Research into practice: Using molecular representations as a learning strategy in chemistry

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Abstract: Research in chemical education over the last 20 years has revealed that many students have unacceptable, incomplete or non-existent mental models of chemical substances and processes at the molecular level. Multimedia resources produced in the VisChem project (see http://vischem.cadre.com.au/) have been designed to address this problem.

This paper investigates the effectiveness of VisChem molecular-level animations in enhancing student' images of substances and processes in first year university chemistry. The effectiveness of these animations, and the way they were presented, were evaluated using a pre- and post-test format, with follow-up interviews of selected students. The pre- and post-test showed the sophistication and scientific acceptability of students' images of molecular and ionic substances, before and after instruction. A comparison of pre- and post-data reveals significant improvements in students' mental models of these chemical phenomena. In addition to this, data on self-perceptions of students' confidence in their responses, and the vividness of their images, reveal a significant increase in both aspects following instruction.

Interviews were used to probe what students believed to be the main sources of any changes in imagery or confidence. Without prompting, the molecular-level animations were commonly identified as a contributing factor.

Introduction

The 'misconception' or 'alternative conception' movement has dominated science education research over the last 20 years; albeit with seemingly little impact on the teaching of science within schools and universities. Much of this research highlights the fact that students find it difficult to form scientifically-acceptable mental models of chemical phenomena in a multitude of chemistry topics[1,3-8,11,13,14,20-22] including the nature of atoms and molecules, structure and bonding in molecular and ionic substances, and chemical reactions.

More recently science educators have begun to develop methods of targeting misconceptions, often through the use of computer animations[10,15-19,23,24]. These authors report varying degrees of success and often state conditions under which the animations should be presented to improve or ensure effectiveness. A paper by Milheim (1993) collates some of these ideas by providing a summary of the ways in which computer animations should be implemented in computer based instruction, to maximise their effectiveness. These include: using animations where the instruction requires visualisation; to show otherwise invisible events; and where the concept to be taught involves movement. On this basis, it would seem that chemistry educators are justified in using animations to depict dynamic, invisible molecular-level processes, providing the animations are scientifically-acceptable and presented in an appropriate manner.

VisChem animations in a learning context

Chemistry involves interpreting visible changes in matter at the **laboratory level** (e.g. colour changes, formation of solids, boiling) in terms of changes in structure and processes at the invisible **molecular level** (including atoms and ions). These changes are represented at an **abstract level** in two ways; *qualitatively*, using specialised notation, terminology, and symbolism (Figure 1); and *quantitatively*, using mathematics (equations and graphs). Johnstone (1991) refers to the three levels as the *macro*, *sub-micro*, and *representational*, and pictures them at the corners of a triangle. Thinking in chemistry is then likened to moving between ‘a series of points within the triangle, depending on the proportion of the three levels at any one time’.

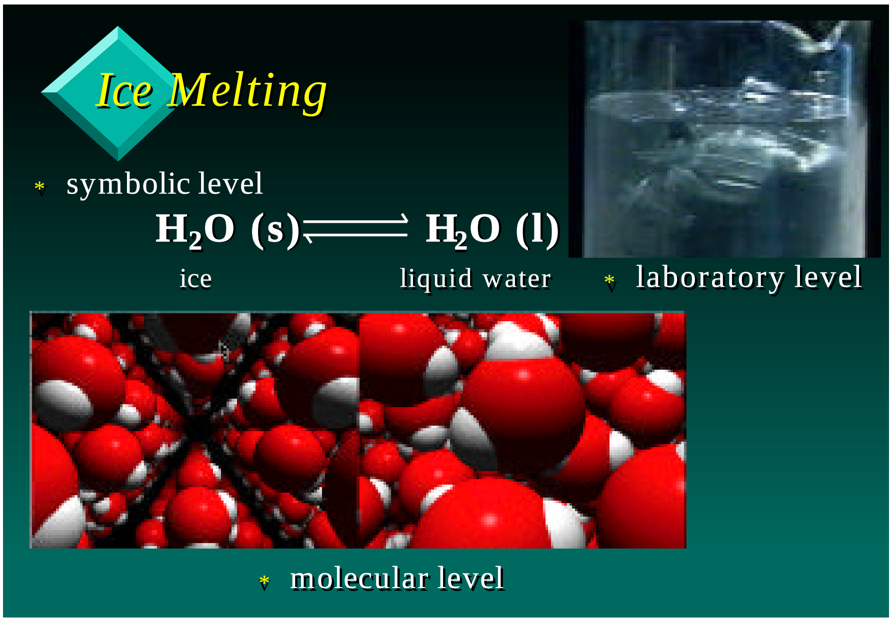


Figure 1. Frame from the *VisChem* presentation on ice melting, showing the three ‘thinking’ levels – the symbolic (chemical equation), laboratory (ice melting in beaker), and molecular (frames from *QuickTime* animation)

Chemistry students generally have difficulty linking observations in the laboratory to imagined molecular structures and processes, and they have difficulty communicating their ideas correctly using abstract notation, terminology, and mathematics.

The aim of the *VisChem* project (see http://vischem.cadre.com.au/) has been to produce multimedia resources (animations, video, text and sound) to explicitly link the three levels – the molecular, laboratory, and symbolic – for a variety of difficult topics in chemistry. The novel resources have been the molecular animations which represent substances in the solid, liquid, and gaseous states; during phase changes (e.g. melting); and when they react together.

Great care has been taken in the representation of molecular structures and processes because research by Ben-Zvi, Eylon and Silberstein (1987, 1988) and others has indicated that misconceptions can be generated easily, and perpetuated, with poorly drawn images.

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

The research hypotheses were that teaching with *VisChem* animations can improve:
- students’ images of the molecular world of certain substances, i.e. students’ images will be more detailed and scientifically acceptable;
- students’ confidence in responding to questions regarding the molecular level; and
- the vividness of students’ visual mental images of certain substances.

Methodology

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).

First year chemistry students at a metropolitan university in NSW, Australia participated in the study in Semester 1, 2000. Students completed a pre-test at the beginning of semester, and a post-test at the end. Of the 48 students, 32 had previously completed chemistry at HSC level (2U Chemistry, 3U 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.

One-to-one interviews were carried out by the first author (RD) with 14 volunteers from the above 48 students. Interviews lasted approximately one hour and followed a semi-structured protocol. Interviews were fully recorded on audio tape and full transcripts were analysed using *NUD*IST 4*.

Participants were never advised that the effectiveness of the animations was being tested.

Design of the pre-test

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

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, or to critically evaluate a variety of 2D representations of the molecular level of pure substances and solutions. The questionnaire was delivered in two parts, the first dealing with molecular substances and the second with ionic substances. In this way our representations provided in the ionic section did not bias responses for student-generated images in the molecular section.

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. Students were asked to rate the confidence they had in their response between 'uninformed guess' and 'total confidence' along an interval scale. Students also rated the vividness of some of their visual mental images along an interval scale between 'no visual image' and 'extremely vivid visual image (like reality)'.

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.

Presentation of animations using best practice

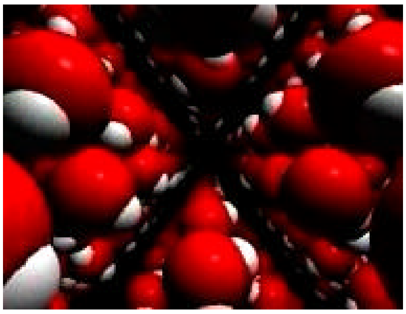
VisChem animations were integrated into the lecturer's teaching strategy. A document describing how to present the animations using 'best practice' was produced by one of the authors (RT, based on practical experience in using the animations at a first year level) and with reference to a review by Milheim (1993). Lectures were delivered by an academic who was not directly involved in the research. The lecturer adhered as much as possible to the 'best practice method'.

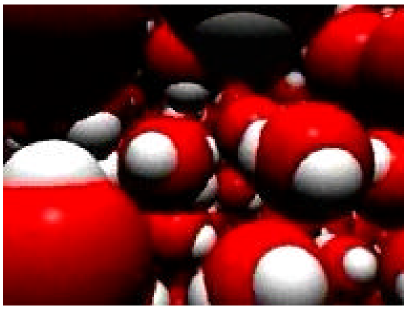
In general, animations were shown at least twice, once with no explanation, enabling students to gain a global perspective of the animation and once with the lecturer pointing out important features in the animation. Macroscopic depictions of the phenomena were also given, and effort made to relate the molecular representations to the symbolic and laboratory representations. The lecturer related the content of the animations to the context of the lesson, so features pointed out varied slightly from one viewing of an animation to the next viewing of that animation.

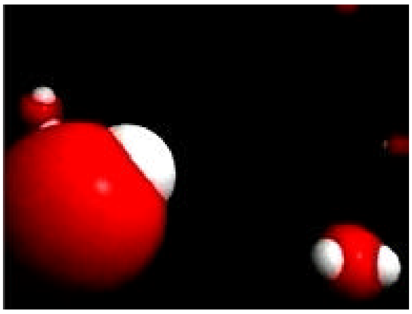
Table 1 lists the relevant animations used during lectures (other animations were also shown) with the weeks they were presented and associated lecture topic. Figure 2 shows key frames from some of these animations. All images assessed using the pre- and post-test were represented at least once using 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 a molecular level and were also expected to draw representations of certain substances in their mid-semester examination.

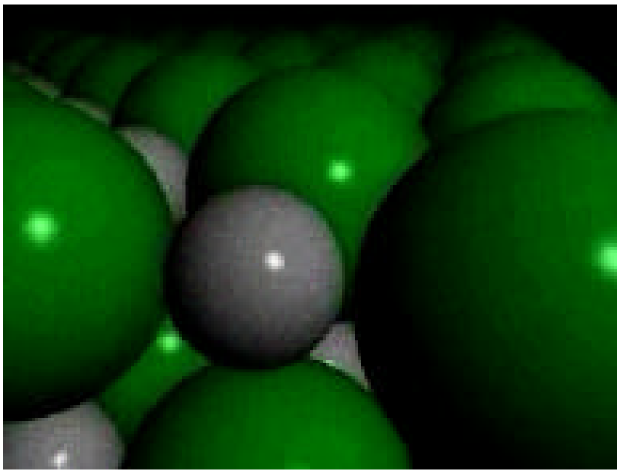
MOLECULAR SUBSTANCE: WATER

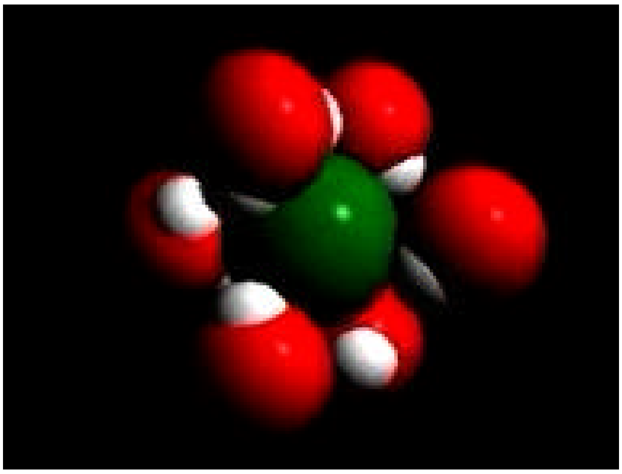

Solid Water (ice)

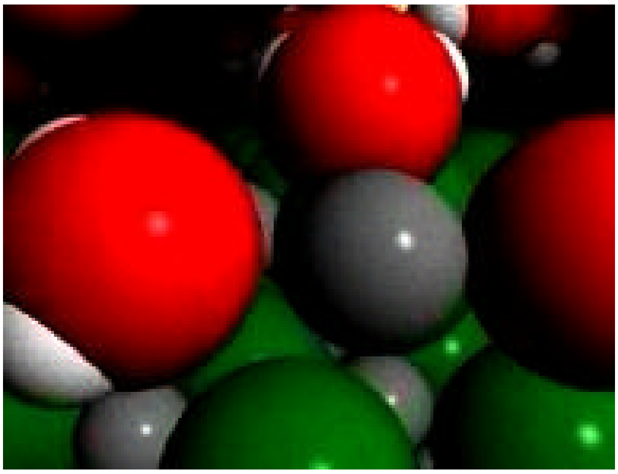

Liquid Water


Gaseous Water

IONIC SUBSTANCE: SODIUM CHLORIDE


Solid Sodium Chloride


Hydrated Chloride Ion


Sodium Chloride Dissolving

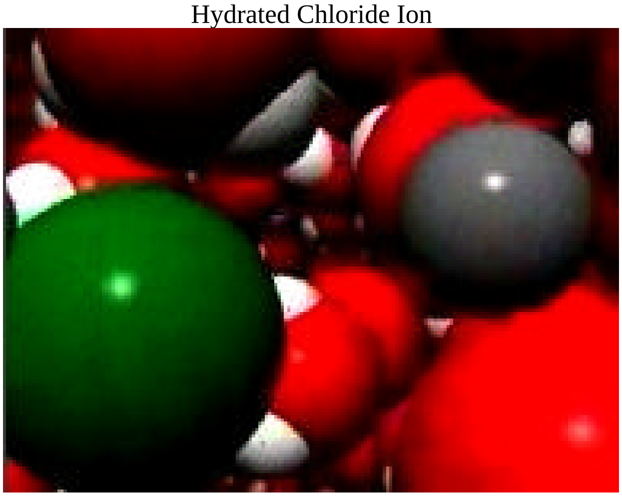

Aqueous Solution of Sodium Chloride

Figure 2. Snapshots from some relevant *VisChem* animations

Week Shown	Animation	Lecture Topic
1	Video: *Water: A Molecular Substance*, showing animations of solid, liquid and gaseous water, evaporation, melting and inside a bubble of boiling water.	The Building Blocks of Substances
3	Solid Sodium Chloride Sodium Chloride Melting Video replay: *Water: A Molecular Substance* Video: *Aqueous Solution of Sodium Chloride* Sodium Chloride Dissolving Hydrated Sodium Ion, Hydrated Chloride Ion Aqueous Solution of Sodium Chloride	The Building Blocks of Substances
7	Formation of a Hydronium Ion	Acids and Bases
10	Solid Sodium Chloride	Structure and Bonding
11	Solid Sodium Chloride Sodium Chloride Melting Sodium Chloride Dissolving Aqueous Solution of Sodium Chloride	Structure and Bonding

Table 1. Relevant animations, their timing of presentation and lecture topic

Development of the 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) (Figure 3).

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 developed certain key ideas about the substances. Each ‘substance’ category was divided into ‘key features’ (Table 2). Altogether, 35 key features were identified, based on:

- ideas that students were expected to develop from animations;
- misconceptions demonstrated by students in previous research and pilot studies;
- 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; and
- how the students interpreted the questions.

Completed questionnaires were inspected to obtain an idea of 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 providing one of these responses (without contradiction in other questions) demonstrated adequate knowledge of a particular key feature. Each student was allocated a mark out of 35 for the number of key features they demonstrated awareness of in the questionnaire.

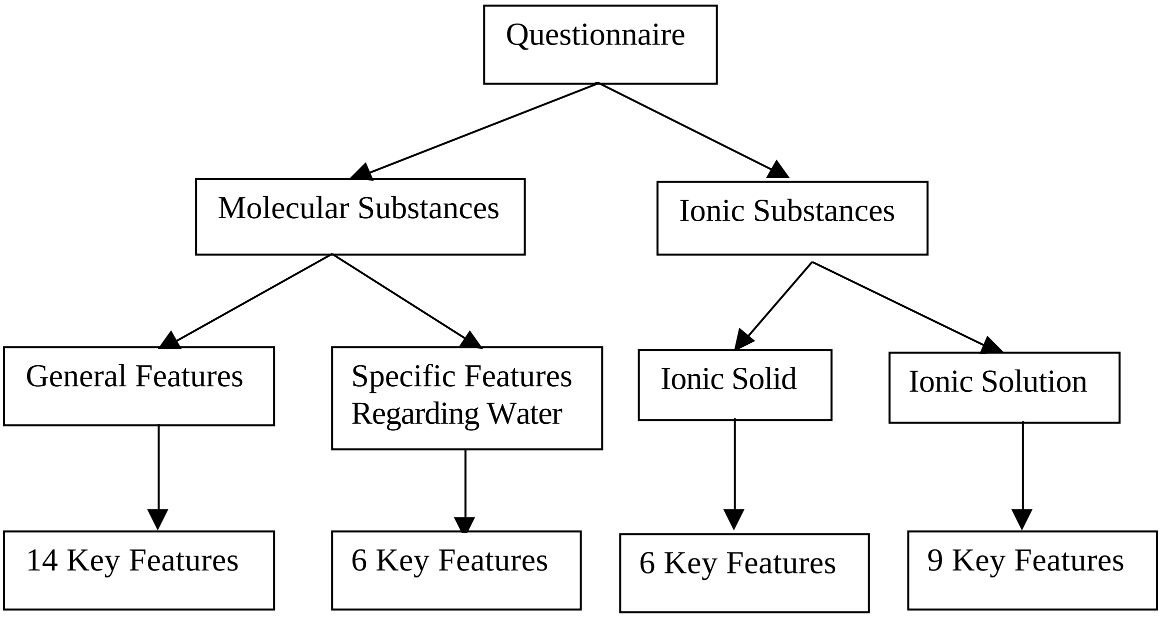


Figure 3. Structure of the marking scheme

Interview protocol

Interviews were used to determine whether students attributed any development of their mental images or improvement in confidence to viewing the *VisChem* animations. The interview questions were worded to minimise the expectation that 'the animations' was a desired response. Students were encouraged to discuss all the factors they believed contributed to the development of their mental images. Animations were never referred to by the interviewer before they were mentioned by the student. The interviews were carried out approximately three months after completion of the post-test.

Results and discussion

Progress from pre-test to post-test is shown in Figure 4. The average number of key features identified by students has increased substantially ($p = 0.0001$, one-tailed paired t-test). This suggests that following instruction involving *VisChem* animations, students on average, had significantly more detailed images of the substances being tested.

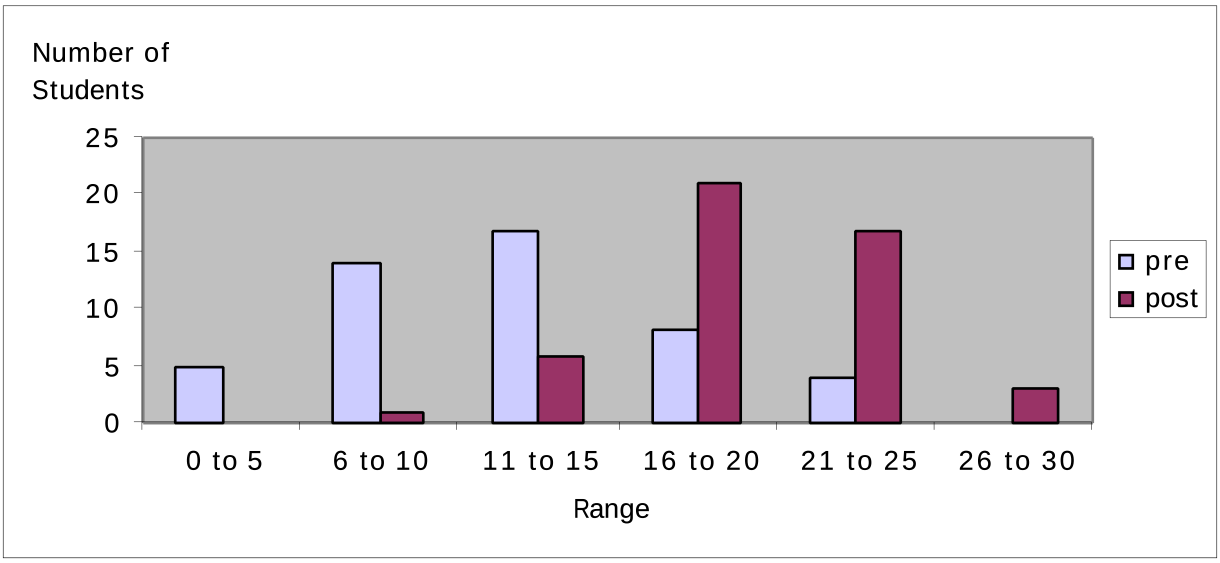


Figure 4. Comparison of pre-test and post-test overall scores

Key features
Breaking down the animations into 'key features' allowed us to closely examine which specific ideas were being developed by students.

The majority of key features were identified by an increased number of students in the post-test, compared to the pre-test. Many of these improvements were substantial. Some of these improvements are demonstrated below using results from the 'Aqueous Solution of Sodium Chloride' component as an example.

Sample results: Aqueous solution of sodium chloride
For the Ionic Solution section of the test, 8 out of 9 key features were identified by a greater number of students in the post-test (Table 2; Figure 5). Surprisingly, in the post-test, no students commented on 'movement' in an aqueous solution of sodium chloride. However, this may be due to the nature of the question. Students were required to comment on 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 dissociation of ions and conductivity in an ionic solution. In the post-test, students focused on other details in the given representations such as hydration and orientation of water molecules.

KEY FEATURE	Percentage of Students Demonstrating Key Feature in Pre-Test N = 48	Percentage of Students Demonstrating Key Feature in Post-Test N = 48
Ionic Solutions		
27 Correct model	15	98
28 High water to salt ratio	10	73
29 Closely crowded	31	77
30 Hydration of ions	4	73
31 There is an electrostatic attraction between water molecules and ions	19	46
32 The solution is electrically neutral	15	40
33 Ions not molecules	54	88
34 Ions not atoms	46	79
35 Dynamic (movement, collisions, water exchange etc.)	6	0

Table 2. Key features and statistical data for 'Aqueous Solution of Sodium Chloride'

It appears that the method of evaluating students' images influences the amount and type of detail students include about what they know. For example, ideas about movement need to be probed in a manner that encourages students to relate this data. This may 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. Ideally students should be interviewed and asked to describe their mental images.

Alternatively, it may suggest that students did not deem movement an important enough concept to relay and that this idea was not at the forefront of their mind when responding to a question regarding an aqueous solution.

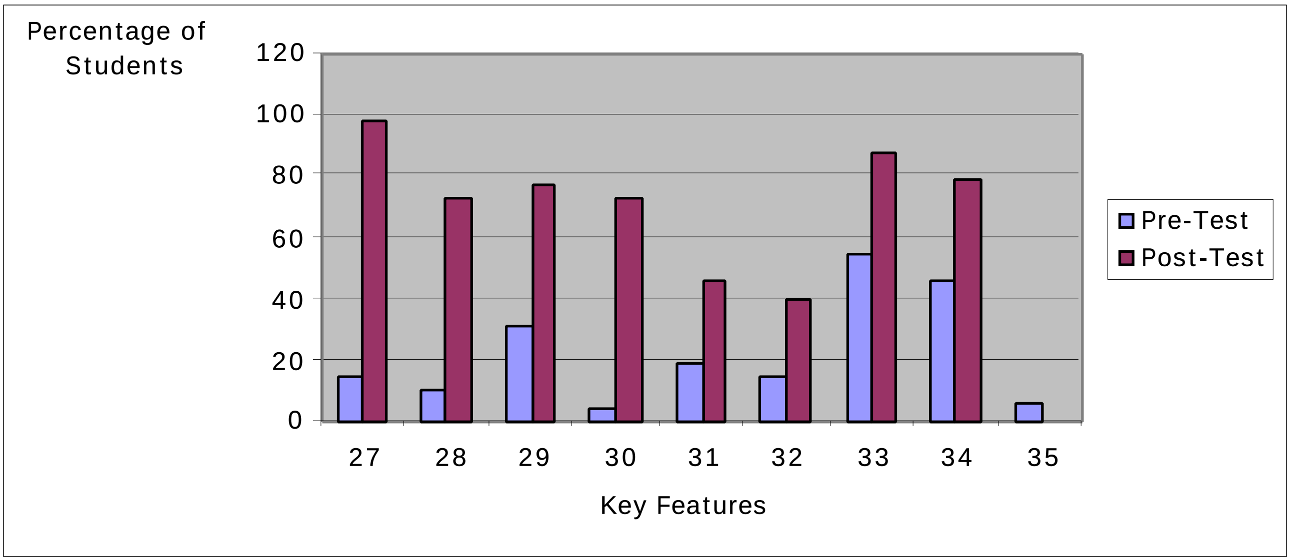


Figure 5. Comparison of the percentage of students identifying particular key features in the pre-test and post-test

Students need to be taught about the importance of movement and collisions for all processes at a molecular level. A firm visual idea regarding these ideas earlier on in schooling is likely to provide a solid foundation on which to build more complex ideas dealt with in topics such as Collision Theory, Kinetics and Equilibrium. Several papers report the notion students have, that chemical reactions are not interactive and that reactions occur via some 'miraculous' process, whereby bonds break spontaneously before reacting to form products[2,5,9]. Extra emphasis on these aspects of the animations may help to remedy these problems. Furthermore, students need to be instructed on how to indicate movement in two-dimensional diagrams, so that it becomes almost second nature for them to do so. This would eliminate the need for elaborate methods of assessment to determine if they are aware of these ideas.

In this study, students were shown the animations during lectures. For large class sizes this is the only viable method for introducing these visualisations. Some students, however, did not develop the ideas shown in the animations. There are likely to be many factors involved in this, including motivation and learning style. It may be that students who did not develop these images sufficiently need further engagement and interaction with the animations. There is some evidence to suggest that when students are given control over the viewing of animations they may gain further benefit from them[12]. We are currently producing interactive multimedia software that encourages students to focus on specific details in the animations using 'hotspots' and questioning.

Confidence and vividness of imagery

One-tailed paired t-tests carried out on data taken from the confidence and imagery vividness scales showed that confidence in responses improved significantly ($p < 0.0004$; Table 3) for all questions. This suggests that students developed greater confidence in responding to questions regarding the molecular level.

Self-perceptions of image vividness for the three states of water (solid, liquid, gas) also increased significantly ($p = 0.0001$; Table 3), suggesting that this method of instruction has helped to improve students' ability to more clearly visualise certain substances at a molecular level.

Content	Scale (0 - 6)	Pre-Test Average (standard deviation)	Post-Test Average (standard deviation)	One-Tailed Paired t-test Probability
Spacing of Molecules in a Liquid	Confidence in choice	4.37 (1.72)	5.20 (0.94)	0.0003
	Confidence in explanation	3.58 (1.47)	4.70 (0.90)	0.0001
Spacing of Molecules in a Gas	Confidence in choice	4.52 (1.64)	5.43 (0.80)	0.0001
	Confidence in explanation	3.64 (1.63)	4.73 (0.93)	0.0001
Size of Molecules in the Three States	Confidence in choice	3.37 (1.81)	4.51 (1.36)	0.0001
	Confidence in explanation	3.04 (1.75)	4.29 (1.35)	0.0001
Model of Water Molecule	Confidence	3.47 (1.52)	4.92 (0.94)	0.0001
Liquid Water	Confidence	3.62 (1.62)	4.92 (0.87)	0.0001
	Imagery Vividness	**3.40 (1.51)**	**4.83 (0.94)**	**0.0001**
Gas Water	Confidence	3.59 (1.58)	4.89 (1.06)	0.0001
	Imagery Vividness	**3.34 (1.55)**	**4.83 (1.04)**	**0.0001**
Solid Water	Confidence	3.54 (1.69)	4.77 (1.15)	0.0001
	Imagery Vividness	**3.43 (1.60)**	**4.77 (1.14)**	**0.0001**
What is Between the Molecules?	Confidence	2.84 (1.75)	4.14 (1.42)	0.0001
Solid Sodium Chloride	Confidence	3.06 (1.88)	4.79 (0.93)	0.0001
Vibrations in Solid Sodium Chloride	Confidence	2.74 (1.72)	4.51 (0.91)	0.0001
Aqueous Solution of Sodium Chloride	Confidence	2.56 (1.75)	4.82 (0.85)	0.0001

Table 3. Statistical comparison of pre-test and post-test results for confidence and imagery scales

Sample interview data: Aqueous solution of sodium chloride

Without prompting during interviews, students commonly identified *VisChem* animations as helping to improve their mental image of an aqueous solution of sodium chloride.

The quotes below demonstrate this point for key features 30 and 31, hydration of ions and electrostatic attraction between ions and water molecules.

Student 1

This student demonstrated high prior knowledge (21 key features identified in pre-test). In the post-test he identified 24 key features. He identified the same 5 key features relating to an aqueous solution of sodium chloride, in the pre-test and the post-test.

Although this student had a good understanding of aqueous solutions prior to university instruction, his confidence in his answer had improved considerably and he acknowledged the impact that the animations had on his visual mental image of aqueous sodium chloride.

Student 1: *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 you thought about those when you were answering this question?*
Student 1: *mm yes*
Interviewer: *…What would be the differences between the animations or your mental picture and this drawing?*
Student 1: *The animation has the advantage of three dimension. However, bearing that in mind, that there [diagram in questionnaire] has … the important details, that is namely, there are lots of water molecules and each ion is buffered, surrounded by water molecules according to polarity …*

Student 2
Student 2 also had relatively high prior knowledge (19 key features identified) and showed only a small improvement in the post-test (22 key features identified). In the pre-test she identified 3 key features for aqueous sodium chloride; in the post-test this had risen to 5 key features.

Student 2 mentioned an animation of a hydrated ion rotating as helping with the idea of hydration of ions.

> ***Interviewer:*** *Can you describe to me the animation that may have helped with this one?*
> ***Student 2:*** *you know, with the water molecules stuck to the ions and they were like spinning it around*

Student 3
The pre-test to post-test scores for Student 3 improved from 10 to 17. In the pre-test he identified 0 key features in the aqueous sodium chloride section of the test; in the post-test this had risen to 5 key features.

This student identified *VisChem* animations as helping develop his image of aqueous sodium chloride. In particular he recalled the electrostatic attraction between ions and water molecules being shown.

> ***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 3:*** *Computer animations again*
> ***Interviewer:*** *[Could you] describe to me what goes on in the computer animation?*
> ***Student 3:*** *Well the water molecules at the positive poles are attracted to the chlorine ions and the negative poles are attracted to the sodium ions*

Student 4
Student 4 identified 13 key features in the pre-test and 23 in the post-test. Specifically, for the aqueous solution of sodium chloride, this student's score rose from 1 to 6.

This student also recalled an animation of a hydrated ion rotating, showing the electrostatic attractions between ions and water molecules.

> ***Student 4:*** *… on the video he'd show the polarity and how the … water molecules would stick to the chloride, and the picture would rotate cause it's a 3D video*

Student 5
This student identified 13 key features in the pre-test and 20 key features in the post-test. Her score for aqueous sodium chloride rose from 2 to 5 key features, from pre-test to post-test.

This student identified animations as helping to develop her image of hydration.

> ***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 5:*** *This is like more of the animations that we got from [the lecturer] that were fairly identical to these actually … probably just the number and the fact that they're actually, I think the term is hydrated, yeah water molecules actually stick to them*

Interviews: A summary
Animations were identified by students in interviews as helping to:
- improve their images of chemical substances;
- improve their confidence in their images;
- improve the vividness of their images;
- confirm ideas they already had; and

- add new mental images of chemical substances to their existing ones.

Conclusions

Animations when used as outlined in this research appear to have a positive effect on helping students develop, modify or confirm their mental models.

Furthermore, the animations appear to have improved both the students' confidence in their images of the molecular world and the vividness of those images.

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