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Developing key concepts in physics: Is it more effective to teach using scientific visualizations?

By David Geelan, Michelle Mukherjee and Brian Martin

A quantitative, quasi-experimental study of the effectiveness of computer-based scientific visualizations for concept learning on the part of Year 11 physics students (n=80) was conducted in six Queensland high school classrooms. Students' gender and academic ability were also considered as factors in relation to the effectiveness of teaching with visualizations. Learning with visualizations was found to be equally effective as learning without them for all students, with no statistically significant difference in outcomes being observed for the group as a whole or on the academic ability dimension. Male students were found to learn significantly better with visualizations than without, while no such effect was observed for female students. This may give rise to some concern for the equity issues raised by introducing visualizations. Given that other research shows that students enjoy learning with visualizations and that their engagement with learning is enhanced, the finding that the learning outcomes are the same as for teaching without visualizations supports teachers' use of visualizations.

INTRODUCTION

There is a growing body of research into the classroom use of 'scientific visualizations' (Frailich, Kesner & Hoffstein, 2009; Lee et al., 2010; Wu, Krajcik & Soloway, 2001). These include diagrams and static images, but the term is more typically 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 visualizations for learning concepts, a number of studies relate more to students' self-reports of their enjoyment and engagement when using visualizations (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 visualization, 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 visualizations in the classroom is based on anecdotal evidence." This paper reports part of an Australian study intended to contribute to remedying that situation.

The data indicating that students enjoy learning with scientific visualizations (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 are valuable, but being enjoyable is not enough. Given that large numbers of teachers are already extensively using visualizations in their teaching it is important that science education researchers provide strong evidence about their effectiveness for learning.

METHOD

Six Year 11 physics classrooms (students aged 15-17) in four Brisbane-area high schools participated in the study. There were six teachers and a total of eighty students in the study. Two of the four schools were co-educational government schools and the other two were private girls' schools. There were thirty-nine male and forty-one female students in the sample. Teachers gave their informed consent to participate, and students and parents (because the students were minors) also signed consent forms to participate after being informed about the research project. Schools, teachers and students are not identifiable within the reports of the study.

The study 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. Results are then compared for the same group of students between the situation when they learned with scientific visualizations 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 – when 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 visualizations and some studied it without visualizations. Each possible combination of conditions and topics was therefore addressed.

Our initial intention for the study was to work in collaboration with the participating teachers to identify two topics that were particularly conceptually difficult for students, to find or make (at the King's Centre for Visualization in Science in Edmonton, Canada) appropriate visualizations to address each of the two concepts, and then to conduct a simple two-way crossover design. There were two problems with this:
(1) the teachers were reluctant to choose or suggest topics, and preferred it if we identified the topics. It also became clear that the problem was a more difficult one, in that it was necessary to identify high quality visualizations that were readily available for a particular topic, and to develop the concept test for each.
(2) The Queensland physics syllabus is quite 'progressive' in nature, and allows considerable freedom for teachers to plan their own curricula, the order in which topics are taught and the approach they take to teaching particular topics. Some topics are taught in real world 'contexts' such as amusement park physics or the physics of household electricity. The physics course is taught over Years 11 and 12, and in some schools, particular topics were taught in Year 11 and in others in Year 12. It was necessary for the crossover design to use the same class for two topics (one with and one without visualizations). This meant that in order to ensure that there were at least two topics that were taught in Year 11 in each of the participating schools, it was necessary to identify, find or adapt visualizations for, and develop, tests for three topics.

The three topics chosen were Newton's First Law, Straight Line (Accelerated) Motion and Momentum. Examples of the kinds of visualizations 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 Visualization in Science)

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

Typically, the visualizations 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 visualizations, only at their educational effectiveness.

While the teachers in the study typically already used some visualizations in their teaching, for comparison purposes, we asked them to use none in the 'no-visualization' classes. While teachers were not given a detailed teaching 'script' for the visualization 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 we and our collaborating teachers and expected that learning with visualizations 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 post-test, teachers were free to then have the students use the visualizations 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 visualizations 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 visualizations – 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 visualizations 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 visualizations 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 visualizations 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 visualization 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 visualizations 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 visualizations in their own particular contexts, given their own particular sets of interests and constraints.

There are a number of possible approaches to defining and measuring 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.

This is a sample test item – an original item rather than one from the Force Concept Inventory – from the Newton's First Law test:

> 12. A boy throws a steel ball straight up. Consider the motion of the ball only after it has left the boy's hand but before it reaches the ground, and assume that forces exerted by the air are negligible.
>
> For these conditions the force(s) acting on the ball is (are):
>
> A. a downward force of gravity along with a steadily decreasing upward force
>
> B. a steadily decreasing upward force from the moment it leaves the boy's hand until it reaches its highest point; on the way down there is a steadily increasing downward force of gravity as the object gets closer to the earth
>
> C. an almost constant downward force of gravity along with an upward force that steadily decreases until the ball reaches its highest point; on the way down there is only the constant downward force of gravity
>
> D. an almost constant downward force of gravity only
>
> E. none of the above. The ball falls back to the ground because of its natural tendency to rest on the surface of the earth.

D represents the correct scientific conception in this instance. E represents a naïve conception of objects having a 'natural state' to which they seek to return. B and C capture students' confusion between force and velocity while A represents an Aristotelian 'impulse' view of force.

While evaluating the effectiveness of learning with scientific visualizations 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 gender of the students and their academic rank within the class.

RESULTS AND DISCUSSION

It is worth noting that the sample size overall for the study – eighty students – is really too small. There were a number of other schools included in the study, but for various reasons - lost data, teacher transfers and withdrawal from participation – those data were not complete and could not be concluded. For statistical significance, a much larger sample would have been ideal, and this means that we need to be modest in reporting these results – particularly for the results for gender and academic achievement, which divide the sample into even smaller groups. Larger samples may have yielded statistical significance for the findings: our results are suggestive rather than definitive.

Each student in the study completed one topic without using scientific visualizations and another with their use. An initial comparison – and the 'headline' finding of this project – can be made between the learning gains (post-test minus pre-test) for the students when learning the concepts with and without visualizations.

Table 1 shows the overall comparison of learning gains. It is important to note throughout the reporting of the results that the 'visualization' and 'no visualization' groups are the same students on different testing occasions.

TREATMENT	GAIN	
	Mean	SD
No visualization (n=80)	0.95	2.22
Visualization (n=80)	1.53	2.38

Table 1: Overall gains for No visualization and Visualization treatments.

Scores are in marks out of twelve. While the two means look quite different on 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=0.116).

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

TREATMENT	GENDER	GAIN	
		Mean	SD
No visualization (n=80)	Male (n=39)	1.00	2.52
	Female (n=41)	0.91	1.90
Visualization (n=80)	Male (n=39)	2.15	1.81
	Female (n=41)	0.93	2.71

Table 2: Gains for No visualization and Visualization treatments versus gender of student.

All of the gains (out of 12 marks) look quite similar to one another except that for male students under the visualization treatment. A t-test comparing male and female students within the visualization group shows a difference significant at the 0.05 level (t(78)=2.37, p=0.02). That is to say, male students benefited equally with female from the no-visualization case but benefited significantly more than female students from learning with visualizations.

However, statistical significance is only one measure of the effectiveness of a teaching innovation. Effect size measures such as Cohen's d, which gives a sense of 'by how many standard deviations' the innovation has improved learning, give some sense of the magnitude of the learning gains achieved. For the visualization groups, d= 1.22/2.26 = 0.54 for the boys' gains over the girls'. This is a medium effect size.

Table 3 summarises the learning gains (out of twelve) for the three ranked groups in terms of academic achievement. 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	GENDER	GAIN	
		Mean	SD
No visualization (n=80)	Lowest (n=15)	0.67	2.35
	Middle (n=40)	0.98	2.36
	Highest (n=25)	1.08	1.96
Visualization (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 for No visualization and Visualization treatments versus academic achievement of student.

A one-way ANOVA for the three groups learning with visualizations shows no significant difference between the mean gain scores in this group (F(79)=0.615, p=0.54). Similarly, for the no-visualization group there is no significant difference (F(79)=0.165, p=0.85). Neither learning with or without visualization yielded significant learning differences between the three ranked academic achievement groups.

CONCLUSION

This quantitative study was intended to answer particular questions about the overall effectiveness of scientific visualizations in physics education that we felt had not been really answered. The logical next research step is to conduct a more qualitative or mixed-methods approach, to look more closely at the details of the visualizations used and the educational uses that students and teachers make of them.

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 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 visualizations. It seems that the educational use of scientific visualizations may have equity implications.

Given that the results are essentially the same from a learning perspective, the research showing students gain positive affective and attitudinal benefits (e.g. Annetta et al., 2009; Cifuentes & Csieh, 2001), still means that physics teachers have the evidence to support their on-going use of scientific visualizations in teaching Physics. More research, however, is required to explore the most effective ways in which to use these new tools.

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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.

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. Elsevier: Atlanta, GA.

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., & Mukherjee, M. M., (2010). Measuring the effectiveness of computer-based scientific visualisations for conceptual development in Australian chemistry classrooms. Global Learn Asia Pacific 2010, Penang, Malaysia, May 17-20, 2010.

Hestenes, D., Wells, M., & Swackhamer, G., (1992). Force concept inventory. *The Physics Teacher* 30: 141-166.

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.

Horwitz, P., (2002). Simulations and Visualizations: Issues for REC. [Online: (accessed 24 Jan 2007) *http://prospectassoc.com/NSF/simvis.htm#3*]

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.

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

Sjøberg, 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.

Stephens, A.L., Vasu, I., & Clement, J.J., (2010). Small group vs. whole class use of interactive computer simulations. Comparative case studies of matched high school physics classes. Paper presented at the annual conference of the National Association for Research in Science Teaching, Philadelphia, March 21-24, 2010.

Wu, H-K., Krajcik, J. S., & Soloway, E. (2001). Promoting conceptual understanding of chemical representations: Students' use of a visualization tool in the classroom. *Journal of Research in Science Teaching*, 38(7), 821-842.

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