SCIENTIFIC VISUALISATIONS

FOR DEVELOPING STUDENTS' UNDERSTANDING OF CONCEPTS IN CHEMISTRY

Some findings and some lessons learned

By David Geelan, Peter Mahaffy and Michelle Mukherjee

Scientific visualisations such as computer-based animations and simulations are increasingly a feature of high school Science instruction. Visualisations are adopted enthusiastically by teachers and embraced by students, and there is good evidence that they are popular and well received. There is limited evidence, however, of how effective they are in enabling students to learn key scientific concepts. This paper reports the results of a quantitative study conducted in Australian Chemistry classrooms. The visualisations chosen were from free online sources, intended to model the ways in which classroom teachers use visualisations, but were found to have serious flaws for conceptual learning. There were also challenges in the degree of interactivity available to students using the visualisations. Within these limitations, no significant difference was found for teaching with and without these visualisations. Further study using better-designed visualisations and with explicit attention to the pedagogy surrounding the visualisations will be required to gather high quality evidence of the effectiveness of visualisations for conceptual development.

INTRODUCTION

'Scientific visualisations'—computer-based animations and simulations of scientific processes, interactions and even concepts—are increasingly used in high school Science education. There is a developing body of research into their use (e.g. Frailich, Kesner & Hoffstein, 2009; Geelan, Mukherjee & Martin, 2012; Lee et al., 2010). Many papers focus on students' enjoyment of learning with visualisations (e.g. Annetta et al., 2009; Cifuentes & Hsieh, 2001; Delgado & Krajcik, 2010), while there is less research evidence demonstrating their effectiveness for conceptual learning.

Evidence suggests that high school students in Australia are 'turned off' by learning science (Fensham, 2006) and this finding is consistent across most developed Western democracies (Sjoberg & Schreiner, 2005). Approaches that enhance students' enjoyment and engagement offer considerable potential, however these things are necessary but not sufficient to warrant the classroom use of any new technology or teaching strategy. It is also important to base decisions on whether and how to use new technologies and strategies on the best available evidence for the educational *effectiveness* of the approaches being introduced.

THEORETICAL FRAMEWORK

Theoretical perspectives on the use of visualisations in Science education tend to focus on the links between cognitive theory, constructivism, mental models and the nature of the relevant scientific disciplines. Buffler, Lubben, Ibrahim and Pillay (2008) reviewed the literature and developed a model-based approach to visualisation in Science education. Their focus is on physics, however most of the features they identify also map to chemistry, with the addition of the notion of the three levels—molecular, symbolic and macroscopic—of representation in chemistry (Gilbert & Treagust, 2009).

Drawing on work from Gobert and Buckley (2000) and Greca and Moreira (2000), Buffler et al. (2008) address the issue of the development of mental models of scientific concepts and phenomena on the part of students. Gobert (2005) has applied her own earlier work on 'model-based teaching and learning' to the issue of visualisations. The notion that rich, detailed, interactive, computer-based visualisations might offer additional resources to allow students to develop rich mental models seems plausible, however research to explore this possibility is in its infancy. Due to the difficulty of accessing students' mental models, the present project does not claim to address this issue, and restricts itself to the more modest project of addressing students' conceptual development (discussed below).

Buffler et al. (2008) extend the work of Johnson-Laird (1983), who suggested that there are three kinds of mental constructs: images, mental models and propositional representations. "Mental models are functional representations of the real world which are constructed by individuals through perception, analogies or by acts of imagination." (Buffler, et al., p. 3). Johnson-Laird suggests that it is the dynamic interplay between these three classes of mental constructs that enables learning, and in particular that mental models allow students to work in the space between mental images and propositional representations. Since students are typically tested on their propositional knowledge of Science content, it can be argued that the external images and models presented by interactive, computer-based visualisations contribute to the dynamic processes by which students construct the mental models that in turn allow them to develop these propositional representations. This offers an explanation for why it might be expected that students would learn more effectively when using visualisations.

Posner, Strike, Hewson and Gertzog (1982) suggest that, by analogy with the social processes of paradigm shift in the scientific community at large described by Kuhn (1970), individuals learn new scientific schemes through a process of 'conceptual change'. This four-part scheme—dissatisfaction with a current conception, addressed by the development of a new conception that is intelligible, plausible and fruitful—forms the theoretical heart of conceptual change perspectives on learning (e.g. Smith, Blakeslee & Anderson, 1993).

It seems plausible to suggest that computer-based scientific visualisations might have the potential to support teachers and students in each of the four dimensions of the conceptual change process. Such visualisations can demonstrate the shortcomings of students' existing conceptual frameworks and help them to develop models of the new conception that are intelligible, plausible and promise to be fruitful. This is particularly important in light of students' development of molecular-level mental models as one key facet of the learning of chemistry.

This study, however, will not directly yield information about the mechanism(s) by which visualisations yield improved conceptual understanding (if indeed they do). The results will show only the extent of any differences (the 'what is happening') in students' conceptual development when learning with and without visualisations. A further qualitative study involving interviews with students, classroom observations and 'think aloud' protocols will be required to explore more deeply the specific learning mechanisms associated with visualisations.

An extensive body of literature has grown up in chemistry education around the conceptual change notion, focused on exploring the 'misconceptions' that students bring to class, and the processes of teaching and learning involved in changing students' conceptions of scientific phenomena from these 'misconceptions' to the 'correct' scientific concept. (It should be noted that, for a variety of reasons, some traditions within educational research prefer the terms 'naïve conceptions', 'alternat(iv)e conceptions', 'prior conceptions' or 'children's science' over the term 'misconceptions', but the latter has been the dominant term.)

The key concept, then, for this study, is the claim that the developed tests—partially drawn from the Chemical Concepts Inventory (Mulford & Robinson, 2002) but complemented with original items in the same style—are actually measuring students' conceptual understanding of the relevant concepts. The claim we are making is that it is plausible that the pretest/posttest design, and the tests used, do provide evidence of changes in students' conceptual understanding.

METHODS

Eleven Chemistry classes participated, at both public and private schools in Brisbane. Some of the classes were in private girls' schools while most were in coeducational schools. The private schools were relatively wealthy schools in the grammar school sector. The public schools were in relatively affluent suburbs in inner western Brisbane. Participating students would typically be considered 'middle class' in socioeconomic terms. Senior Chemistry classes in the participating schools were typically small, containing between 12 and 20 students.

The study was quantitative in approach and quasi-experimental in design. There are a number of difficulties with conducting experimental or quasi-experimental research in school classrooms, however we are committed to classroom-based evaluations because we believe it is essential that research in Science education serve the profession as directly as possible (Hirschkorn & Geelan, 2008). These difficulties include challenges with random assignment of students to experimental and control groups when they are already in established classes, and the almost insurmountable challenges of finding classes that are well enough matched to be compared with one another in an experimental design. The project used a modified crossover (Ratkowsky, Evans & Alldredge, 1993) design. Crossover designs help to meet these challenges by essentially making each class-and-teacher unit its own control group. This is done by having each class complete one teaching sequence with and one without the innovation—in this case the scientific visualisations. Results are then compared for the same group of students between the situation when they learned with scientific visualisations and when they did not.

A range of different technological contexts existed in the participating schools, from laptop programs in which each student worked directly on a laptop to situations in which the computers were in a computer laboratory that needed to be booked for the class. In most classes students interacted directly with the interactions on a computer, either individually or in groups of 2–3, but in some classes the teacher demonstrated the visualisation on a projection screen or interactive whiteboard. This significantly limits the conclusions that can be drawn—one would reasonably expect that a demonstration of a visualisation by an expert is a very different learning experience than hands-on interaction with that visualisation.

While evaluating the effectiveness of learning with scientific visualisations for all students is valuable, it is also plausible that a particular teaching approach might be more or less effective for particular students. Two additional characteristics of students were identified anonymously by the participating teachers for the research team: the gender of the students and their academic rank within the class—whether they were in the highest, middle or lowest third of the class in terms of academic achievement.

A total of 129 Year 11 Chemistry students participated in the study. They came from 11 different classes in seven different Brisbane-area public and private secondary schools. Each student completed one topic using scientific visualisations and one topic without. Pretest and posttest data are available for both topics, so most of the analyses below include a total of 258 data points.

The students were identified as male (28) or female (101). One school in the study, in which there were three large classes, was a private girls' school, which has further unbalanced these results—but it is typical for Queensland Chemistry classes to be about 1/3 male and 2/3 female. Teachers were asked to indicate whether participating students where in the highest (23), middle (72) or lowest (34) third of their class. The 'thirds' are not of equal size, but this may be because some students in the classes chose not to participate in the study or were absent on the day of one or more of the tests.

Under the crossover design of the study (Ratkowsky, Evans & Alldredge, 1993), students essentially serve as their own 'controls', since each student is represented in both the 'experimental' treatment group—learning with visualisations—and the 'control' group—learning without visualisations. The groups are therefore perfectly matched for academic ability, gender balance and other factors, because the same individuals are in each group. The students also completed both trials with the same classmates and the same teacher. Some students completed the visualisation trial first and the no-visualisation trial some months later, and others completed the trials in the reverse order, reducing the effects of maturation on the part of students.

Specific concepts that appear in the Queensland Year 11 Chemistry syllabuses were chosen for the study. Groups of students in a number of purposively chosen Brisbane-area public and private high schools were taught these concepts in their normal Science classes, and the conceptual knowledge tests used before and after each teaching sequence to measure students' conceptual development. One constraint on the study was that the Queensland senior Science syllabuses are very flexible, and do not prescribe the order in which topics will be taught across the two-year (Year 11 and 12) courses. That meant that in some schools specific topics were taught in Year 11 while in other schools they were taught in Year 12, and in other cases topics were taught very early or late in the school year. The crossover design of the study required two topics to be taught in each class, but in order to ensure that at least two of the selected topics were taught in Year 11, it was necessary to choose three topics in total, and to find visualisations and develop pre- and posttests for each of these topics.

The three concepts chosen were Le Chatelier's Principle (and dynamic chemical equilibria more broadly), Intermolecular Forces (and other interparticle forces) and Thermochemistry. These were linked to teaching sequences intended to take three to four lessons, or about one week of normal Year 11 Chemistry lessons. One or more web-based visualisations were chosen for each concept—links to the visualisations are included below. We chose to use existing resources that were available on the net. This may have led to less directly comparable visualisations in terms of approach and style, but we felt that it allowed us to model more closely what really happens in school classrooms.

While we are grateful to those who develop these free resources and make them available on the web, there are some significant issues and problems with some of them. Some of these are outlined on the next page.

As can be seen from these brief descriptions (and further understood through looking at the sites themselves), there were two problems for this study in terms of the available scientific

LE CHATELIER'S PRINCIPLE

http://www.mhhe.com/physsci/chemistry/essentialchemistry/flash/lechv17.swf

This visualisation is not an interactive simulation (Fan & Geelan, 2013), and is only minimally interactive. Interaction is by clicking to navigate the sections. The audio narration makes it difficult to use in a computer laboratory unless the students have headphones, and makes it difficult to use with small groups (2–3) instead of individual students or whole classes. It is also unclear how what is being graphed relates to initial conditions, conditions immediately after making a change and conditions once equilibrium has been reached. The audio narration slowed the changes sufficiently that students often clicked away before the change they were intended to see had occurred.

INTERMOLECULAR FORCES

http://www.kentchemistry.com/links/bonding/bondingflashes/bond_types.swf

This animation represents electrons in orbits (rather than orbitals), includes spelling mistakes and errors when naming chlorine and chloride, seems to suggest bonding is intentional (anthropomorphism) and doesn't distinguish the differences in strength and type between hydrogen 'bonds' and ionic/covalent bonds. The same issues with audio narration that were present for the previous visualisation also impact the effectiveness of this one.

http://faculty.washington.edu/dwoodman/IntrFrcs/dswmedia/IntrFrcsW.html

This one was working, and worked reasonably well (although still with audio narration) at the time of the study, but has since been abandoned and does not work properly any longer.

http://www.chm.davidson.edu/ronutt/che115/Phase/Phase.htm

This is much more of an interactive simulation that allows students to change settings and observe the results of the changes on the equilibrium position of the system. It allows students to conduct 'virtual experiments' with an independent and a dependent variable and controlled variables. Geelan and Fan (in press) have discussed the use of interactive simulations for teaching in some detail and outlined a pedagogical sequence.

THERMOCHEMISTRY

http://www.bravus.com/visual/bondenthalpy.mov

This is a non-interactive, movie-style visualisation. While it is helpful in facilitating students' developing understanding of bond enthalpy, the only form of interaction available is stopping or starting the video, or 'scrubbing' it forward and backward to observe the process. There are also issues with the colouring of the bonds formed that suggest the bonds 'belong' to one or other of the reaction species, potentially exacerbating misconceptions. The bonds are not shown as involving electrons.

http://schools.matter.org.uk/Content/Reactions/BondEnergy.html

This visualisation, while visually simple, is more interactive than many of the others used. It could perhaps have been enhanced by adding the ability to work with a variety of different elements and compounds other than HCl, however it does illustrate the energy implications of making and breaking bonds. (NB: This visualisation requires Java and will not work for all browsers.)

http://schools.matter.org.uk/Content/Reactions/BE_enthalpyHCl.html

This visualisation complements the one immediately above, and includes a variety of different species and calculations. It is intended to scaffold students' development of the concepts and skills required for thermodynamic calculations.

visualisations. The first is that some were simply not of acceptable quality—they had serious flaws that could leave unchallenged, or even reinforce, students' misconceptions. The second issue is that they are not especially comparable, either in their content—for example some are interactive simulations that require students to manipulate variables or complete calculations while others are passive 'movies' explaining concepts—or for the ways in which students interacted with them. These shortcomings mean the findings reported below are qualified, and there is space for more tightly controlled experimental research to develop stronger evidence in relation to the educational effectiveness of scientific visualisations in classrooms.

Conceptual development on the part of students was measured using conceptual knowledge tests based on the Chemistry Concept Inventory (CCI) (Mulford & Robinson, 2002). The tests were designed to distinguish the extent to which students developed the 'correct' scientific concept in relation to a topic, rather than any of a number of possible 'misconceptions'. Each topic test is made up of 12 multiple-choice items, with four possible answers for each, and the distracters focus on the common misconceptions as identified in the Chemistry Concept Inventory.

In a larger-scale, more-formal study it would have been appropriate to validate all the tests in their final form, but this was not feasible within the scope of the present project. This in turn means that the claims made on the basis of the tests are tentative and suggestive rather than definitive.

Here are a few sample test items:

Le Chatelier's Principle

Question 10 relates to the reversible reaction of iron (III) ions, Fe^{3+}, with thiocyanate ions, SCN^- to produce iron thiocyanate, $FeSCN^{2+}$, ions in accordance with the equation:

$$Fe^{3+}_{(aq)} \text{ (pale yellow)} + SCN^-_{(aq)} \text{ (colourless)} \rightarrow FeSCN^{2+}_{(aq)} \text{ (red)}$$

10. If colourless solid potassium thiocyanate, $KSCN_{(s)}$, is added to the solution, it will dissolve producing thiocyanate, $SCN^-_{(aq)}$, ions according to the reaction

$$KSCN_{(s)} \rightarrow K^+_{(aq)} + SCN^-_{(aq)}$$

As it comes to its new equilibrium the colour of the solution will:

a. become more red
b. become paler
c. stay the same
d. there is not enough information to tell

Intermolecular Forces

9. Although the water molecule has no overall electric charge (it is neutral), a stream of water will be attracted to a charged rod. This attraction is due to:

a. an induced dipole in the water molecule
b. the water molecules separating into charged H^+ and OH^- ions
c. the existing dipole (charge separation) between the O and H atoms in water molecules
d. electrons being removed from the water by the charged rod to create H_2O^+ ions

Thermochemistry

1. The reaction between octane and air is very exothermic, and yet an open container of octane can be left at room temperature for several days without catching fire (i.e. reacting) (although it will evaporate). This is because:

a. octane is naturally in a liquid state
b. energy must be supplied to start the reaction
c. there is not enough oxygen in the air to start the reaction
d. energy must be removed from the system to break the bonds in the octane before it can react

Data on student academic achievement and gender were also collected.

FINDINGS

Each student in the study completed one topic without using scientific visualisations and another with their use.

The three chosen topics were considered by the participating teachers to be of approximately equal conceptual difficulty. There were 99 students who completed the Thermochemistry topic, 111 who completed Equilibrium and 48 who completed Intermolecular forces (this is a total of 258, since each of the 129 students completed two topics). Table 1 shows the means and standard deviations of the gain (posttest minus pretest) scores for the three topics.

Table 1: Comparing difficulty of chemistry topics—gain scores.

TOPIC	MEAN (N=258)	SD
Thermochemistry	1.72 (n=99)	2.76
Equilibrium	2.04 (n=111)	2.79
Intermolecular Forces	1.60 (n=48)	2.08

A one-way ANOVA on these gain scores shows that the differences are not statistically significant ($F(257)=.594$, $p=.55$), suggesting that in fact the topics are not significantly different in terms of their difficulty for student learning.

The 'headline' analysis of this study—addressing questions about whether teaching with visualisations is more effective in helping students come to understand chemistry concepts—involves comparing students' achievement when taught with visualisations with their achievement when taught without visualisations. Table 2 shows the means for the students under the visualisation and no visualisation teaching conditions.

Table 2: Comparing visualisation and no visualisation—gain scores.

TREATMENT	MEAN (N=258)	SD
No Visualisation	1.74 (n=129)	2.67
Visualisation	1.92 (n=129)	2.65

It is almost unnecessary after looking at those results, but a two-tailed, independent-samples t-test shows no significant difference in the learning gains between the two treatments ($t(256)=-.538$, $p=.59$).

Overall, with all students combined, learning with visualisations does not seem to have yielded significantly better (or worse) learning gains in Chemistry than teachers' own explanations and teaching approaches. It is interesting, however, to look a little deeper into the data in terms of two additional dimensions studied: academic achievement and gender. Table 3 shows the mean gain scores for male and female students learning with and without visualisations.

TREATMENT	GENDER	GAIN	
		MEAN	SD
No visualisation (n=12av	Male (n=28)	1.75	2.08
	Female (n=101)	1.74	2.82
Visualisation (n=129)	Male (n=28)	2.54	2.27
	Female (n=101)	1.75	2.74

Table 3: Learning gains by gender and treatment.

By inspection the means for female students are almost identical. The means for male students appear to show higher gains for students using visualisations, but a t-test shows that the differences are not statistically significant ($t(54)=-1.35$, $p=.18$).

Table 4 shows the gain scores for students in the lowest, middle and highest achieving thirds of their classes, learning with and without visualisations.

Means for the lower and middle thirds are very similar across the treatments,

TREATMENT	LEVEL OF ACHIEVEMENT	GAIN	
		MEAN	SD
No visualisation (n=129)	Lowest (n=34)	1.24	2.13
	Middle (n=72)	1.89	2.91
	Highest (n=23)	2.04	2.60
Visualisation (n=129)	Lowest (n=34)	1.26	2.87
	Middle (n=72)	1.82	2.44
	Highest (n=23)	3.22	2.63

Table 4: Learning gains by academic achievement and treatment.

particularly given the size of the standard deviations. Results in the highest-achieving group appear to exhibit a larger difference, however a t-test shows that the difference is not statistically significant ($t(44)=-1.522$, $p=.14$).

CONCLUSIONS

There is considerable scope for further research in this area. This quantitative study was intended to answer particular questions about the overall effectiveness of scientific visualisations in Chemistry education that we felt had been slid across rather than really answered in research up to that point. The findings in this study are tentative, partly because of the relative small sample sizes and the nature of the concepts and visualisations used, partly because of the difficulty of standardising the learning experiences in real classrooms and partly because the tests used had not been validated, except informally by the participating teachers, who offered feedback on the 'fit' between items and the relevant concepts to be learned. The fact that the participating schools all came from suburban areas in eastern Australia is also relevant in terms of the extent to which the results can be generalised, although it could be argued that senior high school Chemistry classes and teaching are very similar in most developed Western nations.

Another issue is the extent to which conceptual learning that occurs using visualisations is assessed using visualisations. The question arises of the extent to which it is valid and appropriate to assess learning with visualisations using paper-and-pencil tests. Some of the test items included images, adding some visual element to the assessment process, but the argument could be made that the unique affordances of interactive visualisations may be better assessed using those some visualisations. (The counter argument, of course, is that students are most often examined using paper-and-pencil tests, and if evidence is sought of the educational effectiveness of visualisations this may be an appropriate mode.) Further study focused on this issue would be valuable.

Having completed and reported this project, it seems to us that the logical next step is to conduct a more qualitative or mixed-methods approach, on a similar scale, to look more closely at both the details of the particular visualisations used and, more particularly, the kinds of educational uses that students and teachers make of them. We plan to apply for further funding to work for extended periods alongside teachers and students in classrooms to better understand the meaning that students make of the representations that are inherent to scientific visualisations.

The results of this research project could be considered as negative findings, in the sense that for all of the questions asked, the answer is 'no significant difference'. Still, given that there is research that shows students enjoy learning with visualisations and that it enhances their engagement with Science learning (e.g. Annetta et al., 2009; Cifuentes & Hsieh, 2001), perhaps this is a useful finding after all. The Hippocratic oath commits doctors to 'first do no harm'. The results reported here show that (at least within the limitations of this study in these classrooms) teaching with visualisations may not do significant 'good' in terms of enhanced learning over the other ways in which Chemistry teachers teach the same concepts, but it also does no harm. The results are essentially the same from a learning perspective. Given that finding, and the research showing students gain positive effective and attitudinal benefits, teachers have the evidence to support their on-going use of scientific visualisations in teaching Chemistry.

Another issue is whether students engage with visualisations individually, in small groups, or as a whole class. Lou, Abrami and d'Apollonia (2001) conducted a meta-analysis and found that student learning gains were significantly higher when learning with computers in small groups rather than individually. In a future study there would be value in ensuring that resources were available such that all participating students used the visualisations in this way for greater comparability of the resultant learning.

The issues with the variable quality and different kinds of visualisations used, described in some detail in this paper, also weakened the findings reported here in terms of generalising them to particular kinds of visualisations. For future research there would be value in narrowing the focus from 'scientific visualisations' in general to 'interactive simulations' (Fan & Geelan, 2013) in particular. Developing these tools specifically for the study rather than using those available on the web would allow further tightening of the comparability of the visualisations used.

ACKNOWLEDGEMENTS

This research project was funded by Australian Research Council (ARC) Discovery grant DP0878589. The Kings Centre for Visualisation in Science is partly funded by the Canadian National Science and Engineering Research Council (NSERC).

REFERENCES

Annetta, L. A., Minogue, J., Holmes, S. Y. & Cheng, M-T. (2009). Investigating the impact of video games on high school students' engagement and learning about genetics. *Computers and Education, 53*(1), 74–85.

Buffler, A., Lubben, F., Ibrahim, B. & Pillay, S. (2008). A model-based framework for understanding the role of visualization in physics education. Paper presented at SAARMSTE 2008, Maseru.

Cifuentes, L. & Hsieh, Y-C. J. (2001). Computer graphics for student engagement in science learning. *TechTrends, 45*(15), 21–23.

Delgado, C. & Krajcik, J. (2010). Technology Supports for Science Learning. In P. Peterson, B. McGaw & E. Baker (Eds.), *International Encyclopedia of Education.* Atlanta, GA: Elsevier.

Fan, X. & Geelan, D. R. (2013). Enhancing Students' Scientific Literacy In Science Education Using Interactive Simulations: A Critical Literature Review. *Journal of Computers in Mathematics and Science Teaching, 32*(2), 125–171.

Fensham, P. J. (2006). Student interest in science: The problem, possible solutions, and constraints. Paper presented at the Research Conference of the Australian Council for Educational Research. [Online: (accessed 10 June 2010) http://forms.acer.edu.au/documents/RC2006_Fensham.pdf]

Frailich, M., Kesner, M. & Hoffstein, A. (2009). Enhancing students' understanding of the concept of chemical bonding by using activities provided on an interactive Website. *Journal of Research in Science Teaching, 46*(3), 289–310.

Geelan, D. R. & Fan, X. (in press). Teachers using interactive simulations to scaffold inquiry instruction in physical science education. In J. Gilbert and B. Eilam (Eds.) *Science Teachers' Use of Visual Representations.* Dordrecht: Springer.

Geelan, D., Mukherjee, M. & Martin, B. (2012). Developing key concepts in physics: is it more effective to teach using scientific visualisations? *Teaching Science, 58*(2), 33–36.

Gilbert, J. K. & Treagust, D. F. (2009). *Multiple Representations in Chemical Education.* Dordrecht: Springer.

Gobert, J. D. (2005). Leveraging technology and cognitive theory on visualization to promote students' science. In J.K. Gilbert (ed.), *Visualization in Science Education*, 73–90. Dordrecht: Springer.

Gobert, J. D. and Buckley, B. C. (2000). Introduction to model-based teaching and learning in science education. *International Journal of Science Education, 22,* 891–894.

Greca, I. M. and Moreira, M. A. (2000). Mental models, conceptual models, and modeling. *International Journal of Science Education, 22,* 1–11.

Hirschkorn, M. & Geelan, D. (2008). Bridging the research-practice gap: research translation and/or research transformation. *Alberta Journal of Educational Research, 54*(1): 1–13.

Johnson-Laird, P. (1983). *Mental Models.* Cambridge: Harvard University Press.

Kuhn, T.S. (1970). *The structure of scientific revolutions* (2nd ed.). Chicago: University of Chicago Press.

Lee, H-S., Linn, M. C., Varma, K. & Liu, O. L. (2010). How do technology-enhanced inquiry science units impact classroom learning? *Journal of Research in Science Teaching,* 47(1), 71–90.

Lou, Y., Abrami, P. C. & d'Apollonia, S. (2001). Small group and individual learning with technology: A meta-analysis. *Review of Educational Research, 71*(3), 449–521.

Mulford, D. R., & Robinson, W. R. (2002). An inventory for alternate conceptions among first-semester general chemistry students. *Journal of Chemical Education, 79*(6), 739–744.

Posner, G. J., Strike, K. A., Hewson, P. W. & Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education, 66*(2), 211–227.

Ratkowsky, D. A., Evans, M. A. & Alldredge, J. R. (1993). *Cross-over experiments: design, analysis and application.* New York: Marcel Dekker.

Sjoberg, S. & Schreiner, C. (2005). How do learners in different cultures relate to science and technology? Results and perspectives from the project ROSE. *Asia Pacific Forum on Science Learning and Teaching, 6*, 1–16.

Smith, E. L., Blakeslee, T. D. & Anderson, C. W. (1993). Teaching strategies associated with conceptual change learning in science. *Journal of Research in Science Teaching, 30*(2): 111–126.

David Geelan *is a senior lecturer in science education at Griffith University, Gold Coast. He has taught high school science in Victoria, NSW and WA and taught teachers in PNG, Canada and Australia.*

Michelle Mukherjee *is a lecturer in ICT education at Queensland University of Technology. She has studied remote sensing and ICT and been a trainer in industry.*

Peter Mahaffy *is Professor of Chemistry at the King's University College in Edmonton, Canada. He has research interests in both chemistry and chemistry education.*