: How would you describe your image now?

Student 9: Now I know that they are all touching different molecules and it's a regular pattern.

Interviewer: Yeah? A regular pattern of what?

Student 9: of the sodium and the chloride.

Interviewer: Ions, atoms?

Student 9: ions, ions….

Interviewer: What do you think helped you to develop that stronger image of sodium chloride at the particle level?

Student 9: Just seeing it all the time in the lectures just…

Interviewer: Seeing it, you mean?

Student 9: Pretty much by seeing it you know, its easier to visualise.

Interviewer: Okay, but seeing it where?
Student 9: … On the computer animations.

**Animation Interpretation**

Student 5: Okay, it looks like there’s an ionic lattice. The molecules or the ions I should say, are vibrating very slowly. It’s a solid cause it’s in a solid formation.

Student 8: That’s the ionic lattice and they’re vibrating. Yep they’re in the lattice. They’re close together…

Student 10: I don't know what molecules they are but they're green and white and white's smaller and for every one green there's four whites around the molecules, so it's in a sort of lattice.

Student 14: How they’re sort of aligned and not all over the shop.

25. Closely packed

**Animation Interpretation**

Student 8: That’s the ionic lattice and they’re vibrating. Yep they’re in the lattice. They’re close together…

Student 13: Well, they're all packed in together at the moment.

26. Vibrations in fixed positions

**Learnt**

Interviewer: Can you describe the video?

Student 1: Well, like that picture of the ice cube, there was the cube and they had the molecules in it and they were just sitting there like that and then they started vibrating more and then they could just go like that.

Interviewer: Moving past one another? … The subtle difference between these two responses is that originally you wrote “the molecules begin to vibrate quickly” and here you’ve got “they start to vibrate more rapidly”… Do you think that there’s a change in idea there?

Student 1: Well that makes sense cause remember earlier on in this first one where I had to draw the representation of the solid…the second one I said they were vibrating in their fixed positions and in this one I didn’t and I don’t think I had a concept of that.
Interviewer: Okay so you’ve developed the image that solids vibrate at room temperature.

Student 1: Yep

Interviewer: And do you think that you transferred the idea from the ice to sodium chloride?

Student 1: Yep

Interviewer: Okay, well when you look at this answer you’ve got more vibrations as the bonds become weaker. What sort of a mental image do you get of that, if any?

Student 5: Well again, the computer animation things are very helpful. One of the ones, the one that I can remember which was the melting of some sort of ionic substance had more or less just increase in kinetic ... they were just moving a lot faster and then they broke off and I guess that’s the sort of image I got in my head when I was answering that one. I don’t think we had those sorts of things when we were at school so I don’t remember ever learning that.

Interviewer: When you say more vibrations... are there vibrations then, before you start heating?

Student 5: Yeah.

Interviewer: Okay, if you bring up a mental image now of sodium chloride, does your image have ions vibrating?

Student 5: Yes.

Interviewer: And do you think that that is an additional feature of your image…

Student 5: Yeah, I think so, I think my understanding of a solid back in high school was more that it was just completely still so.

Interviewer: Do you think that your mental model or mental image of sodium chloride solid has changed at all since the beginning of the year?

Student 7: ... even though if they're really solid they vibrate a bit as molecules

Interviewer: ...How do you think you developed that image or that idea?

Student 7: Well, I’d say … from the head projector you know.

Interviewer: ...So can you remember a particular video projection…

Student 7: Yeah it had green and silver little bits and you sort of zoomed across it and you saw it and

Interviewer: And the ions were vibrating?

Student 7: Yeah, just a little bit.
Interviewer: Computer animations again? Did you get anything else out of the computer animations. Like is there anything that that diagram doesn't show that you got from the computer animations?

Student 9: Yeah. They're constantly moving. They're vibrating.

Interviewer: Okay, so we take some of that sodium chloride now…and we heat it up. …What sort of changes do you imagine happening at the particle level, if any?

Student 13: Well they start to vibrate a bit more than usual.

Interviewer: …So now you're telling me that as you add more heat, the particles start to vibrate more?

Student 13: Yeah.

Interviewer: How do you think you developed that sort of an image?

Student 13: Well I think go back to computer animations again.

Interviewer: Mm hmm

Student 13: Cause that's one thing I tended to look at a lot and it got stuck in my head a fair bit as well.

Interviewer: ...Can you identify a particular animation that helped you with this sort of an image?

Student 13: ...I think there was one with sodium chloride getting heated up like the question said and they started vibrating a lot more...

Reinforced

Interviewer: Can you please identify the differences between this drawing here and the animation? You already mentioned it is three-dimensional, are there any other differences?

Student 2: The animation is more realistic because on account it’s three dimensional and…flat drawings don't have that advantage.

Interviewer: Okay

Student 2: And also the animations can be made to vibrate which gives again the image, the idea of three-dimensionality.


**Animation Interpretation**

*Student 5:* Okay, it looks like there’s an ionic lattice, the molecules or the ions I should say, are vibrating very slowly.

*Interviewer:* Okay, anything else happening in there?

*Student 10:* They're vibrating.

*Student 11:* One of the things we learnt was that…atoms are never…still, they're always moving.

*Interviewer:* Anything else you wanted to point out?

*Student 14:* Just how they’re vibrating. They’re not totally stationary.

*Interviewer:* …Okay, earlier when you were telling me about that questionnaire there, you said that it only started vibrating as you heated it up.

*Student 14:* Well, it vibrates more.

*Interviewer:* Okay.

*Student 14:* Yeah.

*Interviewer:* Okay, so at room temperature would it be vibrating?

*Student 14:* Yeah

28. High water to salt ratio

**Learnt**

*Student 2:* The only ones I would bring up in memory would be the animation images. They're the ones that you bring up mentally.

*Interviewer:* And do you think that you thought about those when you were answering this question?

*Student 2:* Mm yes.

*Interviewer:* …So what would be the differences between the animations or your mental picture and this drawing?
**Student 2:** The animation has the advantage of three dimensions... However, bearing that in mind, that there has the details... that is namely there's a lot of water molecules...

**Interviewer:** So do you think that your mental image of sodium chloride in water has changed at all since the beginning of the year?

**Student 11:** This is like more of the animations that we got from [lecturer] that were fairly identical to these actually.

**Interviewer:** Okay.

**Student 11:** …Judging by my what I’ve actually written, probably just the number and the fact that they're actually I think the term is hydrated, yeah water molecules actually stick to them…which obviously I didn't realise in the beginning and then the number of water molecules would be much greater.

**Interviewer:** And do you think you got those images from the animations?

**Student 11:** Mm [in agreement]

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**Animation Interpretation**

**Interviewer:** …Solution of sugar question…how is that one relevant?

**Student 3:** Because it basically shows you that there’s lots of water.

**Interviewer:** Okay, so it’s like a ratio of water to solute thing?

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**Student 10:** There's heaps of water molecules and they're everywhere

**Student 12:** …The ratio of ions to water molecules is very low.

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29. Closely crowded

**Animation Interpretation**

**Student 5:** It’s fairly obvious that it’s liquid water cause it’s moving around… molecules sliding all over the place fairly close.

**Student 7:** Yeah, you can sort of see like the water molecules that are sticking to it… And they’re like crowding around each other.
30. Hydration of ions

**Learnt**

*Interviewer:* Can you describe to me the animation that may have helped you with this one?

*Student 7:* You know with the water molecules stuck to the ions and they were like spinning it around…and they didn't show the other water molecules.

*Interviewer:* Can you bring up a picture of what’s going on in the video you remember?

*Student 8:* They had sodium chloride in a big lattice and the water molecules moving in and as like the water molecules move in the sodium chloride they just start separating and then the chloride’s surrounded by water and the sodium’s surrounded by water so there’s no connection. Like they’re not together. So that’s how I pictured it.

*Student 10:* …like on the video like, he’d show the polarity and how … water molecules, would stick to the chloride, and like the picture would rotate cause like it’s a 3D video.

*Interviewer:* So do you think that your mental image of sodium chloride in water has changed at all since the beginning of the year?

*Student 11:* This is like more of the animations that we got from [the lecturer] that were fairly identical to these actually.

*Interviewer:* Okay

*Student 11:* Judging by my what I’ve actually written, probably just the number and the fact that they're actually I think the term is hydrated. Yeah, water molecules actually stick to them.

*Student 13:* Sodium chloride in water…chloride is a negative ion but then it's surrounded by water molecules with the positive end of the water molecules.

*Interviewer:* Mm hmm. How do you know that?

*Student 13:* Well, I learnt that during the year, first semester.

*Interviewer:* How did you learn it?

*Student 13:* Going to lectures and the animations again.

**Reinforced**

*Student 2:* The only ones I would bring up in memory would be the animation images. They're the ones that you bring up mentally
Interviewer: And do you think that you thought about those when you were answering this question?

Student 2: Mm yes.

Interviewer: Yeah, okay and so what would be the differences between the animations or your mental picture and this drawing?

Student 2: The animation has the advantage of three dimension…However, bearing that in mind, that there has … the important details. That is namely, there's a lot of water molecules and each ion is buffered, surrounded by water molecules, according to polarity…

Animation Interpretation

Student 1: Whatever that green ion is, it's surrounded by the water molecules…and there’s the other half of whatever the ion solution is and that's surrounded by six water molecules as well.

Student 3: That’s hydrated. I know that, surrounded by six water molecules.

Student 5: Okay, you’ve got an ion there which is being surrounded by the water molecules in solution. There’s another ion, moving round. Like I said before, there’s a few interactions between ions and water molecules.

Student 7: Yeah, you can sort of see like the water molecules that are sticking to it.

Interviewer: … I’ll just play it again. Is there anything else you want to point out?

Student 7: Yeah, the way they’re sticking to each other. There’s about six. You can see that better on a 3D animation …

Student 8: It becomes [an] aqueous solution and the…sodium chloride, they separate and are surrounded by water molecules, six water molecules.

Student 10: There's heaps of water molecules and they're everywhere…there's six of them, six water molecules surrounding them…

Student 11: Hydrated ions dodging round.

Student 12: There’s two ions, and one’ll come up later… That’s obviously a negative ion, the green one because … the hydrogens of the water molecules are facing towards it… That must make the other one positive.
Student 12: But yeah, some waters are attaching and other ones are attracting to it but generally it always has six around it.

Interviewer: Okay, so the ones that are around it are changing?

Student 12: Yeah, yep, some come off and others reattach to it.

Student 13: It's sodium ions and chloride ions, surrounded by water.

Interviewer: Yep. Which ones are the sodium and which are the chloride?

Student 13: …The sodium's the white one… The green's the chloride…

Interviewer: …How do you know that that's the chloride?

Student 13: The chlorine? Because it's surrounded by the hydrogen part of the water, which is the positive ion.

Interviewer: Okay and what about the other one? What charge does that one have?

Student 13: That’s got a positive charge.

Interviewer: And how do we know that?

Student 13: It's surrounded by the negative… side of the water, oxygen.

31. There is an electrostatic attraction between water molecules and ions

Learnt

Interviewer: Do you want to give me an idea of what you were thinking when you answered this and whether or not any particular learning strategies or teaching strategies helped you to answer this particular question?

Student 4: …I’d have to say the animations again

Interviewer: Okay, do you think when you answered this question that you actually … pictured… an animation in your head?

Student 4: Yeah.

Interviewer: …Can you describe to me if there are any other differences between this picture here and the mental image that you are bringing up of there of sodium chloride and water?

Student 4: Yeah, this one looks a bit crowded now but um…it also looks to be the best one out of the lot of them still.

Interviewer: Okay, and what makes it better?
**Student 4:** The dipoles... It's showing the reaction and what they do.

**Interviewer:** Do you think that your model of water in the different states has changed at all since the beginning of the year?

**Student 7:** Yeah, a bit.

**Interviewer:** What do you think might have influenced that change?

**Student 7:** ...Just looking at water states on the projector

**Interviewer:** Yeah.

**Student 7:** ...I couldn't really remember being taught that you know, ions attracted to water, water attracted ions.

**Interviewer:** What particular features of the lectures do you think helped you to develop that sort of an image of sodium chloride in water?

**Student 9:** Computer animations again.

**Interviewer:** Yeah, do you reckon you could describe to me what goes on in the computer animation?

**Student 9:** Yeah well the water molecules are at the positive poles are attracted to the chlorine ions and the negative poles are attracted to the sodium ions.

**Student 10:** On the video like, he'd show the polarity and how ... water molecules, would stick to the chloride, and like the picture would rotate cause like it's a 3D video.

**Student 13:** Sodium chloride in water...chloride is a negative ion but then it's surrounded by water molecules with the positive end of the water molecules.

**Interviewer:** How do you know that?

**Student 13:** Well, I learnt that during the year, first semester

**Interviewer:** How did you learn it?

**Student 13:** Going to lectures and the animations again.

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**Reinforced**

**Student 2:** The animation has the advantage of three dimension... However, bearing that in mind, that there has ... the important details, that is namely ... each ion is buffered, surrounded by water molecules according to
polarity…

### Animation Interpretation

**Student 3:** Na’s positive so then it’s got to have the O next to it. The water molecules, how they attach to the ion itself… Chloride is a Cl minus therefore the positive H ions are attached to it.

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**Student 4:** Okay, this one shows water being poured onto a sodium chloride crystals and any second now you’ll see how the dipole forces on the water molecules pull apart the crystal…

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**Student 5:** Okay, you’ve got an ion there, which is being surrounded by the water molecules in solution. There’s another ion. Moving round. Like I said before, there’s a few interactions between ions and water molecules. Looks like one of them was a positive ion and another one was a negative.

**Interviewer:** Which one’s which?

**Student 5:** Okay, the green one there is a positive, no it’s negative, negative ion yep.

**Interviewer:** Why is it negative?

**Student 5:** Because of the polarised water molecules. The hydrogen end is the positive end and they’re all pointing towards the molecule so…this grey one that comes up must be a positive, yep it’s a positive, cause all the negative ends, the oxygen are pointing towards it.

---

**Interviewer:** Okay. I’ll just play it again. Is there anything else you want to point out?

**Student 7:** Yeah, the way they’re sticking to each other. There’s about six, you can see that better on a 3D animation and the, the red side’s connected, that’s the oxygen side, is connected to the sodium while the other sides connected to the chlorine because of the negativity.

**Student 10:** …for the grey one, it’s like the red part of the molecule hydrating…the oxygen surrounding it.

**Interviewer:** And why does it do that?

**Student 10:** …the oxygen’s attracted to the positive polarity …

---

**Student 12:** There’s two ions, and one’ll come up later… That’s obviously a negative ion, the green one because the … hydrogens of the water molecules are facing towards it…That must make the other one positive.

**Interviewer:** Which ones are the sodium and which are the chloride?

**Student 13:** …The sodium's the white one…the green's the chloride…
Interviewer: Yep, how do you know that? How do you know that that's the chloride?

Student 13: The chlorine? Because it's surrounded by the hydrogen part of the water, which is the positive ion.

Interviewer: Okay and what about the other one? What charge does that one have?

Student 13: That's got a positive charge…It's surrounded by the negative … side of the water, oxygen.

Interviewer: Do you notice anything, anything else?

Student 14: Yeah, how the hydrogens are going, like pulling towards the green one, so that means the green one’s a negative one, so that’d be the chloride ion.

32. The solution is electrically neutral

Learnt

Interviewer: What particular features of the lectures do you think helped you to develop that sort of an image of sodium chloride in water?

Student 9: Computer animations again.

Interviewer: Yeah, do you reckon you could describe to me what goes on in the computer animation?

Student 9: Yeah well the water molecules are at the positive poles are attracted to the chlorine ions and the negative poles are attracted to the sodium ions…and there’s an even number of each.
Animation Interpretation

*Student 12:* There’s two ions, and one’ll come up later… That’s obviously a negative ion, the green one because … the hydrogens of the water molecules are facing towards it… That must make the other one positive.

---

33. Ions not molecules

Learnt

*Interviewer:* Can you bring up a picture of what’s going on in the video you remember?

*Student 8:* They had sodium chloride in a big lattice and the water molecules moving in and as like the water molecules move in the sodium chloride they just start like separating and then like the chloride’s surrounded by water and the sodium’s surrounded by water so there’s no connection like they’re not together so that’s how I pictured it.

---

*Interviewer:* Do you think that your mental image of sodium chloride dissolved in water has changed at all?

*Student 14:* Yeah

*Interviewer:* What aspects?

*Student 14:* …They break up. The water separates the chloride and the sodium ions apart…

*Interviewer:* …Okay, and how did you develop that sort of an image?

*Student 14:* From the lectures. From the animations.

Reinforced

*Student 2:* The animation has the advantage of three dimension…However, bearing that in mind, that there has the details…that is …the fact that individual ions are borne off…

---

Animation Interpretation

*Student 1:* They come together because they do have an attractive force…like a positive and a negative charge but the forces of the water molecules pulling them away is greater than the force keeping them together.

---

*Student 3:* Okay, they were passing by each other and their attraction to connect sort of happened but it wasn’t strong enough so then they stayed ions.
Student 4: Okay, this one shows water being poured onto a sodium chloride crystals and any second now you'll see how the dipole forces on the water molecules pull apart the crystal…one ion at a time and potentially there's enough water there…the whole crystal will be broken up.

Student 4: …That's sodium chloride solution and you'll see for a moment there a sodium and a chloride ion come into contact and there's still some attraction between them but the water again pulls them apart and they go their separate ways.

Student 7: …The water’s pulling it all apart…so it turns into a solution.

Student 8: It becomes an aqueous solution and the…sodium chloride they separate and are surrounded by water molecules, six water molecules.

Student 10: …You sort of remember these things because [the lecturer] would talk you through them but then you think yeah, why don't they stay together? …Why don't they form a solid? But like he'd say there's heaps of water molecules around them.

Student 12: There’s two ions, and one’ll come up later. That’s obviously a negative ion, the green one because…the hydrogens of the water molecules are facing towards it…That must make the other one positive.

Interviewer: Okay, so what's this one trying to show?

Student 13: It's sodium ions and chloride ions, surrounded by water.

Student 14: The green one’s the sodium, small one’s the chloride or…

Interviewer: And how do you know that?

Student 14: Hopefully I just remembered it.

Interviewer: Okay, can you tell from the animation?

Student 14: Maybe because they’re separated

34. Ions not atoms

Learnt

Student 13: Sodium chloride in water, well you see chloride is a negative ion but then it's surrounded by water molecules with the positive end of the water molecules.
Interviewer: How do you know that?

Student 13: Well, I learnt that during the year, first semester...going to lectures and the animations again.

**Animation Interpretation**

Student 1: They come together because they do have an attractive force...like a positive and a negative charge but the forces of the water molecules pulling them away is greater than the force keeping them together.

Student 3: Na’s positive so then it’s got to have the O next to it. The water molecules, how they attach to the ion itself... Chloride is a CI minus therefore the positive H ions are attached to it.

Student 5: Looks like one of them was a positive ion and another one was a negative.

Interviewer: Which one’s which?

Student 5: Okay, the green one there is a positive, no it’s negative, negative ion yep.

Interviewer: Why is it negative?

Student 5: Because of the polarised water molecules, the hydrogen end is the positive end and they’re all pointing towards the molecule so...this grey one that comes up must be a positive, yep it’s a positive, cause all the negative ends, the oxygen are pointing towards it.

Student 12: ...That’s obviously a negative ion, the green one because ... the hydrogens of the water molecules are facing towards it... That must make the other one positive.

Interviewer: Which ones are the sodium and which are the chloride?

Student 13: ...The sodium's the white one...the green's the chloride...

Interviewer: Yep, how do you know that? How do you know that that's the chloride?

Student 13: The chlorine? Because it's surrounded by the hydrogen part of the water, which is the positive ion.

Interviewer: Okay and what about the other one? What charge does that one have?

Student 13: That's got a positive charge...It's surrounded by the negative ... side of the water, oxygen.

Interviewer: Do you notice anything else?
Student 14: Yeah, how the hydrogens are … pulling towards the green one, so that means the green one’s a negative one, so that’d be the chloride ion.

35. Dynamic (movement, collisions, water exchange etc)

Learnt

Interviewer: What particular features of the lectures do you think helped you to develop that sort of an image of sodium chloride in water?

Student 9: Computer animations again.

Interviewer: Yeah? Do you reckon you could describe to me what goes on in the computer animation?

Student 9: …they're all moving everywhere.

Interviewer: Okay, now if you, can you bring up a mental image of the animation in your head? …Are there any differences between what you're picturing in your head and what's illustrated here?

Student 13: Only that they're moving around a little bit...

Animation Interpretation

Student 1: …The water molecules just cruise around.

Interviewer: Okay, so tell me what’s going on…What’s it a representation of?

Student 3: Water molecules floating around and they are hydrating the ions.

Student 5: Okay, you’ve got an ion there, which is being surrounded by the water molecules in solution. There’s another ion. Moving round…It’s fairly obvious that it’s liquid water cause it’s moving around … molecules sliding all over the place...

Student 7: They’re like in a liquid state and they want to bounce around.

Student 10: There's heaps of water molecules and they're everywhere, no specific pattern and they're rotating and they're moving
Student 11: It's all moving and everything, then sometimes they're going to sort of bounce into each other…

Student 12: Some waters are attaching and other ones are attracting to it but generally it always has six around it.

Interviewer: Okay, so the ones that are around it are changing?

Student 12: Yeah…Some come off and others reattach to it.

---

Direct transfer

MOLECULAR SUBSTANCE: IODINE

Application of Water Animations

Student 5: Yeah, I’d say this probably was helped by the animations. I’m not sure if I’m correct or anything. I don’t really know how iodine acts. The first thing I got in my head was that iodine…sublimes so I was going hang on liquid, I didn’t know how to draw that but I think probably got helped straight away from the…animations, I’d say. The fact that it sublimes, I knew that from high school. I just, that was one of the ones that we just learnt in class…I did know vanderwaals forces as well, I knew that from high school so.

Interviewer: Okay, so what features did you get from the animations, do you think?

Student 5: I guess, I don’t know, maybe the orientation, I don’t know. I just think again it just gives you a clearer image. I mean, maybe it’s something you understand, that it just, it becomes a solid, but maybe you don’t understand…how it interacts… I suppose a lot of it probably came from knowledge that I had already but …maybe some of it was knowledge and some of it came from the actual the animation that I’d used to get an image.

Interviewer: These were the states of iodine… Any particular animations help you to answer these?

Student 7: Yeah, like the ice one, the picture of the water molecules as ice…the one with liquid water would help you with that one I suppose

Interviewer: Iodine in the three states, any animations influence that question…?

Student 9: The water ones. The water ones influenced it.

Interviewer: This is iodine in the solid, liquid and gaseous states. Any particular animations spring to mind when you were answering these questions…?
**Student 11:** Probably the same animations from before… The ones about the solid, liquid gas, yeah…the same animations again, it was just because this was a slightly different, I mean we hadn’t actually learnt about something like this specifically which was probably why again I wasn't terribly confident about my answer.

**Interviewer:** Okay, so you were applying your ideas from the water molecules videos…?

**Student 11:** Mm hmm

---

**Interviewer:** So do you think that the water animations influenced these ideas?

**Student 13:** Yeah, they did again.

**Interviewer:** And so, would you say that when you answering this you’d actually bring up, try and bring up some sort of a mental image of those animations in your head?

**Student 13:** Yep.

**Interviewer:** And perhaps apply those ideas to something else? Can you explain why you feel that the animations were relevant to this question?

**Student 13:** Well, as I say they helped with that mental picture…that helps me work out the answer. Before I saw those, I couldn’t really get a picture in my head.

---

**Interviewer:** So you’ve got a tightly packed organised structure there with very slight movement. What do you think influenced…that representation of the solid there?

**Student 14:** How he explained how solids are; that they’re all aligned and still vibrating a tiny bit but they’re not moving anywhere.

**Interviewer:** So it was just things that he verbally said in the lectures?

**Student 14:** And the diagrams, the water so I sort of related it back to that.

**Interviewer:** The water?

**Student 14:** The animation one

**Interviewer:** Okay, so you think that the structure is probably similar to that of ice? Structure and vibrating?

**Student 14:** Yeah, that’s what I thought at the time, yeah.

**Interviewer:** Okay. Now describe what happens as you melt the iodine to form liquid iodine.

**Student 14:** How the thingys break up and form separate ones and they start moving around more and it’s getting all liquidish.

**Interviewer:** Okay, and where did you get, how did you form that sort of an idea?

**Student 14:** From the animations
IONIC SOLID: POTASSIUM BROMIDE

Application of Solid Sodium Chloride Animation

Interviewer: Do you think any particular learning strategies helped you to develop that image of...this type of a solid?

Student 1: ...The videos got the idea across of like the alternating, actually not so much the alternating that way but

Interviewer: Three dimension

Student 1: Yeah, that it went back that way as well...and if you took one, no matter where you looked around it, that the surrounding one would be the opposite charge.

Interviewer: You've mentioned that a lot of your images have been influenced by these overhead projections, these animations, I was just wondering if for any of the questions in this questionnaire whether you brought up any images of the animations and which animations?

Student 2: The lattice-work animation…

Interviewer: Okay, so that's what you imagined for this one...the sodium chloride lattice I assume?

Student 2: Yes.

Interviewer: So potassium bromide, do you think that any of the animations helped you to answer that question?

Student 7: ...I already knew basically what it looked like but if any projection helped it would have been the zoom in of the ionic solid; sodium chloride.

Interviewer: Okay, so you feel that the animation of sodium chloride was at least relevant to this question?

Student 7: Yeah

Interviewer: Do you think that you might have actually brought that image up into your head when you were answering it?

Student 7: Oh yeah.

Interviewer: You don't have to say yes, I mean…

Student 7: Well yeah, [when I] think about what the ionic solid would look like...it just pops up in my head.

Interviewer: Did any of the animations come to mind when you were looking at solid potassium bromide?

Student 9: Yeah, just that it needs to be in a regular pattern.

Interviewer: Okay, which animation?
Student 9: The sodium chloride.

IONIC SOLUTION: AQUEOUS SOLUTION OF BARIUM CHLORIDE

Application of Animations Related to Aqueous Sodium Chloride

Interviewer: I was just wondering if for any of the questions in this questionnaire whether you brought up any images of the animations and which animations?

Student 2: The lattice-work animation, brought up the dissolving animations there.

Interviewer: Do you want to describe to me the dissolving animation?

Student 2: There you'd have the solid lattice of barium chloride, water molecules pouring down, water molecules working their way around ions, the barium or chlorine ions, they're wobbling around and they kind of randomly float off…one by one.

Student 5: …I probably think the animations might have helped in the sense that I did know there was ions in water but perhaps the water molecules themselves, I didn’t have a complete understanding of how they, in water acted. I knew about the polar bonds, how they joined to the ions but maybe the rest of them how they … almost exchange as they move through the water… one of these might sort of float away, another one’ll join and things like that so I guess it was clear understanding of the mechanics of it I suppose as it moves through.

Interviewer: Any particular animation help you with this?

Student 7: …The one with the little water molecules attracted to the ions.

Student 11: The second one was definitely an animation. We saw a lot of those animations actually…

Interviewer: Okay, so which particular animation do you think is relevant to this question?

Student 11: Oh, the same animation... It actually showed virtually the same thing only it would have been sodium chloride maybe… as well as the animations, [the lecturer] drew that about 50 times, that exact same thing, this is going to be in your test.

Interviewer: Do you think his drawings of it influenced your image more than the animations?

Student 11: No, I don't think so. The animations because they were animated they made me sort of pay more attention because it was sort of moving and gives you a better image whereas when he drew it on the board it sort of gave us an idea of what we had to draw in the exam.

Applied transfer
Appendix D

PRECIPITATION OF COPPER HYDROXIDE

Application of Aqueous Sodium Chloride Animations

Interviewer: Do you think that when you were answering that question you thought about animations?

Student 9: …Yeah, well just all the ions floating around in the water and the water being attracted to them.

Student 10: …The polarities are just from the books and the lecture notes and stuff, the water polarity and how it sort of is attracted to ions…that came from the video too, how like there's heaps of water molecules around ions.

Interviewer: Do you think for the image…that the sodium chloride in water animation is relevant?

Student 11: Yeah, I do actually because I mean, from what I’ve said is wrong with it, to my way of thinking there’s not enough water molecules because if you think about how much water you'll need there should be a lot more water molecules and they should actually be hydrating ions rather than just be free and that's the same principle that I got from the animations.

Application of Precipitation of Silver Chloride Animation

Student 5: I’d say, yes, the animations do help … I think this second one would have been probably helped be the animations and also from school. Like I said we did know that but they aren’t surrounded, those potassium and nitrate aren’t surrounded by water and they should be… they should be forming a lattice rather than just free floating molecules … I’d say that was definitely helped by the animations.

Interviewer: Okay, which particular animation?

Student 5: The one that I mentioned before where you saw them joining two and then four

Interviewer: Precipitation

Student 5: Yep. I think that was probably was really helpful because I wouldn’t have understand the interactions, like you said before. From school I wouldn’t have understood that because … I just knew that suddenly it became a solid. I didn’t know how. So I think that probably helped a lot.

AQUEOUS SOLUTION OF HYDROCHLORIC ACID

Application of Aqueous Sodium Chloride Animations

Interviewer: This is your depiction of hydrochloric acid solution … Any particular animations that you thought of when you were drawing this?

Student 4: …They're all pretty much the same after a while aren't they? They're all sort of waters bouncing around and everything’s dissociated…

Interviewer: So you were applying the same ideas...
Student 4: Yeah, I think so yeah

Interviewer: This is your representation now of hydrochloric acid solution. Anything in particular help you form that sort of an image?

Student 5: … maybe ions… in solution which I saw in one of the animations...

Interviewer: Okay, so this is your representation of a solution of hydrochloric acid? … Do you think that any of the animations helped you with that question?

Student 7: Sodium chloride one with the water molecules stuck to it.

Interviewer: Any animations spring to mind when you were doing that…?

Student 9: The salt one again.

Interviewer: Okay, once again I’m interested in whether or not you brought up any particular animations into your head when you were thinking about this and if not what were you thinking?

Student 11: That probably would have been once again the same one. The same animation.
PRODUCTS OF REACTION BETWEEN AQUEOUS SOLUTIONS OF HYDROCHLORIC ACID AND SODIUM HYDROXIDE

Application of Aqueous Sodium Chloride Animations

Interviewer: An aqueous solution of sodium chloride? … When you were drawing that do you think any mental images came into your head?

Student 4: The one I've drawn, pretty much.

Interviewer: Okay, what do you think influenced that image…? …

Student 4: Yeah, I don't know...yeah those fantastic animations.

Interviewer: Do you think that any of the animations helped you with that question?

Student 7: Sodium chloride one with the water molecules stuck to it

Interviewer: ...and the products of that reaction after we accidentally put some sodium hydroxide in there?

Student 7: Yeah, probably about the same thing.
Appendix D


The following is the complete list of responses given by third year students in the Attitudes Survey, relating to the benefits of VisChem animations.

**Improved Visualisation**

“helped to imagine molecules (basic), see more clearly”

“imagining how reactions take place/understanding why”

“helped in imagining what the concepts in chemistry were about”

“understand and image reaction in everyday life”

“Helped to visualise in the exam.”

"the animations give a guide that can be applied in other situations, it's the visualising and thinking about them which made them most useful"

“…did enable broader thought as I had the actual images in my mind I could substitute other molecules for and play in my mind.”

“created a visual image in mind”

“Helps visualise a certain element or molecules behaviour in various conditions.”

“helped in developing visual images”

“got a better idea of how molecules look and interact with each other”

“helps me visualise interactions between molecules”

“Observation via visual aids made it easier to picture out the events during chemical reaction”

“it added colour to my images and more clarity”

“I could visualise what lectures were trying to communicate”

**Assisted with Idea of Movement and Interactions**

"helps me visualise interactions between molecules"

"They helped me visualise interactions of different molecules”

“the interactions around in air and water or the surrounding are explained in a visual manner”

"everything is moving"

“science of positive and negative”
“chemistry is the interaction of molecules and transfer of electrons”

“the world seems static at times, but now I understand reactions and molecules are always on the move ie. equilibrium”

“everything is a result on transfer of energy”

“to know a solid material, in essence, from a molecular point of view, is constantly vibrating”

“it is a constantly moving environment”

“how things react and bond together.”

“the way molecules react in their different states”

“Better able to think of eg a glass of water as a mobile mass of constant motion rather than a glass of water on a cupboard, still.”

“the way they attached to other molecules to form compounds”

“I was able to understand how the atoms interacted at the levels that one could never see in the naked eye or microscope”

“got a better idea of how molecules look and interact with each other”

“helps me visualise interactions between molecules”

**Improved Understanding**

“things started to make sense, and we can give a clear explanation”

“made a better visual understanding of the structures (as if they are tangible)”

“not only made lectures interesting but a better visual understanding of chem”

“animations gave better understanding”

“the way the molecules are not ball and stick molecule and electron cloud theory”

“gave an understanding of molecules better than just ball and stick model”

“increased my ability to understand concepts – linking pictures/diagrams to information presented.”

“understanding reactions on a micro scale at the molecular level”

“imagining how reactions take place/understanding why”

“views of atoms were better understood”

“understand and image reaction in everyday life”

“Strengthened my basic understanding which is what I had to build on”
"I was able to understand how the atoms interacted at the levels that one could never see in the naked eye or microscope"

"to understand and able to interpret some aspects at the molecular level"

**Made Learning Easier**

"made work easier to understand, than just with text-books or overheads"

"made it easier to perceive a molecule at an atomic level"

"easier and better way of presenting ideas"

“They made things a lot easier in the sense, you could see exactly what happened.”

“made it easier to learn 1st year”

“grasping of concepts visually as I learn quicker visually”

“gave a better conceptual image of different molecular species and enable easy understanding”

“visualising made chemistry easier”

**Interpretation of Macroscopic Phenomena**

“you can imagine the molecules, atoms, structures, on a molecular level instead of just a macro level”

“things aren’t always as you see them”

“when I see ice, I picture static water molecule not being allowed much movement”

“see thing in 2 ways normal and molecular”

"it allowed me to picture processes"

"make you visualise something which you cannot always see"

“It makes you think what is happening in that test-tube, beaker etc. Not just what you see.”

“nothing looks the same anymore”

“Gives you an idea of what to expect, how it works, during experiments”

“Better able to think of eg a glass of water as a mobile mass of constant motion rather than a glass of water on a cupboard, still.”

**Aroused Interest/Curiosity**

"increased interest in chemistry"

“I wonder was is actually going on”
"made it [chemistry] more interesting, meaningful"

" they helped inspire my imagination of what is happening at the scale of atoms and molecules."

“not only made lectures interesting but a better visual understanding of chem”

“helped shake those daunting boring images of chemistry texts of the 70s”

**Improved 3D Thinking**

"helped to visualise at the molecular/atomic level, in 3D"

“helped in developing visual images…especially 3d models ie lattices”

“animations helped me think in a 3-dimensional way with all molecules”

“it was the 1st time I started seeing molecules as 3-d structures”

**Good Foundation for Further Study**

“Understanding of 1st yr Chem ideas and concepts made a good foundation for years that followed.”

“helped to have a vivid basis to build further ideas on”

“Strengthened my basic understanding which is what I had to build on”

“any new ideas that were taught to me, I’d have a better understanding on why it was happening”

**Application**

"the animations give a guide that can be applied in other situations, it's the visualising and thinking about them which made them most useful"

“…did enable broader thought as I had the actual images in my mind I could substitute other molecules for and play in my mind.”

**Improved Ability to Draw Molecules**

“They helped me to draw molecules”
Appendix E: Statistical Data

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**. This is an upper bound of the true significance.
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a. Lilliefors Significance Correction

Wilcoxon Matched-Pairs Signed Ranks Test

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<th>POSTTOT - PRETOT</th>
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<td>-3.516*</td>
<td>-4.847*</td>
<td>-4.000*</td>
<td>-5.846*</td>
<td>-5.842*</td>
<td>-5.838*</td>
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</table>

a. Based on negative ranks.
b. Wilcoxon Signed Ranks Test
### E.1.2. Confidence and Imagery

#### Shapiro-Wilks Test of Normality

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** This is an upper bound of the true significance.

* This is a lower bound of the true significance.

a. Lilliefors Significance Correction
E.1.3. Pre-test and Post-test 2001

Shapiro-Wilks Test of Normality

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<tr>
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<th>Kolmogorov-Smirnov</th>
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**. This is an upper bound of the true significance.
*. This is a lower bound of the true significance.
a. Lilliefors Significance Correction

Wilcoxon Matched-Pairs Signed Ranks Test

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<tr>
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<th>POSTSPEC - PRESPEC</th>
<th>POSTMOL - PREMOL</th>
<th>POSTSOLI - PREISOL</th>
<th>POSTSOLN - PRESOLN</th>
<th>POSTION - PREITOT</th>
<th>POSTTOT - PRETOT</th>
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a. Based on negative ranks.
b. Wilcoxon Signed Ranks Test
E.1.4. *Transfer Test*

Shapiro-Wilks Test of Normality

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**a.** This is an upper bound of the true significance.

*. This is a lower bound of the true significance.

. Lilliefors Significance Correction
### Pearson Correlation Coefficients

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<th>APPSOL</th>
<th>POSTTOT</th>
<th>POSTISOL</th>
<th>TRANSISOL</th>
<th>TRANSAPP</th>
<th>POSTAPP</th>
<th>DISAPL</th>
<th>POSTPTE</th>
<th>APPPOST</th>
<th>APPTRANS</th>
<th>POSTPOST</th>
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<td>.000</td>
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<td>.000</td>
<td>.000</td>
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<td>.000</td>
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### Spearman Correlation Coefficients

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<td>35</td>
<td>35</td>
<td>35</td>
<td>35</td>
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</tbody>
</table>

*Correlation is significant at the 0.05 level (2-tailed).
*Correlation is significant at the 0.01 level (2-tailed).
E.1.5. Modelling

Shapiro-Wilks Test of Normality

Tests of Normality

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<th>Shapiro-Wilk</th>
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** Note: This is an upper bound of the true significance.

a. Lilliefors Significance Correction

Wilcoxin Matched-Pairs Signed Ranks Test

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a. Based on negative ranks.
b. Wilcoxon Signed Ranks Test
E.1.6. Third Year Study

Mann-Whitney Test (non-parametric)

Ranks

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<td>783.00</td>
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<td>Total</td>
<td>43</td>
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Test Statistics\(^b\)

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<td>.006(^a)</td>
<td>.042(^a)</td>
<td>.000(^a)</td>
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\(^a\) Not corrected for ties.

\(^b\) Grouping Variable: VAR00001
E.2. Chapter 3 Statistics

E.2.1. Attitudes Questionnaire: Principle Components Analysis

Communalities

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Total Variance Explained

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Component Matrixa

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Extraction Method: Principal Component Analysis.

a: 2 components extracted.
### E.2.2. CSPQ: Principle Components Analysis

#### Communalities

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#### Scree Plot

![Scree Plot](image)
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Extraction Method: Principal Component Analysis.
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**Extraction Method:** Principal Component Analysis.

*a. 9 components extracted.*
### E.2.3. Case Summary 2000

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<sup>a</sup> Limited to first 100 cases.
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*a.* Limited to first 100 cases.
### E.2.4. Pearson Correlation Coefficients 2000

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* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).
## E.2.5. Normality Tests 2000

**Tests of Normality**

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* This is a lower bound of the true significance.

a. Lilliefors Significance Correction
E.2.6. Normality and Outliers: Box-plots and Histograms 2000

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Reflect and Log GEFT

Histogram

Attitudes

Histogram

Simplicity

Histogram
Appendix E

Post-test

Histogram

Direct Transfer

Histogram

Applied Transfer

Histogram
Appendix E

Topic Transfer

![Box plot for Topic Transfer]

![Histogram for Topic Transfer]

Log Topic Transfer

![Box plot for Log Topic Transfer]

![Histogram for Log Topic Transfer]

Pre-post Gain

![Box plot for Pre-post Gain]

![Histogram for Pre-post Gain]
E.2.7.  Linearity: Scattergrams 2000

PRETOTAL

POSTTOT

VVIQ

SURFACE

POSTTOT

DEEP

RLOGGEFT

POSTTOT

ATTITUDE
### E.2.8. Multicollinearity: Tolerance 2000

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a. Dependent Variable: POSTTOT
E.2.9. Regression Analyses 2000

Post-test

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Model Summary

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a. Predictors: (Constant), RLOGGEFT, SIMPLICI, VVIQ, ATTITUDE, SURFACE, PRETOTAL, DEEP
b. Predictors: (Constant), RLOGGEFT, VVIQ, ATTITUDE, SURFACE, PRETOTAL, DEEP
c. Predictors: (Constant), RLOGGEFT, VVIQ, SURFACE, PRETOTAL, DEEP
d. Predictors: (Constant), RLOGGEFT, SURFACE, PRETOTAL, DEEP
e. Dependent Variable: POSTTOT

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a. All requested variables entered.
b. Dependent Variable: POSTTOT
### Coefficients

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**a.** Dependent Variable: POSTTOT

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**Normal P-P Plot of Regression Standardized Residuals**

**Scatterplot**

**Dependent Variable: POSTTOT**

**Observed Cum Prob**

**Regression Standardized Predicted Value**
## Direct Transfer

### Variables Entered/Removed

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<th>Method</th>
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### Model Summary

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- <sup>a</sup> Predictors: (Constant), RLOGGEF, SIMPLICI, VVIQ, ATTITUDE, SURFACE, PRETOTAL, DEEP
- <sup>b</sup> Predictors: (Constant), RLOGGEF, SIMPLICI, VVIQ, ATTITUDE, PRETOTAL, DEEP
- <sup>c</sup> Predictors: (Constant), RLOGGEF, SIMPLICI, ATTITUDE, PRETOTAL, DEEP
- <sup>d</sup> Predictors: (Constant), RLOGGEF, ATTITUDE, PRETOTAL, DEEP
- <sup>e</sup> Predictors: (Constant), RLOGGEF, ATTITUDE, PRETOTAL
- <sup>f</sup> Predictors: (Constant), ATTITUDE, PRETOTAL
- <sup>g</sup> Predictors: (Constant), PRETOTAL
- <sup>h</sup> Dependent Variable: DIRECT
## Coefficients

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2 (Constant) | 6.708 | 8.168 | 0.821 | 0.424 | -10.703 | 24.118 | .796 | 1.256 |
| PRETOTAL | .605 | .249 | .541 | 2.430 | .028 | .074 | 1.135 | .812 | 1.232 |
| VVIQ | -.878 | 2.241 | -.086 | -.392 | .701 | -5.654 | 3.899 | .610 | 1.235 |
| DEEP | 8.98E-02 | .148 | .140 | .606 | .554 | -.226 | .406 | .740 | 1.352 |
| ATTITUDE | 1.011 | 1.211 | .194 | .901 | .362 | -1.379 | 3.400 | .849 | 1.178 |
| SIMPLICI | -.478 | 1.055 | -.092 | -.453 | .657 | -2.725 | 1.770 | .960 | 1.042 |

3 (Constant) | 5.894 | 7.688 | 0.767 | 0.454 | -10.403 | 22.192 | .861 | 1.161 |
| DEEP | 7.22E-02 | .138 | .113 | .525 | .607 | -.219 | .364 | .814 | 1.228 |
| ATTITUDE | 1.078 | 1.078 | .207 | 1.000 | .332 | -1.207 | 3.364 | .870 | 1.150 |
| SIMPLICI | -.512 | 1.023 | -.098 | -.501 | .623 | -2.680 | 1.656 | .967 | 1.034 |

4 (Constant) | 5.978 | 7.515 | 0.796 | 0.437 | -9.877 | 21.833 | .883 | 1.132 |
| PRETOTAL | .613 | .225 | .549 | 2.727 | .014 | .139 | 1.087 | .817 | 1.224 |
| DEEP | 7.65E-02 | .134 | .119 | .570 | .576 | -.207 | .360 | .817 | 1.224 |
| ATTITUDE | 1.082 | 1.054 | .208 | 1.026 | .319 | -1.142 | 3.306 | .870 | 1.150 |
| SIMPLICI | -.512 | 1.023 | -.098 | -.501 | .623 | -2.680 | 1.656 | .967 | 1.034 |

| PRETOTAL | .594 | .218 | .532 | 2.724 | .014 | .136 | 1.052 | .903 | 1.107 |
| DEEP | 1.205 | 1.012 | .232 | 1.190 | .249 | -.922 | 3.331 | .908 | 1.101 |
| RLOGGEFT | 8.041 | 2.626 | .306 | .006 | 2.544 | 13.538 | .998 | 1.002 |

6 (Constant) | .647 | .205 | .579 | 3.149 | .005 | .217 | 1.077 | .998 | 1.002 |
| ATTITUDE | .965 | .956 | .186 | 1.009 | .325 | -1.036 | 2.966 | .998 | 1.002 |

7 (Constant) | 8.159 | 2.625 | .310 | .006 | 2.683 | 13.634 | 1.000 | 1.000 |

---

**Normal P-P Plot of Regression Stand**

**Scatterplot**

Dependent Variable: DIRECT
### Applied Transfer

#### Variables Entered/Removed

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#### Model Summary

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\(^a\) Predictors: (Constant), RLOGGEF, SIMPLICI, VVIQ, ATTITUDE, SURFACE, PRETOTAL, DEEP
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\(^d\) Predictors: (Constant), RLOGGEF, SURFACE, PRETOTAL, DEEP
\(^e\) Predictors: (Constant), SURFACE, PRETOTAL, DEEP
\(^f\) Predictors: (Constant), PRETOTAL, DEEP
\(^g\) Predictors: (Constant), PRETOTAL

\(^h\) Dependent Variable: APPLIED

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\(^a\) All requested variables entered.

\(^b\) Dependent Variable: APPLIED
### Appendix E

#### Coefficients

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a. Dependent Variable: APPLIED

#### Normal P-P Plot of Regression Standardized Residuals

- **Dependent Variable:** APPLIED
- **Expected Cum Prob:** 0.00, 0.25, 0.50, 0.75, 1.00
- **Observed Cum Prob:** 0.00, 0.25, 0.50, 0.75, 1.00

#### Scatterplot

- **Dependent Variable:** APPLIED
- **Regression Standardized Predicted Value:** -2.0, -1.5, -1.0, 0.0, 1.0
- **Regression Standardized Residual:** -2.0, -1.5, -1.0, 0.0, 1.0
## Appendix E

### Topic Transfer

<table>
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<th>Variables Entered/Removed</th>
<th>Method</th>
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- **Variables Entered/Removed**
- a. All requested variables entered.
- b. Dependent Variable: LOGTOPIC

### Model Summary

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- c. Predictors: (Constant), RLOGGEFT, SIMPLICI, SURFACE, PRETOTAL, DEEP
- d. Predictors: (Constant), RLOGGEFT, SURFACE, PRETOTAL, DEEP
- e. Predictors: (Constant), RLOGGEFT, SURFACE, DEEP
- f. Dependent Variable: LOGTOPIC
## Appendix E

### Coefficients

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### Normal P-P Plot of Regression Standardized Residual

**Dependent Variable: LOGTOPIC**

---

### Scatterplot

**Dependent Variable: LOGTOPIC**

---

*a. Dependent Variable: LOGTOPIC*
Pre-post Gain

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Model Summary

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- c. Predictors: (Constant), RLOGGEFT, VVIQ, SURFACE, PRETOTAL, DEEP
- d. Predictors: (Constant), RLOGGEFT, SURFACE, PRETOTAL, DEEP
- e. Dependent Variable: PREPOST

a. All requested variables entered.
b. Dependent Variable: PREPOST
## Appendix E

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\(^a\) Dependent Variable: PREPOST
E.2.10. **FIT Analysis: Tests of Normality, Box-plots and Histograms, Correlations**

**Tests of Normality**

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<sup>a</sup> This is a lower bound of the true significance.

<sup>a</sup> Lilliefors Significance Correction

**FIT**

![Box-plot for FITTOTAL]

**Histogram**

![Histogram for FITTOTAL]

**GEFT**

![Box-plot for GEFT]

**Histogram**

![Histogram for GEFT]
Appendix E

### Post-test

![Boxplot for Post-test](image)

![Histogram for Post-test](image)

- **Histogram**: 
  - Frequency: 0, 1, 2, 3, 4, 5
  - Mean: 19.2
  - Standard Deviation: 5.00

- **Histogram**: 
  - Frequency: 0, 1, 2, 3, 4, 5
  - Mean: 19.2
  - Standard Deviation: 5.00

### Direct Transfer

![Boxplot for Direct Transfer](image)

![Histogram for Direct Transfer](image)

- **Histogram**: 
  - Frequency: 0, 1, 2, 3, 4, 5
  - Mean: 15.7
  - Standard Deviation: 4.87

- **Histogram**: 
  - Frequency: 0, 1, 2, 3, 4, 5
  - Mean: 15.7
  - Standard Deviation: 4.87

### Applied Transfer

![Boxplot for Applied Transfer](image)

![Histogram for Applied Transfer](image)

- **Histogram**: 
  - Frequency: 0, 1, 2, 3, 4, 5
  - Mean: 7.5
  - Standard Deviation: 3.78

- **Histogram**: 
  - Frequency: 0, 1, 2, 3, 4, 5
  - Mean: 7.5
  - Standard Deviation: 3.78
Topic transfer

![Box plot and histogram for Topic transfer](image)

Pre-post Gain

![Box plot and histogram for Pre-post Gain](image)

Tests of Normality

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<thead>
<tr>
<th></th>
<th>Kolmogorov-Smirnov&lt;sup&gt;a&lt;/sup&gt;</th>
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<sup>a</sup> This is a lower bound of the true significance.

<sup>A</sup> Lilliefors Significance Correction
## Reflect and Log GEFT

### Histogram

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- Std. Dev = .30
- Mean = .58
- N = 13.00

### Correlations

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- Correlation is significant at the 0.01 level (2-tailed).
- Correlation is significant at the 0.05 level (2-tailed).

**Note:** Correlation is significant at the 0.01 level (2-tailed).

*Correlation is significant at the 0.05 level (2-tailed).
### E.2.11. Case Summary 2001a

**Case Summaries**

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|   | Total N | 34 | 34 | 34 | 34 |

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a. Limited to first 100 cases.
### E.2.12. Pearson Correlation Coefficients 2001a

#### Correlations

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* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

### E.2.13. Normality Tests 2001a

#### Tests of Normality

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* This is a lower bound of the true significance.
\(^a\) Lilliefors Significance Correction
E.2.14. Normality and Outliers: Box-plots and Histograms 2001a

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Pre-post Gain

Histogram

Std. Dev = 4.64
Mean = 7.3
N = 34.00
E.2.15. Linearity: Scattergrams 2001a
### Multicollinearity: Tolerance 2001a

#### Coefficients

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a. Dependent Variable: RLOGPOST
E.2.17. Regression Analyses 2001a

Post-test (N = 34)

Variables Entered/Removed\(^a\)

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Model Summary\(^a\)

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Dependent Variable: RLOGPOST

Coefficients\(^a\)

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Dependent Variable: RLOGPOST
Pre-Post Gain (N = 34)

Variables Entered/Removed

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Model Summary

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b. Predictors: (Constant), PRETOT, BASICTOT
c. Dependent Variable: PREPOST

Coefficients

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a. Dependent Variable: PREPOST
Normal P-P Plot of Regression Standardized Residual

Dependent Variable: PREPOST

Scatterplot

Dependent Variable: PREPOST

Regression Standardized Predicted Value

Regression Standardized Residual
### E.2.18. Case Summary 2001b

#### Case Summaries

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*a. Limited to first 100 cases.*
E.2.19. Pearson Correlation Coefficients 2001b

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* Correlation is significant at the 0.05 level (2-tailed).
** Correlation is significant at the 0.01 level (2-tailed).

E.2.20. Normality Tests 2001b

Tests of Normality

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* This is a lower bound of the true significance.

a. Lilliefors Significance Correction
### E.2.21. Normality and Outliers: Box-plots and Histograms 2001b

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Appendix E

Basic Skills

![Box plot for Basic Skills](image1)

Histogram

- Std. Dev = 3.17
- Mean = 32.4
- N = 32.00

Post-test

![Box plot for Post-test](image2)

Histogram

- Std. Dev = 4.84
- Mean = 15.9
- N = 32.00

Reflect and Log Post-test

![Box plot for Reflect and Log Post-test](image3)

Histogram

- Std. Dev = .30
- Mean = .76
- N = 32.00
Appendix E

Pre-post Gain

Histogram

Std. Dev = 4.42
Mean = 6.9
N = 32.00

PREPOST

Frequency

-2.5 0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5

PREPOST

N = 32.00

Std. Dev = 4.42
Mean = 6.9
E.2.22. Linearity: Scattergrams 2001b
### E.2.23. Multicollinearity: Tolerance 2001b

#### Coefficients

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*a. Dependent Variable: RLOGPOST*

### E.2.24. Regression Analyses 2001b

#### Post-test: Model 1 (N = 32)

#### Variables Entered/Removed

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*a. Predictors: (Constant), PRETOT, BASICTOT, RSQRGEFT*

*b. Predictors: (Constant), PRETOT, BASICTOT*

*c. Predictors: (Constant), PRETOT*

*d. Dependent Variable: RLOGPOST*

*a. All requested variables entered.*

*b. Dependent Variable: RLOGPOST*
Appendix E

**Coefficients**

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a. Dependent Variable: RLOGPOST

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**Normal P-P Plot of Regression Standardized Residual**

---

**Scatterplot**

---

**Post-test: Model 2 (N = 32)**

**Variables Entered/Removed**

<table>
<thead>
<tr>
<th>Model</th>
<th>Variables Entered</th>
<th>Variables Removed</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PRETOT, BASICTOT, RSQRGEFT</td>
<td>.</td>
<td>Enter</td>
</tr>
</tbody>
</table>

a. All requested variables entered.

b. Dependent Variable: RLOGPOST

**Model Summary**

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.616</td>
<td>.380</td>
<td>.313</td>
<td>.25100</td>
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</table>

a. Predictors: (Constant), PRETOT, BASICTOT, RSQRGEFT

b. Dependent Variable: RLOGPOST
Appendix E

Coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>Collinearity Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
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<tr>
<td>1</td>
<td>(Constant)</td>
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<td></td>
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<td>.015</td>
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<tr>
<td></td>
<td>RSQRGEFT</td>
<td>7.089E-02</td>
<td>.053</td>
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<td></td>
<td>PRETOT</td>
<td>-2.77E-02</td>
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</table>

a. Dependent Variable: RLOGPOST

Pre-Post Gain (N = 32)

Variables Entered/Removed

<table>
<thead>
<tr>
<th>Model</th>
<th>Variables Entered</th>
<th>Variables Removed</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>PRETOT, BASICTOT, RSQRGEFT</td>
<td></td>
<td>Enter</td>
</tr>
</tbody>
</table>

a. All requested variables entered.
b. Dependent Variable: PREPOST

Model Summary

<table>
<thead>
<tr>
<th>Model</th>
<th>R</th>
<th>R Square</th>
<th>Adjusted R Square</th>
<th>Std. Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>.577^a</td>
<td>.332</td>
<td>.261</td>
<td>3.80337</td>
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</tbody>
</table>

a. Predictors: (Constant), PRETOT, BASICTOT, RSQRGEFT
b. Dependent Variable: PREPOST
### Coefficients

<table>
<thead>
<tr>
<th>Model</th>
<th>Unstandardized Coefficients</th>
<th>Standardized Coefficients</th>
<th>Collinearity Statistics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>B</td>
<td>Std. Error</td>
<td>Beta</td>
</tr>
<tr>
<td>Model 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Constant)</td>
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</tr>
<tr>
<td>BASICTOT</td>
<td>.533</td>
<td>.226</td>
<td>.382</td>
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<tr>
<td>RSRQGEFT</td>
<td>-1.645</td>
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<td>-.346</td>
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<tr>
<td>PRETOT</td>
<td>-.667</td>
<td>.203</td>
<td>-.584</td>
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</tbody>
</table>

- Dependent Variable: PREPOST

---

Normal P-P Plot of Regression Standardized Residuals

Dependent Variable: PREPOST

Scatterplot

Dependent Variable: PREPOST
### Appendix E

#### CSA: t-Tests 2001

##### Group Statistics

<table>
<thead>
<tr>
<th>WA</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
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</thead>
<tbody>
<tr>
<td>PRETOT</td>
<td>1.00, 3.00</td>
<td>9.9000</td>
<td>3.4464</td>
<td>1.0899</td>
</tr>
<tr>
<td>POSTTOT</td>
<td>1.00, 3.00</td>
<td>15.9000</td>
<td>3.4464</td>
<td>1.0899</td>
</tr>
<tr>
<td>PREPOST</td>
<td>1.00, 3.00</td>
<td>6.0000</td>
<td>3.2660</td>
<td>1.0328</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>WA</th>
<th>N</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Std. Error Mean</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRETOT</td>
<td>1.00, 3.00</td>
<td>8.0588</td>
<td>3.8319</td>
<td>.9294</td>
</tr>
<tr>
<td>POSTTOT</td>
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<td>2.0868</td>
</tr>
<tr>
<td>PREPOST</td>
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<td>6.6250</td>
<td>4.0333</td>
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</table>

#### Independent Samples Test

<table>
<thead>
<tr>
<th></th>
<th>Levene's Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
<th>95% Confidence Interval of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Sig.</td>
<td>t</td>
<td>df</td>
</tr>
<tr>
<td>PRETOT</td>
<td>.021</td>
<td>.886</td>
<td>.352</td>
</tr>
<tr>
<td>POSTTOT</td>
<td>1.431</td>
<td>.248</td>
<td>.097</td>
</tr>
<tr>
<td>PREPOST</td>
<td>1.384</td>
<td>.256</td>
<td>.466</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Levene's Test for Equality of Variances</th>
<th>t-test for Equality of Means</th>
<th>95% Confidence Interval of the Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>F</td>
<td>Sig.</td>
<td>t</td>
<td>df</td>
</tr>
<tr>
<td>PRETOT</td>
<td>1.807</td>
<td>.192</td>
<td>1.779</td>
</tr>
<tr>
<td>POSTTOT</td>
<td>.020</td>
<td>.890</td>
<td>.625</td>
</tr>
<tr>
<td>PREPOST</td>
<td>.903</td>
<td>.352</td>
<td>.742</td>
</tr>
</tbody>
</table>

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Appendix F: Important Documents

F.0. “BEST PRACTICE” PROTOCOL ................................................................. 181
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Appendix F: Important Documents

F.0. “Best Practice” Protocol

Guidelines for Effective Use of VisChem Animations

The following steps are based on practical experience using the VisChem animations in teaching chemistry at first year university level in lectures and tutorials, and educational research on the most effective way to present animations.\(^1\)

Steps:

1. The physical and chemical properties of the substance (perhaps a reactant or product in a reaction) are demonstrated or shown at the laboratory level. For example liquid water flows with a high surface tension; copper(II) sulfate solution is blue whilst anhydrous copper(II) sulfate is white; copper is malleable, shiny and electron-donating; sodium chloride is crystalline and shatters. This is important since the molecular-level model must be consistent with these properties.

2. Students are asked to draw a representation of the substance (or process occurring between two species in a reaction) at the molecular level. This is best done by providing a box, of adequate size to enable the minimum, but sufficient, number of particles to be drawn as a representation. A key should be provided once models (ball & stick, space-filling, etc.) for the particles have been discussed.

Note that the student should be asked to show relative sizes of particles and any movement (if any!!?). Labelling is essential. A separate box should be provided for a text description to supplement and complement the graphic depiction.

---

3. The symbolic representation (chemical formula) of the substance should also be written down.

4. The student should be asked if their representation of the substance at the molecular level is consistent with the lab level properties observed in Step 1.

5. Before showing the whole animation a key of the building blocks should be shown, as in the example below.

| A frame from an animation showing a hydrated iron(III) ion as it is rotated. | A frame from the animation depicting aqueous iron(III) nitrate. Most of the solvent water molecules shown earlier are now omitted for clarity, to reveal the separate hydrated ions. |

6. The animation is shown in its entirety, without commentary, with students asked to observe as many things as they can about what they see. The animation is then shown again – this time with commentary, stopping and starting to clearly point out features of importance. Attention to wording is important, occasionally repeating the point that they are watching a representation.

7. Ask for comments and questions from the students.
8. Ask students to modify their diagram in view of the animation and the key features provided. Add movement, annotations, and, if appropriate, indications of forces operating between and within particles.

9. Highlight what the symbolic notation does, and does not, indicate about the molecular level. For example, NaCl(s) is not made of Na and Cl particles in NaCl pairs but Na⁺ and Cl⁻ ions in a close-packed arrangement; and NaCl(aq) does not contain hydrated NaCl ion pairs as the main species.

10. In order to make sure students have interpreted appropriately, provide students with feedback on their drawings either by marking them individually, or, in the case of large scale classes by providing them with a "model" answer and allowing them to modify their drawings.

11. Summarise the connections between the lab-level observations, the molecular-level depiction, and the symbolic notation.

12. Make it clear to students how the animations relate to the work they are covering in class. Provide still shots of animations in lecture/class notes to help cue student recall, at the appropriate points in the notes. This may serve to help integrate information from notes with information from animations.

The order of showing the animations is also important, and is listed here for information.

1. Liquid Water
2. Ice
3. Ice Melting
4. Water Evaporating
5. Water Vapour
6. Inside a Bubble of Boiling Water
7. Oxygen liquid
8. Oxygen gas
9. Copper Solid
10. Sodium Chloride Solid
11. Sodium Chloride Dissolving in Water
12. Sodium Chloride Solution
13. Copper(II) Nitrate Solution

Following this the order is dictated by the concepts to be covered. The above series is a core introduction to the three states of matter, three types of substances (molecular, metallic, and ionic) and to ionic solutions. The relationship between the animations is summarised in the Reaction Map below.
F.1.  Ethics Approval


