Research into practice: visualisation of the molecular world using animations

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Abstract: Most chemistry teaching operates at the macro (or laboratory) level and the symbolic level, but we know that many misconceptions in chemistry stem from an inability to visualise structures and processes at the sub-micro (or molecular) level. However, one cannot change a student's mental model of this level by simply showing them a different, albeit better, model in an animation. Molecular-level animations can be compelling and effective learning resources, but they must be designed and presented with great care to encourage students to focus on the intended 'key features', and to avoid generating or reinforcing misconceptions. One misconception often generated is the perception of 'directed intent' in processes at the molecular level, resulting from the technical imperative to minimise file size for web delivery of animations. An audiovisual information-processing model – based on a combination of evidence-based models developed by Johnstone and Mayer, cognitive load theory, and dual-coding theory – has been used to inform teaching practice with animations, and seed questions for research on student attributes affecting development of mental models using animations. Based on this model, the constructivist *VisChem Learning Design* probes students' mental models of a substance or reaction at the molecular level before showing animations portraying the phenomenon. Opportunities to apply their refined models to new situations are critical. [*Chem. Educ. Res. Pract.*, 2006, **7** (2), 141-159]

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Introduction

Chemistry involves interpreting *observable* changes in matter (eg. colour changes, smells, bubbles) at the concrete *macroscopic* or *laboratory level* in terms of *imperceptible* changes in structure and processes at the imaginary *sub-micro* or *molecular level***.** These changes are then represented at an abstract *symbolic level* in two ways: qualitatively, using specialized notation, language, diagrams, and symbolism; and quantitatively, using mathematics (equations and graphs).

Figure 1 illustrates these three levels for an iron(III) thiocyanate equilibrium. The apparently unchanging solution in the beaker at the laboratory level can be linked to an animation portraying the dynamic, invisible processes at the molecular level. The equation represents the equilibrium at the symbolic level. Our initial hypothesis, later revised from our studies described below, was that simply showing an animation of this equilibrium at the molecular level might help students build a better conceptual understanding of what it means for a system to be at equilibrium, and to interpret the real meaning of the double arrows.

Figure 1. Chemical equilibrium presented at the three thinking levels.

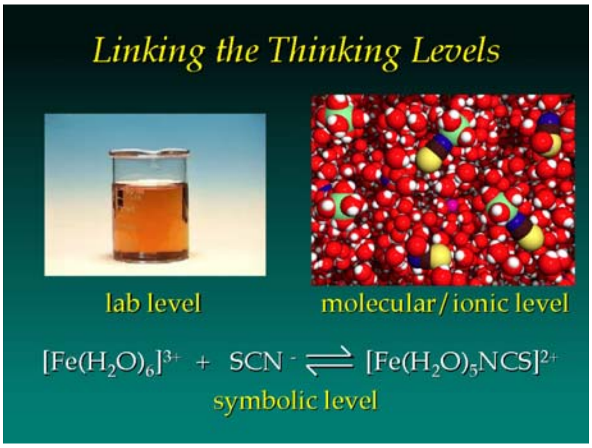
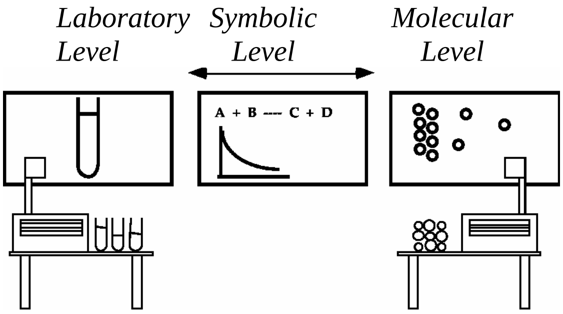


Figure 2. Using the three thinking-level approach in the lecture theatre. This approach is reinforced in the laboratory notes, tutorials and assessment.



The need to be able to move seamlessly between these three ‘thinking levels’, first described by Johnstone (1982, 1991), is a major challenge for students learning chemistry (Kozma, 1997). One of the authors (RT) first used these levels *explicitly* as a teaching strategy in the late 1980s (Tasker, 1992), allocating each part of the lecture stage to a thinking level (Figure 2), rewriting laboratory manuals specifying when each level is relevant, and designing exam questions to probe a student’s ability to integrate laboratory work and theory at each level. Other researchers have recommended teaching with these levels in an explicit way, and helping students to draw links between them (Tasker, 1996, Russell, 1997; Hinton, 1999). Now almost every general chemistry textbook (e.g., Bell, 2005) mentions this presentation strategy in early chapters, whilst few reinforce the idea throughout the text.

Need to develop mental models of the molecular level

Since the mid-1970s there has been convincing evidence (Kleinman, 1987; Lijnse, 1990, and references therein) that many student difficulties and misconceptions in chemistry result from inadequate or inaccurate mental models at the molecular level. Moreover, many of the misconceptions are common to students all over the world, and at different educational levels, and even amongst students who were performing well in formal examinations (Nurrenbern, 1987; Nakhleh, 1992, 1993a; Nakhleh, 1993b; Niaz, 1995). The most important finding was that many misconceptions were extraordinarily resistant to change, despite targeted teaching interventions.

Until the early 1990s there was a shortage of convincing resources that portrayed the dynamic molecular level with sufficient accuracy to help students to construct useful mental models of structures and processes at this level. Most teaching was restricted to the laboratory and symbolic levels, in the hope that students’ models of the molecular world would ‘develop naturally’. Students were left to construct their models from the static, often oversimplified, two-dimensional diagrams in textbooks; confusing ball-and-stick models; and their own imaginative interpretation of chemical notation - for example, does “NaCl(aq)” mean that ionic solutions contained dissolved ‘NaCl molecules’?

The purposes of this paper are to:

- show how the Johnstone three "thinking-level" model acted as the seed for the *VisChem* project to assist students to construct useful mental models at the molecular level
- describe research on the effectiveness of the *VisChem* animations, and the need to embed them within a 'learning design'
- present an audiovisual information-processing model, based on work by Johnstone, Mayer, Paivio, and Sweller, to inform the development of learning designs
- illustrate one such design – the *VisChem Learning Design* – with an example for developing a student's molecular-level model for ions in aqueous ionic solutions.

The VisChem project – visualising the molecular level with animations

Motivated by a frustration with the lack of resources in the early 1990s depicting Johnstone's sub-micro level, the *VisChem* project was funded to produce a suite of molecular animations depicting the structures of substances and selected chemical and physical changes (Tasker et al., 1996; also see vischem.cadre.com.au for availability). The animations were produced as useful models at this level, with careful attention to the often-competing demands of scientific accuracy (e.g., close proximity of adjacent molecules in the liquid state; internal molecular bond vibrations; and the diffuse nature of electron clouds), the 'artistic license' required for clear communication (e.g., reduced speed of molecules in the gaseous state; less crowding in the liquid state; absence of internal molecular bond vibrations; and use of shiny boundary surfaces), and technical computing constraints (close-up view to limit the number of moving 3D objects to be rendered; and the directed depiction of portrayed events to minimise the number of animation frames, and file size). Resources were then developed to link these animations to the macro and symbolic levels.

What kinds of messages can be communicated in molecular-level animations?

The molecular world is multi-particulate, dynamic and, in the liquid state, crowded; and the interactions are often subtle (e.g., electron transfer) and complicated. Animations can be effective for helping students to construct and apply useful mental models of this world. However, as we will see below, effective use of these resources for meaningful learning should be based on a learning theory that is evidence-based, and able to inform teaching practice. Some of the *VisChem* animations described below can be downloaded (Tasker, 2002b – http://www.learningdesigns.uow.edu.au/exemplars/info/LD9/index.html, and go to the molecular construction tool and animations 'Crosslink').

In contrast to textbook illustrations, animations can show the dynamic, interactive, and multi-particulate nature of chemical reactions explicitly. For example, the laboratory-level observation of silver crystals growing on the surface of copper metal shown in Figure 3 is hardly consistent with the misleading diagram, often written on a whiteboard, of one copper atom donating an electron to each of two silver ions. An animation (Figure 4) can show reduction of *many* silver ions on the copper surface, with concomitant release of *half as many* copper(II) ions from the metal lattice. This is a much better explanation for the 2:1 stoichiometric ratio in this reaction.

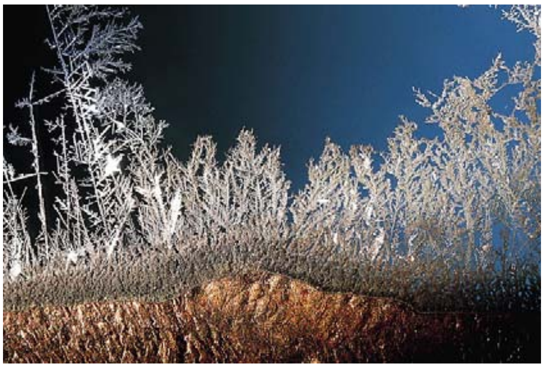


Figure 3. When copper metal is covered with silver nitrate solution, silver crystals form on the surface of copper metal; some copper 'dissolves', and the solution gradually turns blue.

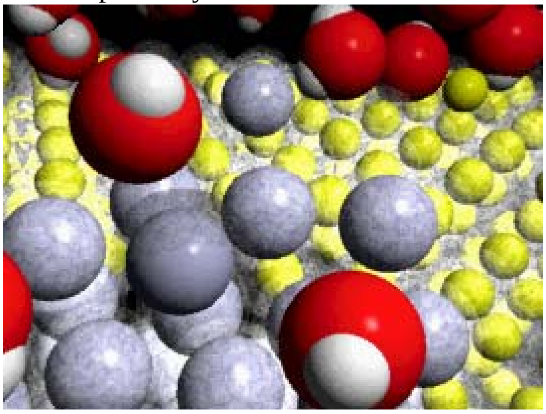


Figure 4. Frame from a *VisChem* animation showing reduction of silver ions to silver atoms on a growing crystal; with concomitant release of copper(II) ions, in a two to one ratio respectively.

Animations of the molecular world can stimulate the imagination, bringing a new dimension to learning chemistry. What could it be like inside a bubble of boiling water, or at the surface of silver chloride as it precipitates, as depicted in Figures 5 and 6 respectively?

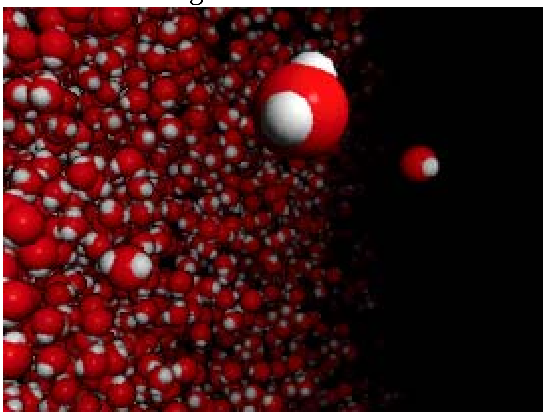


Figure 5. A frame of the *VisChem* animation that attempts to visualise gaseous water molecules 'pushing back' the walls of a bubble in boiling water.

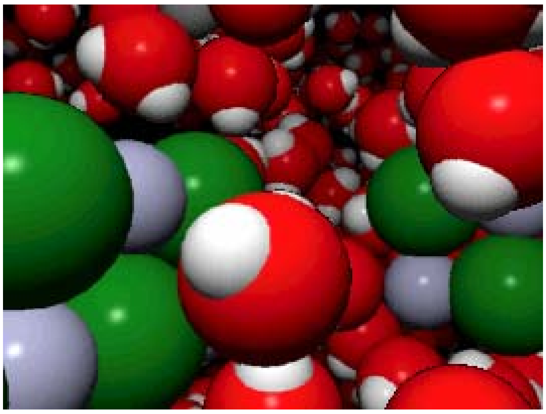


Figure 6. A frame from another animation that depicts the precipitation of silver chloride at the molecular level.

Most molecular-level processes involve competition. Examples include the competition for a proton between an iron(III)-bound hydroxide and a solvent water molecule (Figure 7); and between lattice forces and ion-dipole interactions when sodium chloride dissolves in water (Figure 8).

Figure 7. Frame from a *VisChem* animation showing the 'tug-of-war' between an iron(III)-bound hydroxide and a solvent water molecule for the proton.

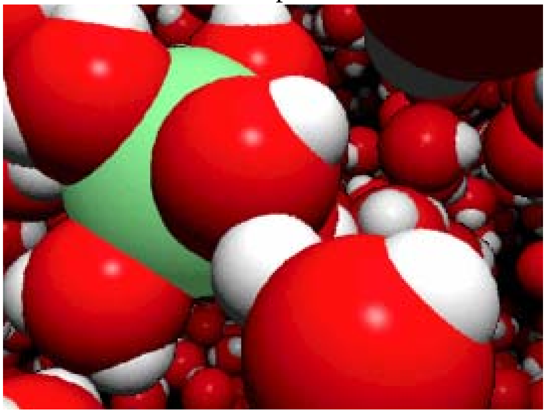
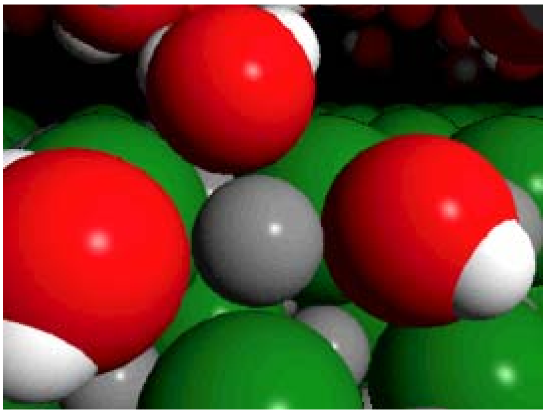


Figure 8. Frame from a *VisChem* animation showing the hydration of a sodium ion on the surface of sodium chloride despite strong attractive forces from the rest of the lattice.



Research on the effectiveness of VisChem animations for constructing mental models

We have conducted research into factors that affect a student's ability to form scientifically acceptable mental models of chemical substances and processes at the molecular level after exposure to *VisChem* animations. Our study examined the changes in mental models of first-year chemistry students (N = 48) following a semester of teaching that emphasized molecular visualisation using the animations (Dalton, 2003). The study used a pre-test/post-test design with follow-up interviews. A transfer-test was also administered after the post-test, and prior to interviews. The animations were presented on the basis of recommendations in the literature (Milheim, 1993) and practical experience over five years of using the animations in lectures (see vischem.cadre.com.au, and go to Educational Support/Resources).

This study demonstrated that showing animations to students, with opportunities for them to practise drawing representations of the molecular world, significantly increased the number of scientifically acceptable 'key features' in students' representations of chemical phenomena at the end of the semester (Table 1). Students developed more vivid mental imagery of these phenomena (Table 2) and had greater confidence in their images (Table 2). Evidence from interviews with fourteen students revealed, without prompting, that changes were largely attributed to having viewed *VisChem* animations. There was also an indication that some students had been able to transfer their ideas from animations to new situations, as evidenced by a statistically-significant correlation between the post-test and transfer test (n = 35, r = 0.69, p = 0.01), and comments in interviews.

Table 1. Means and standard deviations for corresponding sections on the pre-test and post-test (N = 48).

Section	Pre-test M	Pre-test SD	Post-test M	Post-test SD
Molecular Substances: General Features	6.2	2.4	8.0*	1.8
Molecular Substances: Specific Features of Water	1.7	0.9	2.2*	0.8
Ionic Solid	2.5	1.5	3.8*	1.6
Ionic Solution	2.0	1.9	5.7*	1.5
Test Total	12.4	5.1	19.8*	4.0

* $p \leq 0.001$, one-tailed paired t-test

Table 2. Means and standard deviations for confidence and imagery vividness scales in the pre-test and post-test.

Scale	Pre-test M	Pre-test SD	Post-test M	Post-test SD
Confidence (N = 30)	3.5	1.3	4.8*	0.7
Imagery Vividness (N = 42)	3.4	1.4	4.8*	0.9

* $p < 0.001$, Wilcoxon matched-pairs signed-ranks test

A longitudinal study of student reflections on VisChem animations

A study with third-year university chemistry students (N = 30) provided evidence that these benefits appeared to persist throughout a chemistry degree. These students demonstrated long-term recall of *VisChem* animations, and some felt that exposure to these resources helped them with various concepts, topics and subjects throughout their degrees. Other benefits identified by these students are outlined in Table 3.

Table 3. Possible benefits of instruction with *VisChem* animations.

Benefit (No. of Students)	Quote
Visualisation (14)	*"….. helped in developing visual images"*
Movement and interactions (13)	*"They helped me visualise interactions of different molecules."* *"It is a constantly moving environment."*
Understanding (10)	*"…. increased my ability to understand concepts."*
Made learning easier (8)	*"…. visualising made chemistry easier."*
Interpretation of laboratory-level phenomena (8)	*"You can imagine the molecules, atoms, structures, on a molecular level instead of just a macro level."*
Aroused interest/curiosity (6)	*"….. increased interest in chemistry."*
Improved thinking in 3D (4)	*"Animations helped me think in a 3-dimensional way with all molecules."*
Good foundation for future learning (4)	*"Understanding of first-year chemistry ideas and concepts made a good foundation for years that followed."*
Application to new situations (2)	*"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."*

These students also revealed some of the possible limitations of *VisChem* animations. For example, two students said that because

"The visual communication (animations) was not supplemented in further years …." they were not as beneficial as they could have been.

Overall, our results indicated that *VisChem* animations can encourage and aid students to develop mental pictures of the molecular level that are multi-particulate, dynamic, interactive and three-dimensional (Dalton, 2003).

Need for simulations to complement and supplement animations

In criticising the *VisChem* animations, one astute student indicated that they were misleading because they appeared to portray chemical reactions as mechanical and deterministic processes, lacking the element of randomness:

"This animation [portraying precipitation of AgCl] ... *shows water molecules ... sort of carrying this structure* [AgCl ion pair] *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 … Surely it must be possible to make it look less deliberate, less mechanical, maybe by showing ... the odd one or two going into the structure but not all of them."*

This student pointed out an important limitation of most chemistry animations. Technical constraints to reduce rendering times, and minimising file size to enable rapid delivery over the web, have resulted in animations that convey the clear perception of 'directed intent' in molecular-level processes, instead of a more scientifically-accurate, probabilistic model.

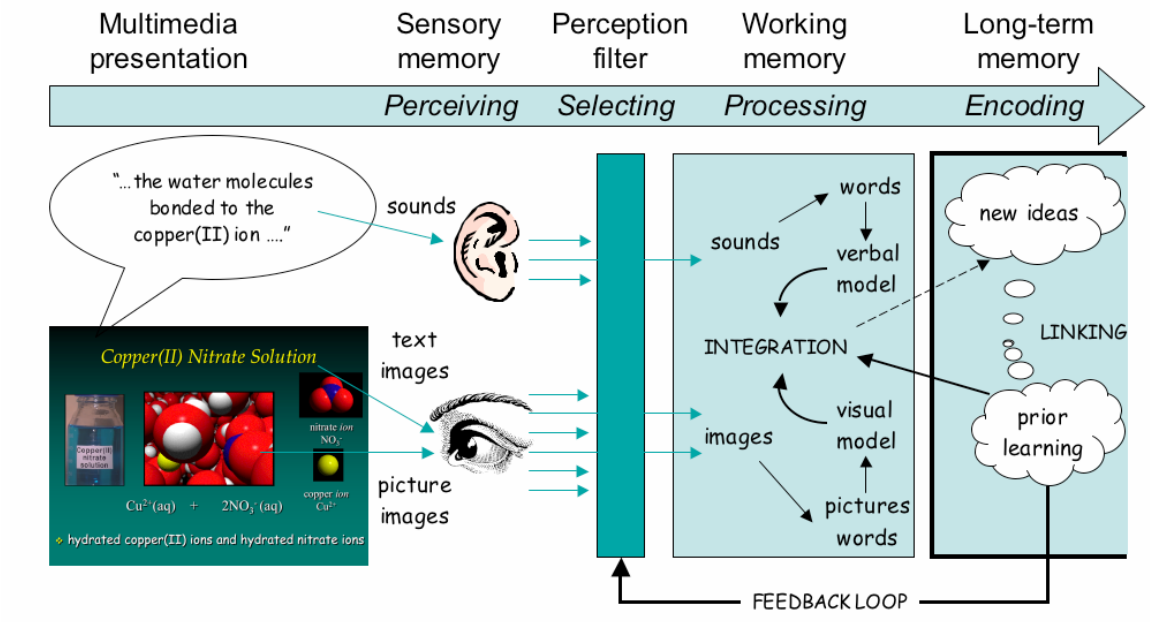
In contrast to choreographed animations, theory-driven simulations (e.g., *Odyssey* by Wavefunction, Inc.; see wavefun.com) offer a more accurate depiction of structures and processes at the molecular level. However, a limitation of simulations is that they often do not show key features of molecular events clearly because they occur rarely (sometimes taking years in the slowed-down timescale used), at random, and usually with intervening solvent molecules blocking the view! Clearly simulations and animations can complement one another.

Even with judicious use of animations and simulations, some students continue to retain poorly formed ideas and harbour misconceptions. We wanted to know how student attributes contributed to whether or not students were able to develop their mental models via the use of visualisation tools. In order to pose useful research questions we used an audiovisual information-processing model based on the wealth of research on how the brain attends to, processes, stores, and retrieves audiovisual information.

An audiovisual information-processing model

The model we used (Figure 9) is a composite of the established models developed by Johnstone (1986) and Mayer (1997), together with ideas from dual-coding theory (Paivio, 1990), and cognitive load theory (Sweller, 1988; 1994). Johnstone has used his model to inform all forms of chemistry teaching (e.g., Johnstone, 1994), and Mayer's model has been used successfully to derive instructional design principles for multimedia explanations (Moreno, 2000).

Figure 9. A multimedia information-processing model for learning from audiovisual information. This is a composite of theoretical models proposed by Mayer (1997) and Johnstone (1986).



The model describes learning in terms of an audiovisual information processing system that involves perceiving verbal and visual stimuli in separate parts of the sensory memory; selection through a filter; integration and processing of the verbal and visual information within a working space of limited capacity; and storage of this information in the long-term memory (LTM), for efficient retrieval and transfer to new situations.

Just as Johnstone's information-processing model has implications for good teaching practice, this embellished model has implications specifically for presentation of audiovisual information, and some of these have been supported with experimental data (Sweller 1994; Moreno 2000).

For example:

- students should be given manual control over the pace and content in animations (e.g., by dragging the Play bar back and forth, and pausing where appropriate, rather than just clicking on the Play button. This reduces the rate of information load presented, and provides time for cause-and-effect reflection
- verbal and visual information should co*mplement* one another, not *supplement* one another, as this risks overloading the working memory space
- text should be presented within graphics rather than separately as captions, and animations presented with simultaneous, rather than separate narration

A significant result from this research is that the working memory capacity can be expanded slightly by mixing the senses used to present information. That is, it is easier to process information when some is presented visually, and the remainder is presented auditorily, than it is when all the information is presented through a single sense – either all visually or all auditorily (Sweller, 1994). This provides a strong argument for the use of narration in animations, rather than using text captions. The latter practice is often done to minimise the animation file size for web delivery, but there is a cost in effectiveness for learning.

This model, with all its implications for teaching practice with animations, provided us with the basis to identify factors that should influence learning with animations.

Research to identify student attributes influencing effectiveness of VisChem animations

A preliminary study was conducted to examine the student attributes affecting the development of students' mental models when *VisChem* animations were used. Factors to examine were selected on the basis of the different stages in the audiovisual information-processing model (Figure 9).

Ability to perceive details in visual displays (disembedding ability) was measured using the *Group Embedded Figures Test* (Witkin, 1971). Visuospatial working memory capacity was measured using the *Figural Intersection Test* (Pascual-Leone, 1969; Johnson, 1982). Relevant prior knowledge held in LTM that might influence perception, was identified using a pre-test. An idea of the extent to which students attempted to relate new information to old, and structure information in LTM, was determined using a modified version of the *Study Processes Questionnaire* (SPQ; Prosser, 2000). This version includes surface and deep factors, but not the achieving factor from the original SPQ. The ability to retrieve key features of molecular structures and processes from LTM was measured using a post-test (equivalent to the pre-test).

Interpretation of the results of a multiple regression analysis (N = 22) suggested that prior knowledge, disembedding ability and deep and surface learning had a significant effect on the development (gain from pre-test to post-test) and the sophistication (post-test score) of students' mental models (Table 4 and Table 5). Note that prior knowledge 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.

In addition, visuospatial working-memory capacity was shown to correlate significantly with post-knowledge ($r = 0.59$, $p = 0.05$, $N = 13$). A follow-up study, replicating aspects of the original study, confirmed the role of prior knowledge, and to a lesser extent disembedding ability, in the sophistication and development of students' mental models. The other factors (surface and deep learning styles) were not examined in the second study.

Table 4. Correlation between pre-/post-test gain and student attributes.

Independent Variable: Pre-/Post-Test Gain (N = 22)			
Variable	Standardised coefficient (β)	Significance (p)	Adjusted R^2
Prior knowledge	-0.64	< 0.005	0.45
Disembedding ability	0.64*	< 0.005	
Surface learning	-0.74	< 0.05	
Deep learning	0.93	< 0.005	

* Disembedding ability data were transformed (reflect and $\log_{10}$) to approach normality. Reflecting the scores reverses their order; hence the sign of ß has been changed to reflect the true directionality of the relationship between the variables.

Table 5. Correlation between post-test score and student attributes.

Independent Variable: Post-test (N = 22)			
Variable	Standardised coefficient (ß)	Significance (p)	Adjusted R^2
Prior knowledge	0.58	< 0.0001	0.76
Disembedding ability	0.43*	< 0.005	
Surface learning	– 0.49	< 0.05	
Deep learning	0.62	< 0.005	

* Disembedding ability data were transformed (reflect and $\log_{10}$) to approach normality. Reflecting the scores reverses their order; hence the sign of ß has been changed to reflect the true directionality of the relationship between the variables.

In 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 learning 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 not surface learning strategies.

In terms of the audiovisual information-processing model, we propose the following interpretation of our results:

- animations encourage a student with low prior knowledge to develop new ideas in LTM to create their mental models
- high prior knowledge in the LTM allows a student to *perceive* subtle but relevant features in an animation enabling development of more sophisticated mental models
- high prior knowledge also enables comparison of an image created in working memory from viewing an animation, with an existing mental model in LTM, leading to confirmation or modification of the existing mental model
- high disembedding ability allows a student to perceive the desired key features in a ‘busy’ animation
- high working-memory capacity ensures a student is able to manage the information from complex animations effectively, and construct and manipulate mental models of the phenomena
- adoption of deep-learning strategies and not surface learning approaches enables a student to relate ‘key features’ in animations to models in the LTM for deep understanding.

Unfortunately the sample size for this study was too small to extract convincing statistical significance (N = 22 for multiple regression, N = 13 for visuospatial working memory capacity correlation), and for this reason the results cannot be generalized. However, the fact that these factors have been reported in the literature as having an influence on other aspects of student learning adds weight to our findings. In general, our results support the value of the audiovisual information-processing model for predicting factors influencing student learning, and the importance of considering each aspect of the model when constructing learning designs.

This research implies that:

- prior knowledge should be revealed so that animations can be presented at a level appropriate to build on this knowledge
- key features in animations must be highlighted in some manner to ensure that students are able to extract the visual information
- students should be encouraged to adopt a deep approach to learning in order to make sense of the features in animations

- animations should be designed and presented so as to minimise extraneous cognitive load.

These recommendations were implemented within commercial constraints in a series of interactive multimedia projects associated with various chemistry textbooks that used the *VisChem* animations (Tasker 1999, 2001, 2002a, 2003, 2004).

Research into teaching practice: the *VisChem* Learning Design

In the growing field of interactive multimedia, a 'learning design' is a research-based sequence of 'learning activities', each involving one or more 'learning objects'. Learning objects are digital assets (e.g., an animation, photograph) in a context (provided by a narration, caption), designed usually with interactivity. The audiovisual information-processing model, with its implications for good practice, and Johnstone's three 'thinking-level' model, informed the development of the constructivist *VisChem Learning Design* (Tasker, 2002b). The design is described below, and then illustrated with an example. More details can be found on the web site for the design (Tasker, 2002b). This is one of a collection of exemplary ICT-based learning designs selected by a panel of Australian university educators to facilitate the uptake of innovative teaching and learning approaches in Australian universities (Harper, 2001).

The *VisChem Learning Design* can be used for any chemistry topic that requires a scientifically acceptable mental model of the molecular world. A typical learning experience in a face-to-face lecture context would involve students:

- *observing* a chemical phenomenon (chemical reaction or property of a substance) as a lecture demonstration, lab activity, or audiovisual presentation; and *documenting* their observations in words and/or diagrams
- *describing* in words, and *drawing* a representation of what is occurring at the molecular level to account for the observations; with the lecturer explaining the need for drawing conventions (eg. to indicate relative size, movement, number, and crowding of molecules)
- *discussing* their representation with a peer, with the aid of the lecturer's advice to focus on the key features of the representation that explain the observations
- *viewing* an animation portraying the phenomenon at the molecular level, first without, then with narration by the lecturer, and looking for key features that might explain the observations
- *reflecting* with the peer on any similarities and discrepancies between their own representations and the animation, and then discussing these with the lecturer
- *relating* the molecular-level perspective to the symbolic (eg. equations, formulas) and mathematical language used to represent the phenomenon
- *adapting* their mental model to explain a similar phenomenon with an analogous substance or reaction

The key criteria for the success of this design to promote visualisation as a learning strategy are the:

- constructivist approach that encourages the student to articulate prior understanding, and focus attention on key features of the prior mental model at the molecular level, *before* seeing the animations
- opportunity to discuss ideas and difficulties with peers
- practice and application of the visualisation skills developed, with the explicit expectation that these skills are valued and would be assessed

The learning outcomes are to assist students to:

- construct scientifically acceptable mental models of substances and reactions at the molecular level
- relate these models to the laboratory and symbolic levels in chemistry
- apply their models to new substances and reactions
- use their models to understand new chemistry concepts that require a molecular-level perspective
- address common misconceptions identified in the research literature
- improve their confidence in explaining phenomena at the molecular level
- enhance their *enjoyment of chemistry by empowering them to use their imagination to explain phenomena*, instead of just rote-learning terms and concepts, and solving problems algorithmically.

An example of the VisChem Learning Design: visualisation of an aqueous ionic solution

The learning design is an attempt to make each stage of the audiovisual information-processing model—perceiving, selecting, processing and encoding—as efficient as possible. In the following example, we will assume that students have had previous experience with visualising simple substances—ionic compounds and water—using *VisChem* animations, and are familiar with graphic conventions for representing molecules and ions.

One important learning outcome of this example is for the student to visualise an ionic solution in terms of moving *hydrated* ions that occasionally form transient ion pairs. The most common misconceptions are that the ions do not interact with the solvent and, more seriously, are clustered together in their 'ionic formula units'. These misconceptions pose significant problems for students understanding solution stoichiometry (e.g., in a solution of 0.1M Na_2SO_4 the $[Na^+]$ is 0.2M) and other related concepts such as colligative properties.

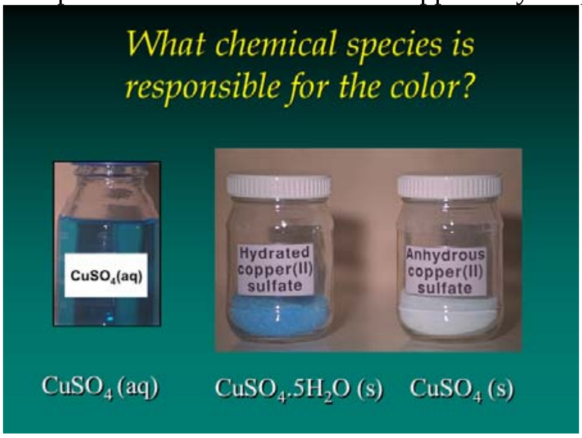
The learning design starts with a simple, but interesting observation.

Step 1. Observing a phenomenon

In the first step of the design students write observations for a laboratory-level chemical phenomenon such as a physical property of a substance (e.g. a metal conducts electricity), or a reaction between substances (e.g. precipitation of an ionic compound). One can present this phenomenon as a live demonstration, or with video, but one must ensure that *all relevant observations* are contributed by students.

Ideally, the phenomenon should be unusual, or counter-intuitive. For example, solid hydrated copper(II) sulfate and aqueous copper(II) sulfate solution are both light blue, but solid anhydrous copper(II) sulfate is white (Figure 10). The question is – what is/are the chemical species responsible for the blue colour?

Figure 10: An example of an observation with an apparently simple explanation.



At this point the instructor should allow students to think about and discuss this observation before rushing in with an explanation. An immediate, but incorrect suggestion might be that, since all bottles contain copper(II) ions and sulfate ions, and only the bottles containing water are blue, perhaps water alone is responsible for the blue colour. A moment's thought tells the student that this volume of pure water is colourless, so the answer must be more interesting!

The aim of this step in the design is to capture attention with an engaging context, and to generate a 'need to know'. In terms of the audiovisual information-processing model, the attention centres in the brain are being activated to select relevant aspects of visual and verbal information from the eyes and ears.

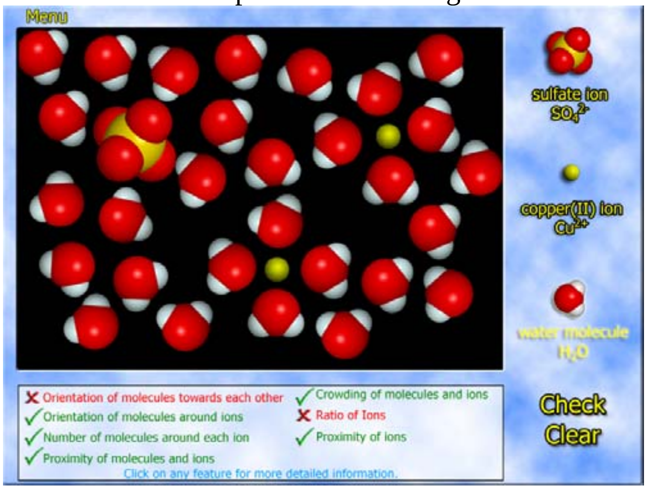
Step 2. Describing and drawing a molecular-level representation

In this step students attempt to explain their observations by drawing *labelled molecular-level representations* of the substance or reaction, and also describe their ideas in words. One needs to develop the 'drawing literacy' of the students by discussing conventions (e.g., representing relative sizes of atoms and ions, using space-filling or ball & stick models), and point out that they will have to do such drawings as part of formal assessment. This is a signal that communicating the details of one's model of the molecular level is a skill worth developing.

At this point ask the students to represent their mental models of the chemical samples in all three bottles to their peers. This should be done in *both* words *and* diagrams to cater for students with a preference for expressing their ideas verbally or visually. With respect to the blue colour, perhaps there is an interaction between the ions and the water molecules in the blue solid and solution?

An alternative to drawing a representation of copper(II) sulfate solution is to use the *Molecular Construction Tool* (a free, downloadable program from the *VisChem Learning Design* web site – Tasker, 2002). The advantage of the tool is the progressive feedback available on the student's representation at any stage of the construction process (Figure 11).

Figure 11. A sample screen from the *VisChem Molecular-Level Construction Tool* (Tasker, 2002) showing feedback on seven key features. In this student's construction the feedback generated shows the ion ratio is incorrect, and too many water molecules are oriented incorrectly for optimum H-bonding.



In terms of the audiovisual information-processing model, the aim of this step in the design is to recall prior knowledge to prime the students' perception filters to focus on the key features of their own mental models.

Step 3. Discussing with peers

Following the advice to students to identify *key features* that explain the observations, they should receive initial feedback on their representations by discussion with peers (or from the *Molecular Construction Tool*). One should not identify correct or incorrect key features at this stage.

The feedback in the Tool is not designed to replace this discussion, but to focus attention on the seven key features of the representations that relate to crowding, proximity of molecules and ions, and ion hydration. At this point student attention will have hopefully been drawn to the key features, now priming the perception filter for selecting relevant verbal and visual information from the molecular-level animations that follow.

Step 4. Viewing animations and simulations

Animations and simulations can depict the dynamic molecular world more effectively than static pictures and words because students are spared the cognitive load of having to 'mentally animate' the content. However, animations are *only effective if they are presented in a way that takes account of the limitations and processing constraints of the working memory*.

In this example, two animations depicting copper(II) nitrate solution would be presented. One animation shows all the water molecules and hydrated Cu^{2+} and NO_3^- ions (Figure 12), the other shows only the hydrated ions (Figure 13). Both animations are 'busy' and, without prior experience with similar animations, the cognitive load on the working memory would be too high. However, since student attention should be focused at this point on searching for something new, they should *perceive* the hydration around the ions.

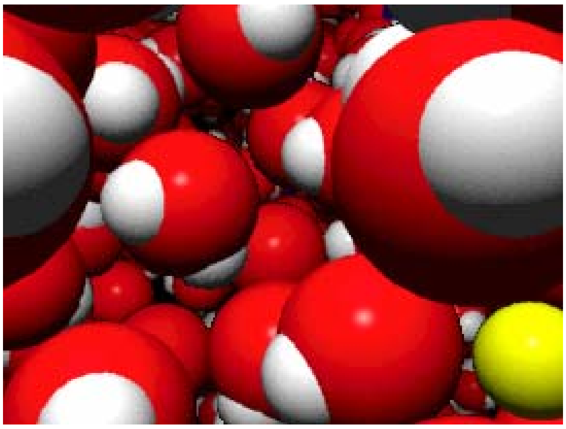


Figure 12. Frame from the *VisChem* animation portraying the hydrated ions in copper(II) nitrate solution.

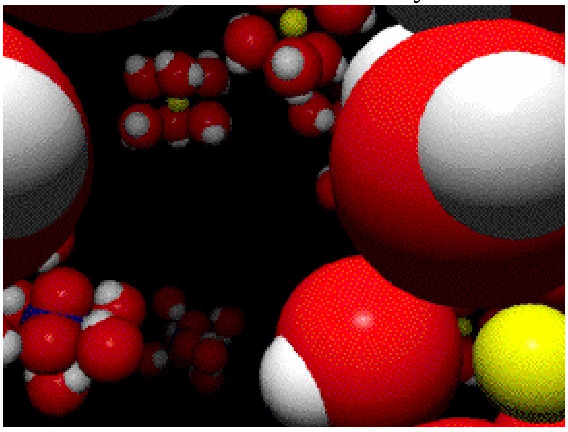


Figure 13. Frame from another *VisChem* animation portraying the hydrated ions in copper(II) nitrate solution, with the solvent water molecules removed for clarity.

Time permitting; each animation should be presented three times:

- First, without commentary, with students encouraged to look for key features they had, or did not have in their own representations.
- Second, in animation stages ('chunks' to reduce the load on working memory), each with narration by the lecturer drawing attention to the important key features, and with responses to any questions from students.
- Third, in its entirety again, with repeated, simultaneous narration.

Step 5. Reflecting on any differences with prior conceptions

In this step students reflect on differences between key features in the animations and in their own representations; *amending their drawings accordingly, if necessary.* Student drawings and descriptions of their conceptions of structures and processes at the molecular level often reveal misconceptions not detectable in conventional equation-writing questions. This activity in the learning design provides the opportunity for students to identify these misconceptions in their own representations, or those of their peers. *Experience shows this is more effective than having the lecturer simply listing common misconceptions.*

Step 6. Relating to other thinking levels

In this step one should encourage student discussion to link the key features of the molecular-level animations to the other two thinking levels. In this example, the following questions would be useful:

Laboratory Level

- Can you see a relationship between the blue colour and hydration of the copper(II) ions? If so, are the copper(II) ions bonded to water molecules in solid hydrated copper(II) sulfate?
- Symbolic Level
- Calculate the ratio of (Cu^{2+} ions : NO_3^{-} ions : H_2O molecules) in a 1 M copper(II) nitrate solution. This enables students to visualise the term 'concentration' in terms of 'crowding', and to give some meaning to '1 M' compared to the concentration of pure water (1000 g/L = 55.6 M). The answer is 1 : 2 : 56.
- How many water molecules, on average, are there between the ions in a 1 M copper(II) nitrate solution? This requires students to think of about 56 water molecules in a cube including one hydrated Cu^{2+} ion and two hydrated NO_3^{-} ions. The answer is about two or three water molecules.

In terms of the audiovisual information-processing model, we are trying to link their new insight from the animations to their prior knowledge.

Step 7. Adapting to new situations

In order to extend the links within the LTM, students are asked to draw a molecular-level representation for an analogous substance or reaction shown at the laboratory level. This establishes whether the students can transfer their ideas to a new example.

We have found that if visualisation is to be taken seriously by students as a learning strategy, it is essential that they are encouraged to practise their new skills with new situations, and assess their visualisation skills in one's formal assessment. In addition to questions that probe qualitative and quantitative understanding of concepts at the symbolic level, we need to design questions that require students to articulate their mental models of molecular-level structures and processes.

One reason student misconceptions at the molecular level are not detected at college level is that questions rarely probe this level of understanding explicitly. A good example of how one can probe deep understanding of difficult chemistry concepts by thinking at the molecular level is illustrated in Figure 14. This question probes whether the student has a molecular-level perspective of the difference between acid strength, acid concentration, and acidity (indicated by pH), in contrast to an algorithmically rehearsed expression in terms of mathematical functions.

Conclusion

The need for a chemistry student to move seamlessly between Johnstone's three 'thinking-levels' is a challenge, particularly for the novice. Our work in the *VisChem* project indicates that animations and simulations can communicate many key features about the molecular level effectively, and these ideas can link the laboratory level to the symbolic level. However, we have also shown that new misconceptions can be generated.

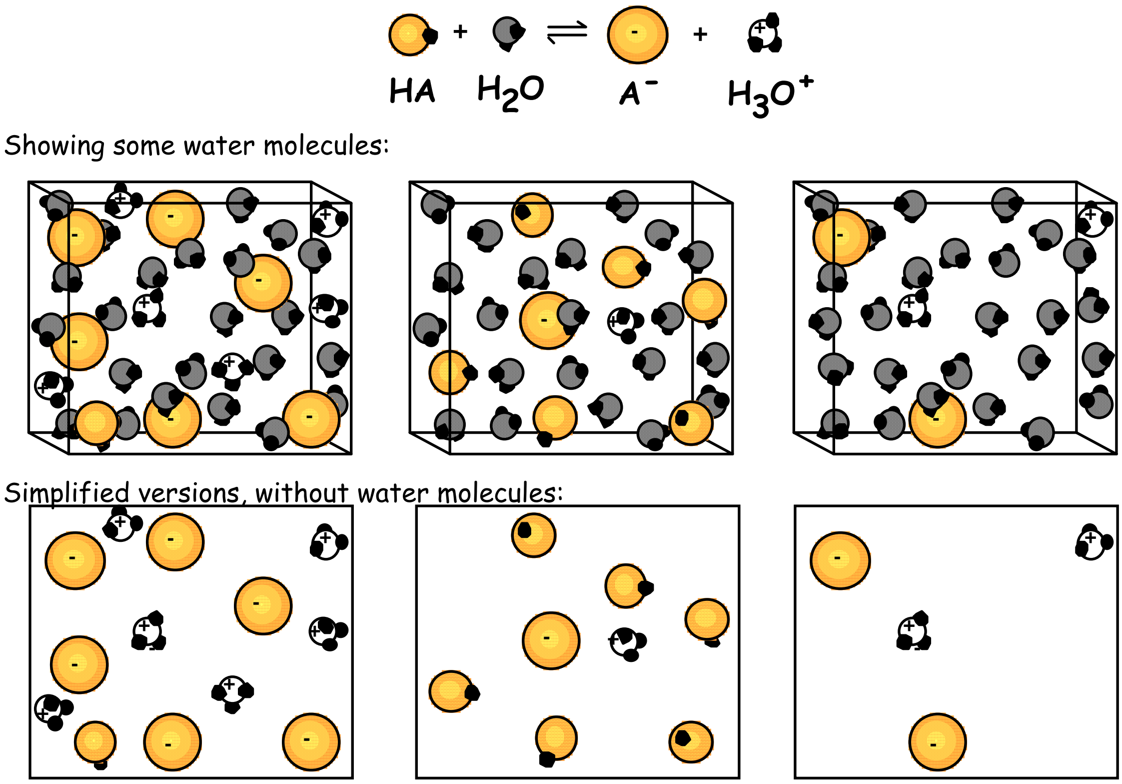
To use animations effectively, we need to direct our students' attention to their key features, avoid overloading working memory, and promote meaningful integration with prior knowledge. We can do this by using constructivist learning designs that exploit our knowledge of how students learn. The audiovisual information-processing model in this paper, based on the work of Mayer and Johnstone, can guide us in developing effective learning designs for this purpose.

'Scarring' misconceptions are those that inhibit further conceptual growth. To identify these misconceptions we need a strategic approach to assist our students to visualise the molecular level, and assess their deep understanding of structures and processes at this level.

Figure 14. A question to probe whether a student understands the difference between acid strength, acid concentration, and acidity at the molecular level.

Compare the diagrams (**X**, **Y**, and **Z**) below and match each diagram to an acid solution (**A**, **B**, or **C**) described in the following table. *Explain your reasoning*.

Solution	Acid	Concentration	K_a
A	trichloroacetic acid, CCl_3COOH	0.010 M	3.0×10^{-1}
B	chlorous acid, $HClO_2$	0.035 M	1.0×10^{-2}
C	benzoic acid, C_6H_5COOH	0.035 M	6.5×10^{-5}



X Y Z

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