Visualization in Science Education

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There is general agreement in the educational community that visualization is an effective teaching tool. Current applications of visualization are found in many teaching contexts, including mathematics, reading, science and technology. In this article, we review key studies in science education that show that visualizations are effective to the extent that they meet relevant instructional goals and objectives and that students have the necessary background knowledge and skills to understand and interpret the information represented in them. We report select findings from a review of 65 empirical studies of visualization in science education, and address the following four questions:

- How is visualization defined and conceptualized?
- What theoretical perspectives inform the application of visualization in science?
- What is the research evidence on visualization in science education?
- What are some recommendations for the most effective development and use of visualizations in science?

Defining Visualization

There is a pervasive lack of clarity about precisely what constitutes visualization. Several terms related to visualization are found in the research literature: *visual representation, visual media, media literacy, visual communication skills, visual literacy, illustrations* and *media illustrations*.

The term *visualization* can be used to name a representation, to refer to the process of creating a graphical representation or as a synonym for *visual imagery.* Bishop (1989) explains that *visualization* can refer to the *what* of visualization (the product, object or visual image) or the *how* of visualizing (the process, activity or skill).

The most common terms in the research literature—*visualization, image, visual aid* and *visual literacy*—often are used interchangeably and remain imprecise. Merriam-Webster Online defines *visualization* as the "formation of mental images" or "the act or process of interpreting in visual terms or of putting into visible form." It defines *image* (noun) as "a mental picture or impression of something" or "a vivid or graphic representation or description," and *image* (verb) as "to create a representation of," "to form an image of" or "to represent symbolically." A *visual aid* is "an instructional device (as a chart, map, or model) that appeals chiefly to vision." Finally, *visual literacy* refers to "the ability to recognize and understand ideas conveyed through visible actions or images (as pictures)."

We identified three important distinctions in the conceptualization of visualization:

- *Visualization objects* can be pictures, three-dimensional models, schematic diagrams, geometrical illustrations, computer-generated displays, simulations, animations, videos and so on. Objects can be displayed in a variety of media formats, including paper, slides, computer screens, interactive whiteboards or videos, and may be accompanied by sound and other sensory data.
- *Introspective visualizations* are mental objects pictured by the mind. They can be thought of as imagined visualization objects.
- *Interpretive visualization* involves making meaning from visualization objects or introspective visualizations in relation to one's existing network of beliefs, experiences and understandings. An interpretive visualization involves a *cognitive action*—a change in thinking as a result of interaction with a visualization object or an introspective visualization (Phillips, Norris and Macnab 2010).

Thus, visualizations are differentiated in terms of *physical objects* (geometrical illustrations, animations, computer-generated displays, picture-like representations); *mental objects* pictured by the mind (mental scheme, mental imagery, mental construction, mental representation); and *cognitive processes* that involve the interpretation of physical or mental visualizations (cognitive functions in visual perception, manipulation, and transformation of visual representations by the mind; concrete to abstract modes of thinking; picturing facts). These distinctions are important for understanding the demands and contexts of visualization use and for determining the most effective application of visualization in the science classroom.

Theoretical Perspectives on Visualization in Science

Visualization in science education can be explained by two theoretical perspectives: (1) dual-coding theory (DCT) and (2) visual imagery hypothesis (VIH). The main difference between these two perspectives lies in the function of or purpose for visualization.

DCT (Paivio 1986; Sadoski and Paivio 2001) focuses on visualization as a means for understanding how linguistic information (words and sentences) and visual information (images) are encoded by two independent mental systems, a verbal one and a nonverbal one. The information stored in each system can be accessed independently of the other. However, the combination of linguistic information and visual information provides dual support for learning and knowledge acquisition. DCT provides important insights into how visual perception affects memory and how visualization can be used to enhance learning and understanding.

VIH (Johnson-Laird 1998; Pylyshyn 2003) focuses on visualization objects. According to Vekiri (2002), graphical representations allow one to process information more efficiently than do verbal ones, ultimately reducing the demand on working memory. VIH underscores several important functions of visualization objects, such as organizing and highlighting key concepts, making information accessible for manipulation and comparison in order to generate inferences to solve problems, and identifying logical and complex interconnections and relationships (Tversky 2001). The basic premise of VIH is that visualization objects and activities provide the necessary information and concepts to facilitate the application of knowledge and skills for problem solving.

Empirical Research on Visualization in Science Education

During the past 20 years, the consensus in the research has been that "visualization objects assist in explaining, developing, and learning concepts in the field of science" (Phillips, Norris and Macnab 2010, 63). Different types of visualization in science can serve different purposes. For example, realistic diagrams (such as an anatomical diagram) highlight the salient features of an object. Schematic diagrams (such as an electrical circuit diagram) illustrate relationships, assist in calculations, or provide descriptions of a phenomenon or process. Other visualizations in science education include photographs, simulations, astrophotographs and scale drawings of equipment. Scientific visualizations can offer a means for imagining the unseen (such as the molecular, atomic and subatomic worlds).

We analyzed 65 research articles on the application of visualization in a number of science subjects. Most of the studies were in chemistry and general science. Our discussion focuses on research involving K–12 students. However, we refer to studies with postsecondary students when the results are pertinent to the application of visualization in elementary, junior high and senior high school. The research review is organized into three parts: (1) visual representations, diagrams and animations; (2) dynamic media and learning performance; and (3) animations, visualizations and conceptual change.

Visual Representations, Diagrams and Animations

We started with studies focusing on how visual representations, diagrams and animations have been used to communicate the essential features and functions of important scientific concepts. These provided an indication of the application of visualization in science, including the merits of various types of visualization for representing scientific content, the contexts and conditions that promote the most effective use of particular visualizations in science, the characteristics of students who benefit most from specific visualizations, and the effect of visualization on student performance.

Some research suggests that certain types of visualization can enhance or even replace verbal or textual explanations of particular scientific concepts. For example, Gilmartin (1982) studied the effect of maps on learning with 133 postsecondary geography students. The students were assigned one of three readings: a text-only passage, the same passage accompanied by a reference map, or the passage accompanied by maps with some of the textual material placed in the map captions. After reading, the students answered a series of questions. Gilmartin found that "maps provided with a passage of regional geography text helped students learn the content of the text, both for immediate testing and for delayed testing" (p 149). These results suggest that maps have the potential to represent spatial relationships more effectively than verbal descriptions do.

Another study showed that the most effective applications of visualization in science are supplemented by textual or verbal information. Mayer and Anderson (1991) found that the combination of visualization (in this case, animation) and verbal or textual information enhanced understanding of scientific explanations and concepts. They conducted an experiment in which 30 undergraduate students viewed an animation of a bicycle tire pump. The students who were presented with both words and pictures performed better in problem-solving activities than the students who were presented with words only or pictures only to clarify the concept. The researchers concluded that "effective understanding of scientific explanations requires a mapping between words and pictures" (p 484).

Visualization has numerous applications in chemistry. Comprehension of chemistry concepts requires highly developed visuospatial skills. Wu and Shah (2004) highlight the importance of learner differences and the role of visualization in reducing how much students have to remember in chemistry. They claim that visualizations provide multiple representations and descriptions of the same information, which enables "students to visualize the connections between representations and relevant concepts" (p 483). In chemistry, visual representations have several important functions: to make connections visible, to present the dynamic and interactive nature of chemistry, to promote the transformation between two-dimensional and three-dimensional thinking, and to reduce how much students need to remember by making information explicit (p 485).

Some research highlights the specific contexts and conditions for visualization in science. Lee, Plass and Homer (2006) studied the most effective conditions for using simulations with 257 Grade 7 Korean students. All the students benefited when a computer simulation of the ideal gas law was separated into two screens showing smaller segments of information. The amount of information contained in the visual simulation, as well as students' prior knowledge, was important for reducing the load on memory. Thus, the more information students already know, the more effective the simulation.

Some studies provide further insight into the characteristics of students who benefit most from specific visualizations and the effect of visualization on student performance in science. For example, Huk (2006) studied the educational value of three-dimensional visualizations in cell biology using a CD-ROM (*The Cell II: The Power Plant: Mitochondrion and Energy Metabolism*) with 106 German biology students in high school and college. The inclusion of complex 3-D models of plant and animal cells most benefited students with high spatial visualization ability by supporting the recall of auditory and visually presented information. However, the addition of the 3-D model resulted in cognitive overload for students with low spatial visualization ability. This finding was similar to that of Wu and Shah (2004), who showed that highly developed visuospatial ability is a prerequisite for understanding visualizations in chemistry.

Other studies provide evidence of particular attributes and benefits of using visualization in science. Winn (1988) maintains that the effectiveness of diagrams in high school science instruction is contingent on a student's ability to focus on and learn the relevant information from a diagram in order to accomplish specific tasks. Wilder and Brinkerhoff (2007) found with 69 Grade 9 students that performance was better on questions that included visualizations on the computer-based biomolecular instructional program Chemscape Chime. Results showed that "computer-based biomolecular visualization instruction was an effective curriculum component supporting the development of representational competence" (p 5).

Dynamic Media and Learning Performance

We found only a few studies that focused on the effects of dynamic media (animations) on student engagement and learning performance. Three recent studies found that animations increased student engagement and interest level, but questions linger about whether the visualizations had any effect on learning and understanding (Annetta et al 2009; Korakakis et al 2009; Limniou, Roberts and Papadopoulos 2008).

Korakakis et al (2009) studied 212 Grade 8 Greek students to determine whether the use of specific types of visualization (3-D illustration, 3-D animation and interactive 3-D animation), when combined with verbal narration and text, enhanced students' learning of methods for separating mixtures (including distillation, factional distillation, pouring, centrifugation, filtering, evaporation, paper chromatography, sieving and magnetic separation). They found that the students assigned to 3-D animations and interactive 3-D animations required more time to learn the task than did the students in the 3-D illustrations group. Those students also experienced more difficulties in constructing relevant information from the dynamic visuals because the information was unfolding too quickly. Similar to two other studies (Gilbert 2005; Gilbert, Reiner and Nakhleh 2008), the study by Korakakis et al (2009) showed that the interactive controls produced an extra cognitive load for students, and they seemed to lack the spatial ability to conceive the visualizations completely. Although students' interest and attraction increased in response to the interactive 3-D animation and the 3-D animation, their understanding of the concept did not improve. Ultimately, the more dynamic animations enhanced student engagement but also placed more demands on their memory.

In another study, Limniou, Roberts and Papadopoulos (2008) investigated how 2-D and 3-D chemical animations designed for a fully immersive virtual reality environment affected students' interest in and motivation for learning. The 14 postsecondary students showed more enthusiasm for and better comprehension of molecular structure and change during a chemical reaction after engaging with 3-D animations than after engaging with 2-D animations. However, it was less clear whether the students truly understood the concepts, given that "they had the feeling that they were inside the chemical reactions and they were facing the 3D molecules as if a real object was in front of them trying to grab them" (p 592).

Annetta et al (2009) made a similar discovery in their investigation of the impact of teacher-created video games on the engagement and learning of 129 high school biology students. A key finding was that students in the gaming group were more engaged than students in the control group (who used paper-and-pencil practice and discussion to review a genetics unit). Interestingly, results from the cognitive assessment showed no difference in student performance. The researchers cautioned that games are not a panacea and called for the development of specific design and evolution criteria that focus more on instructional content and less on animation, text and audio.

These studies show that a significant attribute of dynamic media is its ability to stimulate student interest and engagement. However, it remains unclear whether dynamic media enhances the learning and understanding of science concepts.

Animations, Visualizations and Conceptual Change

Another body of research examines the influence of specific animations and visualizations on understanding and conceptual change for students of varying ages in various science subjects. The studies provide information about specific types of visualization, purposes for and methods of application, and the contexts and conditions in which visualizations have been used successfully to support conceptual understanding.

Although some studies have found that animations do not make a significant difference in student learning and conceptual change, others have shown that under certain circumstances animations can be a useful learning resource.

Özmen, Demircioğlu and Demircioğlu (2009) investigated the effects of animations on overcoming alternative conceptions of chemical bonding. The study included 28 students who received conceptual change texts coupled with computer animation instruction, and a comparison group of 30 students who received regular instruction with a teacher who used lots of examples and illustrations in a "chalk and talk" approach. The computer animation instruction, which involved active engagement and interaction, did not significantly change students' alternative conceptions of chemical bonding. These results suggest that it may be necessary to consider other ways of enhancing the learning of particular chemistry concepts.

In contrast, Yarden and Yarden (2010) compared the comprehension of the polymerase chain reaction (PCR) by Grade 12 students using animations as an aid with that of students using still images. The most salient finding was that PCR animations showed a distinct advantage over still images for student learning. However, the researchers caution that although animation was effective for demonstrations of molecular phenomena, the results may not generalize to other physical phenomena, such as motion.

Similarly, Holzinger, Kickmeier-Rust and Albert (2008) found discernible differences in learning performance between students who were exposed to dynamic media and those who were exposed to static media. Their study of 129 undergraduate computer science students indicated that the more complex the learning material, the greater the advantages of the dynamic media compared with the static. However, the researchers caution that "dynamic media are only appropriate and facilitate learning when they represent a meaningful model of a process or a system. This representation must also be within the limits of the cognitive system, and it must build upon learners' previous knowledge and expertise" (p 287).

Rieber (1990) compared the effects of using static graphics, animated computer visualizations and no graphics in elementary physics lessons. Results showed that "animated presentations of the lesson content influenced student performance when practice was provided; however, this effect was eliminated without practice" (pp 138–39). Rieber concluded that animations can be useful in science when lessons are adequately challenging and when an animation cues students' attention to the detail in the graphic. He suggests the following practices for the most effective application of animations in elementary science: (1) use lessons that require visualizing motion; (2) use material that is adequately, but not unreasonably, challenging; (3) cue students' attention to the detail of the graphic; and (4) use other instructional activities in conjunction with animations.

Computer visualization programs have been developed to supplement traditional textbooks in chemistry. Wu, Krajcik and Soloway (2001) report that a computer program called eChem was an effective visualization tool for helping Grade 11 chemistry students visualize, understand, and mentally manipulate interactions between and among chemical molecules. They found that using a combination of computational and concrete models helped students to acquire conceptual knowledge at the microscopic and macroscopic levels and to gain a more accurate understanding of properties, structures and underlying concepts.

The influence of diagrams on conceptual learning and understanding in science is another area that has been explored. Mathai and Ramadas (2009) studied the role of diagrams and text with 87 Grade 8 students learning about the digestive and respiratory systems. They found that the students experienced "difficulties in comprehending diagrams related to understanding of cross-sections, microscopic or chemical processes, and structure–function relationships" (p 449) and that the students showed more competence with and a preference for text over diagrams. This finding is not surprising, given that diagrams often cannot stand alone—they must be explained.

In contrast, Dechsri, Jones and Heikkinen (1997) examined whether illustrations and diagrams would improve the recall and comprehension of 83 undergraduate chemistry lab students. Their findings revealed that the students in the experimental group (who used a lab manual with accompanying pictures and diagrams) were better at interpreting data, better comprehended reaction rates and equilibrium, and demonstrated a more positive attitude toward laboratory work than the students in the control group (who used a lab manual with no pictures or diagrams). The study showed that "students perform better in the cognitive, affective and psychomotor domains" (p 901) when visual aids are accompanied by text in chemistry manuals.

By and large, the research on animations, visualizations and conceptual change indicates that visualizations are not effective in isolation. The application of scientific visualizations requires specific conditions. If visualizations are to support knowledge acquisition and conceptual change in science, they must take into account the levels and abilities of students and provide opportunities for explicit instruction on how to use visualizations. In addition, students must have the visual and spatial skills to understand and interpret the visualizations.

One study in particular underscores the importance of explicit instruction to ensure effective use of visualizations in science. Linn (2003) found that visualizations are useful for interpreting ideas. However, without instruction in visualization techniques, students often experience difficulty interpreting three-dimensional information. She discovered that learners may be confused by scientific visualizations because they do not have the same background knowledge as the people who created the visualizations. Although she recognizes the role of technology in science, Linn concludes that "the appeal of visualizations overshadows the challenges of designing effective material" (p 746). Linn's concerns draw attention to the importance of planning when and how to use different types of visualization in order to maximize their usefulness.

Visualization in science serves many purposes across a variety of disciplines. They provide a means for transforming, representing and communicating the essential functions and features of complex scientific concepts. Hall and Obregon (2002, 8) state that "images and graphics can be easily used to relay information over any distance, and in almost any discipline." Thus, visualizations have a wide range of possibilities and potential applications for those who understand how to read them and when to use them.

This review of visualization in science provides important insights into the application of various types of visualization in various science contexts. The research offers instructive guidelines and principles for making the most of scientific visualization.

Recommendations for the Development and Use of Visualization in Science

The effectiveness of visual representations is related to the contexts in which they are used; there is no direct path from visualization to understanding. Visualizations serve two primary functions: (1) to promote learning and understanding, and (2) to aid in analysis and problem solving. It is important to note that the purpose of an educational activity should have a bearing on the type of visualization chosen and on how it is used. The following recommendations are applicable to both static visualizations (drawings, graphs, diagrams) and dynamic media (animations, computer-based visualizations).

Recommendations for Visualization Objects

Visualization objects are used in science as an aid for both understanding and analysis. The dual-coding theory provides guiding principles for how visualizations can be used to help build understanding. From the DCT perspective, the fundamental premise is that visualizations must be accompanied by language-rich instruction. Based on our research and that of Vekiri (2002), we offer the following suggestions:

- Visual aids must be relevant to the lesson objectives. Expectations must be clearly articulated, and the type of visualization must be relevant to and appropriate for the particular task, the scientific concept, and the students' background knowledge and skills.
- The content of the visual aid is more important than the presence of colour or the depth of realism in drawings.
- Students require a repertoire of knowledge and skills to use visualization objects effectively. Visuospatial abilities are crucial to understanding and interpreting visualization objects in relation to space and time. Encourage students to construct their own visualization objects when it seems appropriate for specific learning outcomes.
- Visual aids should be combined with verbal or textual information for conceptual understanding. The visualization object should be coordinated with the verbal or print text so that students can see how the two fit together.
- Provide explicit explanations or guidance about the most relevant features and the application of the display. To avoid confusion or informational overload, there should be a match between the visualization object and the key components of the corresponding linguistic instruction (Vekiri 2002). Thus, the words and the visualization object should be presented in close proximity and simultaneously.
- Use visual aids as a supplement to text, not a replacement for text. Using a combination of visuals and printed information enables students to access information through the text, the visual or both.

The visual imagery hypothesis outlines how visualization objects are used as computational aids; thus, in this perspective, the most important aspect of visual images is to support thinking rather than to serve as an aid to encode nonvisual information. The interaction between the visual image and language is not important; rather, the main function of the image is to help students process and analyze information more efficiently, thus reducing the load on working memory. Information based on the image may allow learners to order, compare and manipulate the information. In turn, if students are to learn from a visualization, they must be able to discern which features are fixed, variable or irrelevant to the problem.

Pylyshyn (2003) outlines five ways in which visualization objects may help thinking:

- Visualization objects that show logical systems of visual operations (for example, a Venn diagram) can help students see logical relationships efficiently.
- Visualization objects can depict larger concepts broken down into smaller concepts.
- Visualization objects can depict the overall relationship between concepts in order to facilitate generalizations (for example, in diagrams and charts).
- Visualization objects can be used to track relationships and seek alternative solutions (for example, a graph that shows a relationship between two variables, which allows students to extrapolate or formulate a new hypothesis).
- Visualization objects provide a picture of the data that students can refer to and review in order to assist during recall of information.

Recommendations for Introspective Visualization

The idea of introspective visualization is prevalent in the popular literature, but there are few empirical studies on its effectiveness. Therefore, the potential benefits have not yet been determined, and this area requires additional research.

Recommendations for Interpretive Visualization

There is much to be learned about the comparative merits of teacher-produced visualization objects and those produced by students. However, there is some evidence to suggest that student-generated visuals are a viable form of interpretive visualization because they are personally meaningful and relevant to students' prior knowledge and the construction of meaning and understanding (Cifuentes and Hsieh 2003; Levie and Lentz 1982). In order to maximize the benefits of visualization, it is advisable to select visualization objects that are appropriate for the level of the students. Teach students how to work with visualization objects, and monitor and assess the appropriateness and effectiveness of visualizations.

Recommendations for Animations and Computer-Based Visualizations

Animations and computer-based visualizations are popular in science classes, and studies have shown a dramatic increase in their use since the 1980s. Like static visualizations, animations and computer-based visualizations can be divided according to function, either as an aid for understanding or for computational purposes. When the purpose of the visualization is to promote understanding, the animation should be supplemented with text or narration. Animations and computer-based visualizations can facilitate student interest and engagement, and provide opportunities for extra practice. However, further research is needed to assess whether and how they improve learning.

Research indicates that students of all ages are highly interested in and engaged with lessons that involve animations and computer-based visualizations. However, interest and engagement are not sufficient. Milheim (1993) acknowledges the powerful learning potential of using animations, but he also recognizes that an animation "will not necessarily be effective whenever it is used simply because it provides information in a somewhat motivating format" (p 173).

We have compiled the following recommendations to guide the development and use of animations in science:

- Animations and other computer-based visualizations are useful for getting students' attention and increasing their motivation and engagement in a lesson.
- Effective animations and other computer-based visualizations focus on the specific and important learning objectives.
- Use animations only when the knowledge to be gained is related to movement or if a concept can be better understood through a 3-D visual.
- Animations are useful for instruction that requires visualization (especially spatially oriented information).
- Use animations that are short, simple and obvious in terms of what is being demonstrated or represented. Avoid including distractions, and guard against visual overload.
- Provide immediate and continuous reinforcement and feedback to students when animations and other interactive or dynamic visualizations are used.
- Ensure that the speed of presentation and the zoom capabilities of animations can be controlled so that particularities can be emphasized when needed.
- Use animations and computer-based visualizations in conjunction with other instruction, not as a replacement for good teaching.

- Choose animations and other computer-based visualizations at a level appropriate to students' abilities and prior knowledge.
- Avoid using animations with novices who are unable to differentiate between the relevant details and cues of the animation. Not all students are prepared to make full use of visualizations.
- Use animations that have the potential to explain concepts that can't be seen (for example, subatomic collisions of particles).

Ultimately, the success of educational visualization, regardless of the form, depends on what learners bring to the task in terms of background knowledge, visuo-spatial skills and interpretive ability. Thus, "a thorough understanding of the nature of visualization objects, their functions . . ., and the interpretive skills essential to assess the plausibility, validity, and value of visual images is critically important" (Phillips, Norris and Macnab 2010, 27–28).

Conclusion

The use of visualization in teaching is advocated far and wide. Moreover, there is a widespread and unchallenged belief that visualization is useful in both teaching and learning. However, research shows that not all visualizations are created equal. The extant research provides evidence that visualization has an important place in science teaching and learning. Nonetheless, science teachers must be vigilant in order to ensure that visualization objects and activities are appropriate for each particular context, for each instructional purpose and, ultimately, for each student in the learning of science.

Note

This article is based on several chapters in Phillips, Norris and Macnab (2010).

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