Research Methodologies in Science Education:
Visualization and the Geosciences

Julie C. Libarkin
Science Education Department, Harvard-Smithsonian Center for Astrophysics
60 Garden Street, MS-71, Cambridge MA 02138; jlibarki@cfa.harvard.edu

Christine Brick
Geology Department, University of Montana
Missoula MT 59812-1296; brick@selway.umt.edu

"Earth system science courses should take advantage of the revolution in multimedia and information technology. Computers allow students access to large spatial and time series databases...Modeling and simulation software provide unique opportunities for students to study systems thinking and to compare model output with real data. Furthermore, appropriate use of the burgeoning volume of multimedia materials will be critical in Earth system science courses."

-Excerpted from Shaping the Future

The ability to visualize geologic phenomena is an oft-cited goal of geoscience courses, especially in upper division classes. Geology has traditionally been a field-based endeavor, and unraveling the history of geologic strata, both in time and space, was and is the backbone of the science. However, modern geoscientists gather data from myriad other sources, ranging from space-based remote sensing down to atomic-level crystal structure. As with traditional geologic mapping, much of this information is inherently three-dimensional. Interpretations of geologic phenomena must be conveyed in a logical manner, and this most often requires visual representations. Computers have provided new means for analyzing, visualizing, and modeling geologic data, and geoscience educators want to train students to perform these tasks. How do instructors know if their students have acquired the skills necessary to visualize and interpret geologic phenomena? What methods are most useful for teaching students these skills? What further research must be done to ensure that accessible educational strategies are effective for enhancing spatial and visualization skills? As touched upon in the quote above, what constitutes "appropriate use" of multimedia materials, especially with reference to enhancing spatial abilities?

VISULIZATION IN SCIENCE

From a theoretical perspective, visualization should make science accessible, provide means for authentic inquiry, help develop skills as well as knowledge, and lay the groundwork to understand and critique scientific issues (Gordin and Pea, 1995). The reality of student learning is, however, often far removed from theoretical perspectives. In educational settings, researchers have found that, unlike most scientists, students are often unfamiliar with how to effectively use and interpret diagrams and other visual aids. It is the challenge of educators to find ways to use the power of visual tools and emerging technologies as positive influences on student learning.

Existing research suggests that the effectiveness of visually based tools likely depends more upon how they are used than the specific tool itself (Kusnick, 2001). Technology-based tools require background, scaffolding, and a sound pedagogical context to be successful. Very few of the tools currently available provide the essential learning environment within the software matrix, and the teacher must remain a central part of the learning process. For example, Edelson and Gordin (1998) observed that requiring students to "explore the data" using global climate visualization software before they had sufficient background resulted in a dead end; students were not motivated to ask questions about something they did not care about. Students need a motivating context, and ultimately it is up to the instructor to provide an inquiry-rich environment. In the end, however, technology coupled with appropriate curriculum may help to address some of the common challenges inherent in inquiry-based education (Edelson et al., 1999).

PREVIOUS RESEARCH

The transfer of knowledge in scientific domains typically relies upon both verbal and visual modes of expression. Verbal descriptions are generally best at explaining linear phenomena, such as descriptions of methodologies or temporal events. Visual representations, on the other hand, are useful for depicting non-linear information, such as diagrams of equipment or real-world observations. Research has revealed that interpreting these different modes of expression requires different cognitive processes, especially when these modes are used in tandem. In particular, cognitive skills must be acquired to assist in interpreting visual representations of actual phenomena. These skills are not necessarily a natural consequence of exposure to visual communication, and scaffolding between verbal and visual modalities may be an integral component of effective communication.

The study of spatial ability and visualization skills has been an active field of research for at least four decades (Pavio et al., 1968; Ekstrom et al., 1976; Carter et

Table 1. Types of visualizations and possible benefits or drawbacks to teaching and learning

	Teaching		Learning	
	Pros	*Cons*	*Pros*	*Cons*
Static	Easy to design, low cost.	Instruction is limited to what is immediately visible.	Low cognitive load. May be easier to evaluate important points.	Learning is typically passive; incorporation of active learning depends on student motivation
Animation	Difficult verbal descriptions can be translated into easily accessible visual images.	Time-consuming to develop.	Illustration of phenomena that occur over unobservable range.	Learning is typically passive; incorporation of active learning depends on student motivation.
Interactive	Majority of in-class time is spent observing learning, rather than leading.	Time-consuming to develop. Control is taken out of instructors hands; may lead to off-task activity. Teacher must remain involved in activity.	Active engagement in a simulation of real-world phenomena; student controls model direction and ideally "discovers" basic principles.	Trade-off between learning technology and learning science. May be difficult to extract important points from complex backdrop.

al., 1987; Gordin and Pea, 1995; Mayer and Moreno, 1998). Researchers have used both quantitative (Ekstrom et al., 1976) and qualitative (Leach and Gull, 1990) methods to evaluate how visual learning occurs, if visual aids help or hinder learning in a variety of contexts, and the factors that influence spatial skill development. Systematic study, especially within educational psychology has provided a wealth of data and theoretical models for understanding visual learning.

At its most basic, spatial skills research focuses on the impact of incorporating visual materials into educational settings that were traditionally verbal environments. Research initially focused on the impact of simple illustrations, such as line drawings, as well as photographs, including the importance of color. Over time, visual pedagogies have evolved to include technology intensive techniques, although our understanding of how visual materials, at any level, influence learning is still quite limited (e.g., Baker and Dwyer, 2000). Most researchers agree that visual stimulation, if used correctly, can help students move information from short term to long term memory (and, hence, students have engaged in learning). However, researchers are split on the level of interaction that must occur in order for knowledge transfer to be fulfilled. Some believe that simple visual cues, such as arrows or color, highlighting the most important aspects of images will stimulate student learning (Braukmann and Pedras, 1993), while others at the opposite extreme believe that visual materials will only be effective if complete interaction is achieved, such as with virtual reality (Smith, 2001; Moreno et al., 2001). A few studies have indicated that a mix of observation and interaction may be most effective (e.g., Smith, 2001). As a result of these studies and improving computing ability, many educators have incorporated technology into their curricula in the hopes that student learning will be enhanced.

As technology has become an increasingly integral part of education, the impact of technology-based curricula has become a topic of active research. In the geosciences, the integration of GIS-based curricula (e.g., Sanders et al., 2001), computer animations (e.g., Kali et al., 1997), and virtual reality (e.g., Regian et al., 1992) necessitates studying the value of replacing traditional visual aids with technology driven ones. More importantly, educators must begin to consider the trade-offs inherent to incorporating technology into the classroom, including increased time needed to learn technologies for both students and teachers, increased expenditures per curricular item, and limited transferability to other institutions with different technology resources.

The literature on spatial visualization is vast, with research emerging from multiple fields, including science, engineering, and mathematics education, psychology, and cognition. We have chosen a few studies to highlight the range of existing research methodologies, educational inter- ventions, and findings. More in-depth reviews of visualization literature from a variety of perspectives can be found in Bishop (1989), Tuckey and Selvaratnam (1993), Rieber (1995), McArthur and Wellner (1996), and Haanstra (1996).

Activities designed to promote visualization skills fall under three categories: static (Figure 1), animated (Figure 2b), and interactive (Figure 2). Static materials include traditional pictures, maps, and physical models,

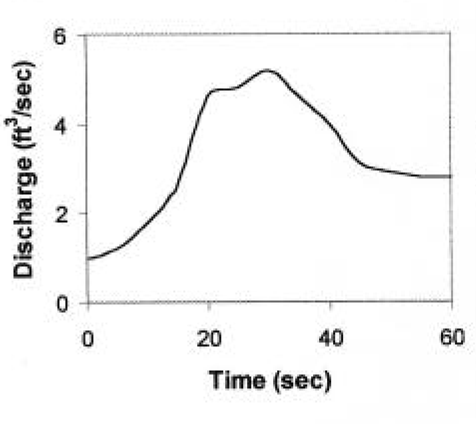

Figure 1. An example of a static visual aid, depicting water discharge as a function of time.

such as wooden fault blocks or ball-and-wire crystal models. Animations always require computers, and include digital represen- tations of static models that allow students to manipulate a 3-dimensional view, or time-sequence representations of geologic processes such as plate tectonics. Interactive models, either physical or computer generated, allow students to manipulate models through input-response interactions.

Static Materials - Static visualizations were a dominant instructional methodology prior to the emergence of technology in education, and are still widely used in education. Baker and Dwyer (2000) performed a meta-analysis of eight static visual treatments and their effect on the learning of over two thousand students. Treatments progressed from simple to realistic, and included drawings (line and realistic) and photographs of both models and actual phenomena. The effect of incorporating color into visual aids was also addressed. This analysis indicates that simple representations of phenomena, regardless of color were more effective than realistic illustrations at facilitating achievement on criterion tests designed to elucidate student understanding. Results also suggest that using color in illustrations, even if the transformation is simple from a black-white to two-tone color system, may stimulate interest independent of the material content. These data are interpreted to suggest that the brain is limited in its ability to interpret visual stimulation, hence the preference for simple rather than realistic illustrations, and that color may aid in the interpretation process.

Of particular interest to the geoscience community are studies of maps and map-reading ability, many of which have concentrated on young children (e.g., Uttal, 2000 and references therein). Most cognitive and educational psychologists would agree that static representations of three- dimensional space are limited by the use of symbolic representations on maps. Geologic maps often consist of layers of information, such as topography, lithology, and structure. Although geologists are trained to access these layers of information succes- sfully, very little research has addressed the issue of geologic map reading ability, especially in adults. A few adult-oriented studies have addressed maps and adults with disabilities (e.g., Espinosa and Ochaita, 1998) or maps with only one layer of information, such as topography (e.g., Schofield and Kirby, 1994), but further research into how geologic maps influence learning, especially at the undergraduate level, is needed.

Animations - Moreno and others (2001) discuss the importance of social relationships in learning, and the potential for development of learner-computer social interactions. Specifically, they investigated the effect of

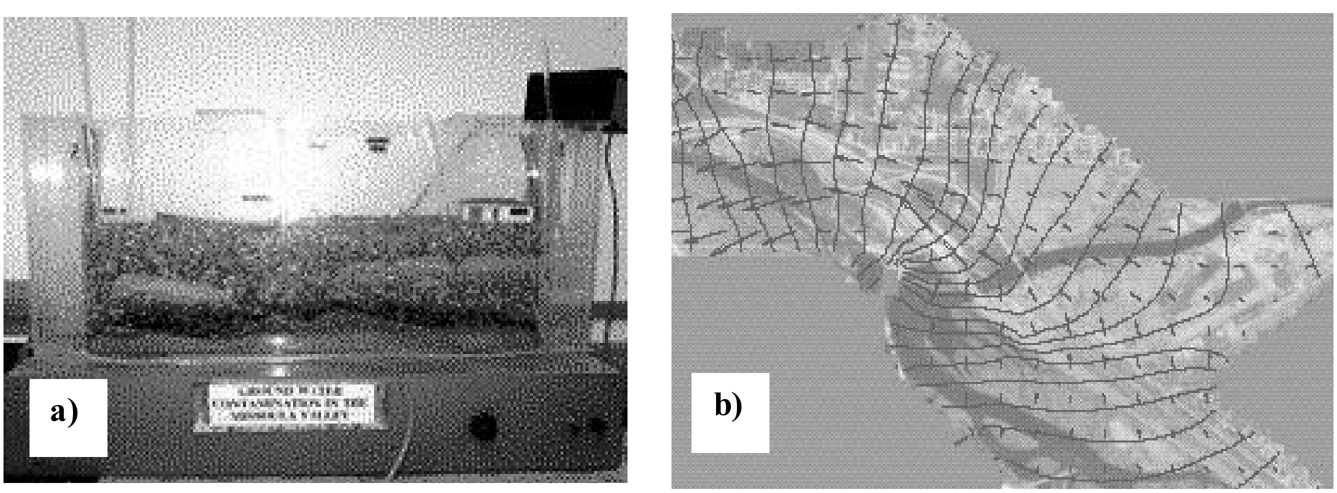

Figure 2. Examples of interactive models. a) A physical aquifer model allowing students to observe plume migration in a heterogeneous aquifer. b) A MODFLOW simulation of groundwater flow that allows students to modify flow parameters. This model can also be used as an animation.

incorporating an interactive animation into computer-based lessons and found that learning was facilitated by this "social" interaction. Sanger and Greenbowe (2000) report on a comparison of computer animations and conceptual change texts, written materials targeted at student miscon- ceptions, for altering high school students' ideas about electrical current. Interestingly, they found that animations were not effective at changing student conceptions, although conceptual change texts were. Alternatively, Garcia (1998) found that computer animations were valuable for bilingual elementary school students, especially for demon- stration of processes that occur over unfamiliar time scales. These disparate findings may be indications that the utility of animations is tied to content and/or pre-existing knowledge, although further research, especially in the field of geosciences, is warranted.

Interactive Models - Audet and Abegg (1996) discuss the trade-off that occurs between learning of technology and learning of science when using technology to teach science. The use of GIS in teaching problem solving skills in a high school classroom had mixed effects, especially for those students with limited initial abilities. Specifically, novice problem-solvers typically relied upon trial- and-error methods from the outset, with increased use of cognitive skills over time. This study suggests that although GIS can be an effective means of facilitating the use of spatial skills in the classroom, learning is mitigated by the amount of time devoted to the technology itself.

The use of virtual reality tools has been extensively studied in recent years, with relevance to the geosciences from astronomy. Barab and others (2000; references therein) report on a virtual reality system designed to assist students in introductory astronomy. Specifically, students engage in the creation of virtual models within some loosely defined parameters. Extensive analysis of qualitative data, including artifacts, interviews, and obser- vations, indicates that through this pedagogical approach students can develop a rich contextual understanding not afforded by traditional methods. Finally, it is still unclear how learning with virtual reality compares to traditional settings on a number of fronts. Many more studies can and should be conducted to ascertain the pros and cons of this technique, especially when used in K-12 or non-major settings, where general knowledge is often considered more beneficial than specific content knowledge.

VISUALIZATION ACTIVITIES IN THE GEOSCIENCES

A flood of geoscience visualization materials is available for the educator, with more materials being developed every year. A few examples are presented here to illustrate the range of materials and how they are effectively used. We refer the reader to the Digital Library for Earth Science Education (http://www.dlese.org) for exploration of available activities.

Static Materials - Pictures and diagrams are the traditional backbone of geoscience education; they have always been crucial for illustrating concepts and explaining processes. But do pictures always convey what we think they do? Traditional geologic maps or diagrams of subduction zones are well understood by geologists, but can be baffling to many introductory geology students. Scientific observation, even when it comes to scientific representations of the natural world, is a skill that must be developed. Reynolds and Peacock (1998) describe a process for incorporating a learning-cycle approach to the use of geologic landscape slides in an introductory class. Instead of the traditional method of projecting a slide and explaining it to students, an observe-question-discuss method is used. Students are asked to observe and pose questions prior to an instructor-guided discussion of terms and concepts that is itself guided by the initial student response. This is followed by concept application to new situations or locations, allowing students to apply newly acquired knowledge to unfamiliar settings.

Animations - Animations are an extension of static images, with the advantage of better illustration of three-dimensional phenomena, processes that occur over large spatial or temporal time scales, and complex mathematical relationships. Examples of these include the XTALDRAW program that displays and animates drawings of crystal structures (Bartelmehs, 2002), plate tectonic reconstructions illustrating the development of ocean basins and continents from the Cambrian to the present (Scotese, 2002), and visualization of Milankovitch cycles through multi-colored global representation of insolation over time (Wolters et al., 1996). Each of these makes difficult concepts and processes outside the range of human observation much more accessible to students. As with static images, it is critical that the materials are used in a way that promotes student engagement, for instance, through a learning-cycle approach or as part of a student investigation.

Interactive Models and Visualizations - Interactive models may be either physical or computer-based; the fundamental difference from static materials is that students must actively engage with the model. Specifically, engagement should involve student thought and interaction that goes beyond simple manipulation or movement via computer prompts. Ideally, interactive models help students understand complex processes through direct manipulation. For example, the STELLA program (High Performance

Systems, Inc.) is a powerful tool for modeling dynamic systems such as Earth's climate. Students can create models themselves, or manipulate models developed independently by the instructor (Bice, 2001).

Physical models and computer models can be used in tandem to encourage real understanding of systems. Physical aquifer-in-a-tank models (Gates et al., 1996) allow students to begin to explore Darcy's law through manipulation of water flow and gradient. Additionally, they can explore the effect of variable hydraulic conductivity by adding colored dye to injection wells. However, student interaction is limited by an inability to modify the physical properties of the modeled aquifer. Digital groundwater flow models, such as Visual Modflow (Waterloo Hydrogeologic, Inc), allow manipulation of all applicable parameters that affect 3-dimen- sional groundwater flow (for an example see Hudak, 1998).

Computers have opened up a whole new world for scientists working with large data sets; students can benefit from the same opportunities. Interactive visualizations enable students to work with large data sets that are increasingly available through the web. Examples in the K-12 realm include World- Watcher, (Edelson et al., 1999). Another recent innovation in interactive visualizations is the development of virtual worlds. In VR Excursions - Exploring Earth's Environment (Kelly et al., 2000), students pose questions, and collect and analyze data in virtual settings. The program simulates a research environment without requiring the re- sources, such as expensive equipment, that are outside the reach of most educational institutions. Likewise, the Virtual Solar System is a University of Georgia course that requires students to construct models of the solar system (Barab et al., 2000). Involving project-based learning, the course enables students to use 3-D virtual reality modeling software to create models that they can use to explore fundamental astronomical phenomena.

ASSESSMENT

Most studies of visualization in the geosciences rely upon existing tools that assess general spatial skills, the most popular of which is the Kit of Factor Referenced Cognitive Tests (Ekstrom et al., 1976). Assuming that a correlation between general spatial skills and visualization of geologic phenomena exists, such tests can be a useful starting point for assessment of interventions. However, visualization in a specific topic requires a unique set of skills; visualization of Earth processes requires spatial and temporal projections not encountered in available assessment tools. Certainly, the field would benefit from instruments specifically designed for studying learning in the Earth system. Indeed, the de- velopment and validation of tools for the assessment of visualization in the earth sciences is a relatively untouched field of research.

Similarly, the use of control groups is a critically needed research tool that would benefit visual- ization studies in geoscience education settings. In particular, programmatic assessment usually focuses on overall learning, and rarely addresses the effects of specific curricular components. For instance, the GLOBE program assesses student learning as a whole, but does not specifically address the visualization components of the program. As a result, it is unknown what role the visualizations play in observed improvements of skills and knowledge (SRI International, 2000). Although research into the use of static visual aids shows significant differences between verbal or visual only and visual-plus-verbal tools (Baker and Dwyer, 2000), the study of interactive physical or computer modalities is still in its infancy. In particular, comparative studies incorporating control groups need to be implemented to determine the relative importance of traditional and emerging visual- ization tools. Specifically, research on the impact of technology on student visualization abilities would benefit from comparison of groups learning with and without the use of technology, although the content of both types of materials must be inherently equal. Although difficult to design, these types of studies are nonetheless necessary to determine the efficacy of technology-based tools.

FUTURE DIRECTIONS

The study of spatial skills has a rich history in cognitive science, and has experienced renewed interest stemming from science, mathematics, and engineering education. The unique set of skills required for studying geologic phenomena suggests that the Earth Sciences in an ideal field for studying spatial and visualization skills in a real educational setting. Worthwhile future research could consider a number of questions, including: 1) What is the relationship between spatial ability and geologic visualization skills, and how can we begin to test these geology-specific skills?; 2) How does familiarity with geological phenomena influence spatial ability?; and 3) How is the use of tech- nology-based visualization tools improving upon learning achieved by more traditional teaching methodologies?

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Libarkin is supported by a National Science Foundation Postdoctoral Fellowship in Science, Mathematics, Engineering, and Technology Education (DGE-9906479) and by a National Science Foundation Assessment of Student Achievement in Undergraduate Education grant (DUE-0127765). Brick is a former NSF Postdoctoral Fellow in Science, Mathematics, Engineering, and Technology Ed- ucation (DGE-9809500).

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