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But does it work? Effectiveness of scientific visualisations in high school chemistry and physics instruction

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Abstract: 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 physics and chemistry classrooms. In general there was no statistically significant difference between teaching with and without visualisations, however there were intriguing differences around student sex and academic ability.

Introduction

Research into the classroom use of 'scientific visualisations' (Frailich, Kesner & Hoffstein, 2009; Lee et al., 2010; Wu, Krajcik & Soloway, 2001) is a developing field within science education. Visualisations can include diagrams and static images, but the term is more often used to denote computer-based, dynamic animations and simulations. While some of the more recent research studies focus on evaluations of the effectiveness of scientific visualisations for learning concepts, a number of studies relate more to students' self-reports of their enjoyment and engagement when using visualisations (e.g. Annetta et al., 2009; Cifuentes and Hsieh, 2001; Delgado & Krajcik, 2010).

Even more papers focus on what we have referred to elsewhere as 'technoboosterism' (Geelan & Mukherjee, 2010) – papers that report narratives of the form 'I developed this particular new computer-based scientific visualisation, I used it in my class, the students loved it!' without real evaluation of learning effectiveness or a critical focus on the costs and benefits of the approach. The situation is improving in terms of evidence of effectiveness, however Horwitz' comment (2002) still holds to some extent: "At the moment, most of our information on how to use simulations and visualisations in the classroom is based on anecdotal evidence". This paper reports an Australian study intended to contribute to remedying that situation.

The data indicating that students enjoy learning with scientific visualisations (Cifuentes & Hsieh, 2001) and experience enhanced engagement with their learning experiences (Annetta et al., 2009) are important: there is a considerable body of research suggesting that high school students in Australia are 'turned off' by learning science (Fensham, 2006) and this finding is stable across most developed Western democracies (Sjøberg & 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 make adoption decisions based on the best available evidence about the educational effectiveness of the approaches being introduced.

Particularly given that large numbers of teachers are already extensively using visualisations in their teaching – all of the teachers participating in this study regularly used visualisations in their teaching – it is important that science education researchers provide strong evidence in relation to questions about whether teaching with scientific visualisations is more or less effective than teaching without them. After all, if the evidence shows that, despite their effects on enjoyment and engagement, scientific visualisations are significantly less effective for learning than other teaching approaches, it would be much harder to make the case for their continuing use in classrooms.

The Studies

The overall study – incorporating separate studies of groups of physics and chemistry classes and some comparisons between those studies – was quantitative in approach and quasi-experimental in design. The project used a modified crossover (Ratkowsky, Evans & Alldredge, 1993) 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.

Crossover designs help to meet this challenge by essentially making each class-and-teacher unit into 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.

It would be ideal from an experimental perspective if the students could be taught the exact same content in each instance, but this is impossible both in terms of human learning – once something has been learned once, learning it again is a dramatically different experience – and due to the constraints of honoring teachers and students' time in class. For this reason different concepts – of comparable conceptual difficulty – were used, but under the crossover design some groups of students studied each concept using visualisations and some studied it without visualisations. Each possible combination of conditions and topics was therefore addressed.

Our original design for the study compared teaching with visualisations to 'traditional' teaching. This was **not** defined as simply lecturing or 'chalk-and-talk', but as whatever these particular teachers usually did in their classrooms. Teachers invited to participate had all been teaching chemistry or physics in Queensland for at least three years, so that their practices could be considered to be stable. In discussion with the teachers, however, it became clear that – to a much greater extent than we had anticipated – the teachers were already using scientific visualisations in their teaching. They felt – and we concurred – that a comparison between their 'traditional' practice, as it was now constituted, and teaching with visualisations would not present a sufficiently clear contrast for the research project: in some instances it would have involved visualisation vs visualisation comparisons.

For this reason, the decision was made to ask the teachers to teach without visualisations – but still using the other teaching tools at their disposal such as physical demonstrations of apparatus as well as lecturing, discussion, calculations on the board and so on – in the 'control' lessons, and to teach with visualisations in the 'experimental' lessons. While teachers were not given a detailed teaching 'script' for the visualisation sessions, they were given notes that suggested some possible teaching activities and approaches, in order to enhance consistency between participating classes.

From an ethical perspective, given that our collaborating teachers and we expected that learning with visualisations would offer learning advantages, we wanted to avoid depriving some students of those benefits for the purposes of the research. This was possible because the instructional sequences were quite short – typically a few lessons, conducted within one week. Once students had completed the posttest teachers were free to then have the students use the visualisations identified for that concept, and they frequently did this.

Another issue that had an impact on the study was the difficulty of gaining access to information technology in many schools. While many teachers were already using scientific visualisations in their teaching, they were doing it in the face of considerable constraints. Some of these were technological – few computers and old computers in schools. Many more related to policy – difficulty in booking computer labs for science classes when they were solidly booked for business classes, and filtering regimes that made it very difficult to access web-based resources such as those used in the study. Others combined the two – the filtering regime used in government schools in the area meant that all web traffic went through a central server, slowing access to a crawl. Some schools prohibited teachers adding or updating software such as Java and Flash – necessary for some computer-based visualisations – on computers in the schools. We ended up buying a class set of second-hand laptop computers and creating non-web versions of as many as possible of the visualisations so that we could offer computing resources to the participating classes, and this helped to some extent. Trying to conduct this study, however, has given us a deeper understanding of the challenges that teachers face in implementing these teaching approaches in the classroom – and a humble appreciation for the fact that they manage to do it anyway.

One consequence of this was that students accessed the visualisations in a variety of different ways. We had suggested to teachers that the ideal approach in most cases was 2-3 students to a computer, interacting with the visualisations and each other and recording results. In some schools the computer labs were arranged in such a way that it was much easier to have students work on one computer each. In others it was impossible to get a computer lab (and our laptops were not yet available) so the teacher displayed the visualisation on a data projector screen at the front of the classroom and the class worked through the activities as a whole. The groups were not large enough for us to be able to conduct quantitative analyses of the differences between these different modes of delivery. Stephens, Vasu and Clement (2010) studied the specific issue of differences between small-group and whole-class use of visualisations in physics learning, and found no significant differences between the situations. One future avenue for research will be to focus in a more naturalistic, qualitative way on the ways in which teachers and students work and learn with visualisations in their own particular contexts, given their own particular sets of interests and constraints.

While evaluating the effectiveness of learning with scientific visualisations for all students is valuable, it is also plausible that this 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 sex 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.

Physics Study

Students in six Year 11 physics classrooms (students aged 15-17) in four Brisbane-area high schools in Australia participated in the physics section of the overall study. There were six teachers and a total of 80 students involved. Two of the four schools were co-educational government schools and the other two were private girls' schools. There were 39 male and 41 female students in the sample. Teachers gave their informed consent to participate, and students and parents (the students were minors) also signed consent forms to participate after being informed about the research project.

The three topics chosen were Newton's First Law, Straight Line (Accelerated) Motion and Momentum. Examples of the kinds of visualisations include:

http://phet.colorado.edu/simulations/sims.php?sim=The_Ramp (for Newton's First Law – from the PhET group at the University of Colorado)

http://kcvs.ca/nonpublic/kinematics/motion1d/motion_1d.swf (for Straight Line Motion - from the King's Centre for Visualisation in Science)

http://qbx6.ltu.edu/s_schneider/physlets/main/momenta3c.shtml (for Momentum - from Lawrence Technological University

Typically the visualisations are not particularly complex or 'high tech', but involve students in actively manipulating variables and exploring the effect of these changes on the motions being demonstrated. The present study was quantitative in approach, and did not look closely at issues like the complexity and 'distraction value' of particular visualisations, only at their educational effectiveness.

There are a number of possible approaches to defining and measure the educational effectiveness of an innovation. For the purposes of this study, rather than using examination results or other scores, we chose to measure students' development of key concepts in physics, using tests based on the Force Concept Inventory (FCI)(Hestenes, Wells & Swackhamer, 1992). Where the concepts being learned related to forces, items from the FCI were used. For other concepts, similar items were constructed. For each of the three concepts studied, a 12-item test was developed and used as both pre- and post-test. Test items were multiple-choice questions in which the correct answer corresponded to the correct scientific conception and the distracters were common student misconceptions in relation to the tested concept.

Chemistry Study

A total of 129 Year 11 Chemistry students participated in the study. They came from 11 different classes in 7 different Brisbane area secondary schools, some public and some private. Each student completed one topic using scientific visualisations and one topic without. Pretest and Posttest data are available for both topics, so there is a total of 258 data points in most of the analyses below.

The students were identified in terms of whether they were 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, learning styles, 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.

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 Grade 11 chemistry lessons. One or more web-based visualisations were chosen for each concept – links to the visualisations are included below.

Le Chatelier's Principle

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

Intermolecular Forces

http://www.kentchemistry.com/links/bonding/bondingflashes/bond_types.swf
http://faculty.washington.edu/dwoodman/IntrFrcs/dswmedia/IntrFrcsW.html
http://www.chm.davidson.edu/ronutt/che115/Phase/Phase.htm

Thermochemistry
http://www.bravus.com/visual/bondenthalpy.mov
http://schools.matter.org.uk/Content/Reactions/BondEnergy.html
http://schools.matter.org.uk/Content/Reactions/BE_enthalpyHCl.html

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.

Conceptual development on the part of students was measured using conceptual knowledge tests based on the Chemistry Concept Inventory (CCI)(Mulford & Robinson, 2002), which owes a conceptual debt to the Force Concept Inventory (FCI)(Hestenes, Wells & Swackhamer, 1992). 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'. The two Inventories have been used extensively internationally and are well validated (Hestenes & Halloun, 1995; Kruse & Roehring, 2005). Each subject test comprises 12 multiple-choice items, with four possible answers, and the distractors focus on the common misconceptions as identified in the Chemistry Concept Inventory.

These two inventories have been used as models for the development of the conceptual tests used in the present study. Each test – the same tests are used as both pre- and post-test – contains 12 multiple-choice items, each with four possible responses; one scientifically correct response and three responses representing common student misconceptions in relation to the concepts taught. Here are a few sample 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:

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

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

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

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 sex were also collected in the chemistry facet of the study.

Findings

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

Physics Study

An initial comparison – and the 'headline' finding of this project – can be made between the learning gains (posttest minus pretest) for the students when learning the concepts with and without visualisations. Table 1 shows this comparison for the physics students. It is important to note throughout the reporting of the results that the 'visualisation' and 'no visualisation' groups are the same students on different testing occasions.

Treatment	Gain	
	Mean	SD
No visualisation (n=80)	.95	2.22
Visualisation (n=80)	1.53	2.38

Table 1 – Overall gains in physics study for No visualisation and Visualisation treatments

Scores are in marks out of 12. While the two means look quite different by inspection, the standard deviations are large, indicating a broad spread of knowledge gains. A two-tailed t-test shows that the difference is not statistically significant (t(158)=-1.58, p=.116). That is to say, neither teaching 'treatment' is significantly better than the other, when all participating students are considered together.

The next phase in the analysis looks at the data through the lens of the sex of participants. Table 2 lays out these results.

Treatment	Sex	Gain	
		Mean	SD
No visualisation (n=80)	Male (n=39)	1.00	2.52
	Female (n=41)	.91	1.90
Visualisation (n=80)	Male (n=39)	2.15	1.81
	Female (n=41)	.93	2.71

Table 2 – Gains in physics study for No visualisation and Visualisation treatments versus sex of student

All of the gains (out of 12 marks) look quite similar to one another except that for male students under the visualisation treatment. A t-test comparing male and female students within the visualisation group shows a difference significant at the .05 level (t(78)=2.37, p=.02). That is to say, male students benefited equally with female from the no-visualisation case but benefited significantly more than female students from learning with visualisations.

Statistical significance is only one measure of the effectiveness of a teaching innovation, however. Effect size measures such as Cohen's d give some sense of the magnitude of the learning gains achieved. A modified form of Cohen's d can be calculated by dividing the difference between the means of the two groups by the mean of the standard deviations of the groups. This gives as sense of 'by how many standard deviations' the innovation has improved learning. For the visualisation groups, for male students vs female students, this form of d is equal to 1.22/2.26 = 0.54. This is a medium effect size.

In terms of the degree to which students at differing levels of academic ability learned with and without visualisations, Table 3 summarises the learning gains (out of 12) for the three ranked groups. We asked teachers to state whether students were in the highest, middle or lowest third of their class in academic terms. The teachers did so, but perhaps reluctance to split groups of students with similar scores or other factors meant that the sample was not evenly divided into three groups.

Treatment	Sex	Gain	
		Mean	SD
No visualisation (n=80)	Lowest (n=15)	.67	2.35
	Middle (n=40)	.98	2.36
	Highest (n=25)	1.08	1.96
Visualisation (n=80)	Lowest (n=15)	2.07	2.76
	Middle (n=40)	1.27	2.26
	Highest (n=25)	1.60	2.36

Table 3 – Gains in physics study for No visualisation and Visualisation treatments versus academic achievement of student

A one-way ANOVA for the three groups learning with visualisations shows no significant difference between the mean gain scores in this group (F(79)=.615, p=.54). Similarly, for the no-visualisation group there is no significant difference (F(79)=.165, p=.85). That is to say, neither learning with or without visualisation yielded significant learning differences between the three ranked academic achievement groups.

Chemistry Study

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.

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

Table 4 – Comparing difficulty of chemistry topics – gain scores

A one-way ANOVA 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.

Treatment	Mean (n=258)	SD
No Visualisation	1.74 (n=129)	2.67
Visualisation	1.92 (n=129)	2.65

Table 5 – Comparing visualisation and no-visualisation in chemistry study – gain scores

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). This finding is consistent with earlier findings in this chemistry study (Geelan & Mukherjee, 2010).

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

		Mean Gain (SD)
Male (n=28)	No Visualisation	1.75 (2.08)
	Visualisation	2.54 (2.27)
Female (n=101)	No Visualisation	1.74 (2.82)
	Visualisation	1.75 (2.74)

Table 6 – Learning gains in chemistry study by sex and treatment

By inspection the means for female students are almost identical. The means for male students are different to look at, 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.

		Mean Gain (SD)
Lowest (n=34)	No Visualisation	1.24 (2.13)
	Visualisation	1.26 (2.87)
Middle (n=72)	No Visualisation	1.89 (2.91)
	Visualisation	1.82 (2.44)
Highest (n=23)	No Visualisation	2.04 (2.60)
	Visualisation	3.22 (2.63)

Table 7 – Learning gains in chemistry study by academic achievement and treatment

Means for the lower and middle thirds are very similar across the treatments, 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). It is possible to calculate effect size using a form of Cohen's d that divides the difference between the means by the mean of their standard deviations. This yields a score of 0.45, which is a medium-sized effect, however the small sample size (23 students) and lack of statistical significance means this result should be treated with caution. It is plausible that it is the most able students who can most effectively make use of multiple representations, but further research is required to explore this issue.

Combined Data

In terms of 'clean' (no missing data) cases from the combined studies there were 157 participating students (34 male, 123 female). 79 students' data appears from the physics study along with that of 78 students from the chemistry study (yielding closely balanced student numbers from the two subject areas. Since each student completes one topic with visualisations and one without, that yielded a total of 314 data points.

Table 8 shows the mean scores for all students across both subject areas when learning without and with visualisations.

Treatment	Gain	
	Mean	SD
No visualisation (n=157)	1.19	2.26
Visualisation (n=157)	1.58	2.39

Table 8 – Overall gains in combined study for No visualisation and Visualisation treatments

Note that the students being compared here are the same students, taught by the same teachers, being compared with themselves for the no-visualisation and visualisation situations. Given the size of the standard variations, it seems likely that these differences would not be statistically significant, and a t-test (t(512)=-1.48, p=.14) bears out this impression.

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 physics and chemistry education that we felt had been elided rather than really answered in research up to that point. Having done so, 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 classroom 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 almost all of the questions asked, the answer is 'no significant difference'. The answer to the overall question about the relative effectiveness of teaching with and without visualisations? No significant difference. The only result that showed a significant difference – and the effect size was only middling – was that male students seem to benefit more than female students from learning with visualisations. Equity issues around gender in physics education have a long history, and in the past typically female students tended to be disadvantaged in terms of physics achievement compared with their male colleagues. This difference has shrunk in recent years, however it seems that the educational use of scientific visualisations may have equity implications.

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 & Csieh, 2001), perhaps a non-finding is a useful finding after all. The Hippocratic oath commits doctors to 'first do no harm'. The results reported here show that teaching with visualisations does no significant 'good' in terms of enhanced learning over the other ways in which physics 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 affective and attitudinal benefits, teachers have the evidence to support their on-going use of scientific visualisations in teaching physics and chemistry.

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