

Understanding and enhancing visualizations: Two models of collaboration between earth science and cognitive science

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ABSTRACT

Geoscience visualizations are commonplace; they appear in television news programs, classroom lectures, conference presentations, and internet hypermedia. But to what degree do individuals who view such visualizations actually learn from them, and if so, why? As visualizations become more commonplace in school, laboratory, and entertainment settings, there has been a concurrent interest in considering the effectiveness of such presentations. How can we build effective collaborations that address pedagogical questions in the earth sciences while also informing theories about the cognitive processes that underlie visualization experiences? In this chapter, we contend that only through directed, collaborative projects between earth scientists and cognitive scientists will significant advances in visualization research take place. We describe two specific models of such collaboration, the advisory model and the reciprocal model, and argue that a reciprocal model presents a more effective framework for addressing important questions about the nature of the visualization experiences. Such a model will inform both the design of effective visualizations for teaching complex geoscience topics, as well as provide insight into the processes that underlie learning from visualizations.

Keywords: visualizations, mental representations, cognitive science, earth science, symbolic development, conceptual change.

INTRODUCTION

Computer-driven visualizations have become commonplace in earth science classrooms. In a variety of situations, instructors use these visualizations to teach theories and concepts that are critical to earth science coursework (Edelson et al., 1999). Visualizations are also used as tools for communicating in the field. Visualizations thus can provide impressive models and demonstrations of

scientific concepts. They are often not just nice, but also necessary, particularly when a topic is challenging to present because of pragmatic (e.g., how do we view geologic activity in real time?), financial (e.g., how do we pay for a class to travel to an actual volcano site?), or even motivational issues (e.g., how do we get students engaged in a lecture on seismic activity?). For all of these reasons, we predict that these types of visualizations will continue to enjoy increased usage in the classroom into the foreseeable future.

As the basic implementation of geoscience-based visualizations continues to increase, so does continued interest in basic research that addresses how students and scientists use, comprehend, produce, and learn from visualizations (Ploetzner and Lowe, 2004). In other words, there is focused interest in the design and assessment of visualizations as educational methodologies. Such work can provide an indication as to the situations in which visualizations will be most effective; it can additionally suggest ways in which visualization experiences can result in successful learning. Up until this point, much of this work has traditionally concentrated on the ways in which computer-driven presentations can appropriately convey educational topics, the acquisition of skills necessary to design and use visualizations, and to a lesser extent, the cognitive underpinnings of visualization learning processes (e.g., Hegarty et al., 2002; Maki and Maki, 2002; Mayer, 2001; Renshaw et al., 1998; Slocum et al., 2001). The goal of our future work should be to empirically validate claims about the definite benefits, rather than the potential gains, of visualizations. The stakeholders interested in these efforts, specifically earth scientists (cutting across geoscientific research areas) and cognitive scientists (cutting across domains including psychology, computer science, and education), are now prepared to systematically hypothesize, build, test, and evaluate visualization systems and their impact on human cognition.

The purpose of this chapter is to contribute to the development of interdisciplinary work that links, as the title of this book implies, the sciences of the earth with the sciences of the mind. Our overarching belief is that only through direct collaboration between earth scientists and cognitive scientists can we hope to make strides in the assessment, application, and understanding of visualizations (as tools for data exploration, hypothesis testing, scientific communication, and learning). Unfortunately, at this point, much of the work on visualizations in the earth sciences, with a few exemplary exceptions, has proceeded in largely a multidisciplinary rather than an interdisciplinary manner. Thus, we argue that the field will best progress as a function of mutually beneficial scientific interactions. These activities can address many important research questions that cut across fields, informing both theoretical and practical issues associated with visualizations. But what form should these interactions take, and what can we do to make them most effective?

In line with this view, we contend that a *reciprocal model* of collaboration will result in productive, interactive relationships between the geosciences and cognitive sciences. In this case, geoscientific questions about the use or understanding of visualizations are directly related to fundamental, theoretical issues in the cognitive sciences. That is, visualization tools can be used to assess underlying cognitive processes (including learning), and the findings of these studies can provide insight into effective educational design (Rapp et al., 2003). This kind of collaborative approach benefits both the geoscience and cognitive science communities. This model contrasts quite starkly with the more traditional interdisciplinary model, which we call an *advisory model*. In this mode of collaboration, cognitive scientists work

to improve the quality of visualizations and students' resulting understanding of them by providing suggestions in line with psychological principles of organization. In this case, cognitive scientists serve essentially in an advisory capacity, offering geoscientists design suggestions based on findings from, for example, the vision sciences, human factors research, and educational technology.

We believe that in the long run the field of visualization is more likely to benefit from a reciprocal model rather than from one-sided, advisory interactions in which cognitive scientists serve as consultants to geoscientists or vice versa. We also argue that grounding these partnerships with respect to theoretically driven questions about knowledge acquisition will result in robust research programs that can directly inform the use of visualizations. To make this case, we provide examples of visualization issues organized around these two types of collaborative models. We begin by describing some research questions that fit with current usage of the advisory model, in which cognitive scientists are asked to help improve geoscience visualizations. We discuss the types of situations these questions are meant to address. Next, we describe the broader scope and utility of the preferred reciprocal model. To expand on this issue, we also describe two sample topics that could be effectively addressed by this model. These topics provide an opportunity for considering important research questions of interest to both geoscientists and cognitive scientists. We close with an optimistic view toward the future of visualization and the nature of effective, robust collaborations among visualization researchers.

THE ADVISORY MODEL OF COLLABORATIVE RESEARCH

Question: How Do We Make Visualizations Look Better?

Broadly speaking, many visualization researchers are interested in the optimal methods for designing a system's visual and functional presentation. This includes establishing the best ways to design a simulation, the appropriate colors to use for attracting attention, the types of controls that will help users navigate a database, and various other surface characteristics associated with a visualization. These questions will, necessarily, be related to other issues that arise in visualization assessment. However, this category of questioning tends to be driven by aesthetic concerns rather than deeper inquiries into the nature of learning.

Although we believe that this type of research can indeed lead to the development of more effective visualizations, we contend that exploring this issue in an extended way will not lead to new insights into how people understand and learn from visualizations. For example, studying the most effective placements for pictures and texts will not inform our comprehension of visualization experiences. This is not meant as a controversial statement; the visual appearance of a presentation is essential from a design point of view, but extended focus on appearances for appearances' sake fails to describe the important ways in

which individuals interact and potentially learn from visualizations. There are several popular texts that attempt to answer these types of questions by providing useful suggestions for improving the surface appearance and impact of visual presentations (e.g., Harris, 2000; Tufte, 2001). But critically, the more educationally valid question as to whether the system will lead to learning is ignored because the focus is on what looks best. At heart, visualization researchers are likely interested in the deeper question of whether and how the visualization improves learning. The advisory model pushes away from this important line of questioning.

In no way should we downplay the importance of the surface qualities of visualizations. Certainly, visualizations should be designed to promote effective (and pleasing) visual experiences; their strength, after all, is that they can make opaque concepts visually perceptible and, consequently, tractable. Perhaps focusing on the question of effective visual design is a necessary first step in developing collaborations between geoscientists and cognitive scientists. But we hope that this sort of research is just that—a first step rather than an end in its own right.

Question: Does a Particular Visualization Improve (or Hurt) Learning?

A second category of research questions to which cognitive science could contribute, but would not specifically advance research in cognitive science per se, concerns the effects of specific visualizations on learning in specific educational settings (e.g., a single earth science class or topic). Visualizations are designed for a variety of reasons, but one of the most popular is for educational purposes (be it for the student, scientist, or layperson). If visualizations are designed for conveying information, one important question to be asked before they are implemented is whether the visualizations actually facilitate learning (Rapp, 2005; Rapp and Kendeou, 2003; Rapp et al., 2004). Many designers of visualizations are interested in finding out whether their particular visualizations “work.” That is, they want to know whether their design increases overall learning or facilitates learning in a particular domain or for a particular test topic.

Addressing this question is certainly of interest to some cognitive scientists. Nevertheless, we have classified the question of whether a particular visualization “works” as an example of collaboration aligning with the advisory model. The reason for this is that these sorts of questions focus on the specific visualization, rather than on the process of learning. Cognitive scientists are prepared to answer the question of whether a visualization works, and doing so is certainly an important contribution, but answering such a question does not in itself contribute to the cognitive agenda of understanding underlying mental processes. Thus, the question of whether a *particular* visualization is effective is, we believe, still derived from the advisory model. A cognitive scientist can make an important contribution to answering this question, but doing so will rarely make an important contribution to the broader geoscience community or cognitive science in general (but see Mayer [2001] for descriptions of work that

generalizes findings to a broader array of learning situations and cognitive processes).

This section has briefly described two kinds of questions that can be answered by one-sided collaborations between cognitive scientists and geoscientists. In answering these questions, the cognitive scientist serves in an advisory role, as a reference source for addressing issues of interest specifically to geoscientists and their visualization designs. In the next section, we provide examples of collaborations that promote a more interactive relationship between cognitive science and the geosciences.

THE RECIPROCAL MODEL OF COLLABORATIVE RESEARCH

Traditional issues of interest to cognitive scientists have included not only the ways in which stimuli (such as visualization presentations) influence thought and behavior, but also the underlying processes involved in those thoughts and behavior. For visualizations, then, analogous concerns would assess whether visualizations lead to comprehension by examining the underlying causes of any presumed benefits. While visualization researchers profess interest in the ways that visualizations influence learning, comprehension, and performance, they have traditionally, although not uniformly, been less interested in the underlying causes of those processes. We contend that a consideration of the underlying mechanisms of learning and memory provides theoretical grounding for addressing the implications of visualizations in a variety of settings. In fact, evaluating these processes directly will lead to the development of more valid answers to the questions posed even by the advisory model.

There are a variety of theories that attempt to account for the underlying processes of comprehension. We now present some examples of this work. Researchers have described the structure and contents of memory (e.g., Baddeley, 1992; Jacoby, 1991; Roediger, 1990). Some have contended that long-term memory involves the encoding of declarative facts, procedural activities, and episodic experiences. By detailing the types of information that are stored in memory, these researchers also seek to outline how to best facilitate the acquisition and retrieval of knowledge. Extensive research has also examined the effects of learning contexts on comprehension (e.g., Jonassen, 1999; Linderholm and van den Broek, 2002; Cordova and Lepper, 1996). This work describes how student goals, motivation, and background knowledge influence the acquisition of information into long-term memory, and its later application in a variety of situations. Cognitive psychologists have additionally examined how individuals process multimedia stimuli by assessing the benefits that accrue as a function of simultaneously studying various stimuli types, including text, pictures, and other media formats (e.g., Brunyé et al., 2004; Hegarty and Just, 1993; Mayer, 2001; Stemler, 1997). Across these domains (and they are but a sample of relevant projects), researchers have developed testable hypotheses that not only contribute to a better understanding of human functioning, but also have been used to

enhance qualities of everyday experience (e.g., in educational interventions, see Fuchs and Fuchs, 1998; in functional object design, see Norman, 1988). Additionally, it should be clear that each of these topics has potential implications for the use of visualizations.

Geovisualizations, then, provide an excellent case example for assessing the cognitive processes that underlie multimedia learning experiences. And based on this research, findings should be useful for conceptualizing the features and characteristics necessary for developing effective visualizations (Rapp et al., 2003). As we have suggested, a concern for the underlying causes of thought and behavior can provide the theoretical underpinnings for thinking about the impact of visualizations on learning. Given what we know about the basic functioning of the human mind, any group of researchers assessing visualizations will be better equipped to make appropriate design decisions and develop visualization applications if they organize their questions around issues of higher-order cognitive functioning.

To better illustrate reciprocal interactions in line with this framework, we next focus on two examples of potential collaborative topics. These topics necessitate the evaluation of underlying mechanisms of cognition, an extended consideration of the ways in which individuals learn, and an overarching interest in the practical application of findings to educational experiences. The topics assess underlying processes involved in learning (of interest to cognitive scientists) and the ways in which learning can be facilitated through geovisualizations (of interest to earth scientists).

SAMPLE RECIPROCAL TOPIC ONE

What does Visualization Use Reveal about Symbolic Development?

This topic illustrates very well the reciprocal, collaborative model that we have in mind. Research on students' understanding of visualizations may prove to be relevant to an issue that cognitive scientists typically call *symbolic development*. Work on symbolic development has tended to focus on how children develop an understanding of symbolic representations and the fundamental knowledge that one thing can stand for another. Examples include research on children's understanding of the relation between maps or scale models and actual spaces (DeLoache, 1995, 2000; DeLoache et al., 2003; Uttal, 2000) or between written text and spoken language (Bialystok and Martin, 2003; Bialystok et al., 2000; Tolchinsky, 2003).

An important finding from this work is that young children often have difficulty grasping the symbolic nature of representations that seem ostensibly simple to adults. For example, children younger than 3 cannot use a simple scale model as a tool for finding a toy hidden in a room (DeLoache, 1987, 2000). In addition, even when symbolic understanding does emerge, children are often highly reliant on iconic representations; they believe that the symbol should look exactly like or otherwise

perfectly resemble what it represents in the world. For example, one child observed that a red line on a map could not represent a road (when in fact it actually did represent a road) because there are no red roads in the world (Liben, 1999). Another child contended that the line was not a road because it was too narrow to fit a car. Likewise, when learning about text, preliterate children may believe that written words must resemble in some ways (e.g., length or size) the spoken words that they represent (Bialystok, 1992).

A related challenge for children involves dealing with the dual nature of symbols (Uttal et al., 1997). All symbols are both representations of something else and objects in their own right. For example, a scale model is both a representation of a particular space and an object itself. Most adults know to focus on the representational aspects of the symbol and to ignore the non-symbolic properties. As you read the words on this page, for example, you take for granted the characteristics of the text and the paper on which it is printed. You know that the meaning is conveyed by the arrangement of the letters to form words; hence, the particular font that is used, or the quality of the paper, becomes much less important. However, young children do not share this understanding. They tend to focus on the symbol as an object itself rather than as a representation of something else. Experimental manipulations that have increased or decreased the salience of objects in their own right have led to changes in children's understanding of the symbolic properties of those objects. For example, encouraging children to play with a scale model actually makes it harder for them to use the model as a guide for finding a hidden toy in a room. Conversely, putting the model behind a pane of glass so that children cannot interact with it makes it easier for them to use the model as a symbol (DeLoache, 2000).

What does research on young children have to do with older students learning to use geoscience visualizations? At first glance, the two might not seem related, but discussions with geoscience colleagues suggest otherwise. There may be an underlying similarity between children's struggles in understanding representations in general, and the understanding of geoscientific concepts that are well-known to experts but are difficult for novices to understand (or visualize). Several geoscience colleagues have told us that their students have difficulty grasping even the basic notion that a complex visualization is a representation (that is, that it stands for something in the world). Instead, they sometimes interpret features and items in the visualization in terms of their properties as objects in their own right, rather than as representations of something else. The students seem to lose track of the representational nature of the complex visualizations, focusing instead on the colors (rather than on what the colors represent) or the shape of the objects. They may see, for example, red or yellow blobs (the surface features), rather than patterns of heat distribution below the Earth's surface (the underlying concepts). These problems strike us as remarkably similar to those that young children face when first learning about symbolic relations. Is it the case that adults, when faced with a new symbol

system, must deal yet again with the dual nature of symbols? Is symbolic development ever really “over,” or does it continue or begin anew when we encounter new types of symbols?

This is a fascinating and potentially fruitful area for the kind of reciprocal collaboration that we envision. The geosciences provide a wonderful testing ground for investigating whether principles of symbolic development continue to apply in adulthood. At the same time, the geosciences would benefit from detailed, theoretically motivated studies of the cognitive and perceptual bases of the processing of visualizations. Pursuing such a question benefits both disciplines, and hence, the issue of symbolic development and geoscience visualization can lead to truly reciprocal collaborations.

SAMPLE RECIPROCAL TOPIC TWO

What do Visualization Experiences Reveal about Processes of Conceptual Change?

Science learning involves the construction of accurate explanations for concepts and principles in particular domains. Traditionally, students come to classrooms with prior knowledge within these domains. This prior knowledge, in the best of all possible worlds, is correct, coherent, and amenable to change as students learn new facts and concepts. However, evidence demonstrates that students often possess incorrect views or misconceptions for scientific topics, and that these incoherent beliefs are highly resistant to updating (Guzzetti et al., 1993; Kendeou and van den Broek, 2005). This occurs in scientific domains including earth science, physics, and chemistry, and these misconceptions are not specific to particular age groups (Pace, et al., 1989). Unfortunately for most instructors, this means that not only do they have to be concerned about presenting the appropriate material to their students, they also need to worry about refuting their students' existing, inaccurate models.

Work on the updating of mental representations in terms of knowledge acquisition for scientific concepts has focused on *conceptual change* (Hynd and Guzzetti, 1998; McCloskey, 1983; Vosniadou, 2003). Conceptual change is the process of restructuring earlier incorrect beliefs with modified, correct information. According to this work, representations in long-term memory are updated when newly experienced information is inconsistent with prior knowledge. The nature of these processes has been studied in a variety of domains including text processing (e.g., Avraamides, 2003; O'Brien et al., 1998; Rapp et al., 2001; Zwaan and Radvansky, 1998), spatial cognition (e.g., Franklin and Tversky, 1990; Klatzky, et al., 1998; Waller et al., 2002), and science learning (e.g., Diakidoy et al., 2003; diSessa, 1982, 1993; Posner et al., 1982; Smith et al., 1993). This work has specified strategies that align with cognitive functioning that are potentially effective in helping students revise their misconceptions (e.g., Alvermann and Hynd, 1989; Dole and Smith, 1989). For example, a mental representation or belief is more likely to be updated when prior information is explicitly refuted as incorrect, an explanation is

provided as to why that information cannot be correct, and an indication is given as to what the correct model should look like (see Kendeou et al., 2003, for a discussion of these issues).

Thus, cognitive scientists and educational psychologists have attempted to outline not only the processes by which information is updated from a mental representation, but also the situations that most effectively lead to successful updating. Much of this work has focused specifically on text information, investigating the use of expository texts, narrative refutation materials, and detailed examples as tools for initiating the updating of misconceptions (e.g., Linderholm et al., 2000). However, computer-based presentations such as visualizations are beginning to replace these source materials in many earth science courses. Thus, the research issue should be readily apparent—can visualizations provide an effective means for updating student misconceptions, and if so, what do these visualizations tell us about the nature of prior knowledge?

Consider the case of a student with a misconception about the interior of Earth (Vosniadou and Brewer, 1992, 1994). Some children possess the belief that the interior of Earth is actually hollow, and that it is possible to walk inside Earth as on the surface. A verbal or text description of why this is wrong would not provide the best opportunity for instantiating revision processes in the student; a visualization might be more effective because it can graphically display the appropriate framework, illustrate why the inappropriate framework could not be plausible, and detail some of the underlying processes at work under Earth's surface. That is, an appropriately designed visualization can convey the important concepts in a way that requires students to update their misconceptions and undergo conceptual change. The use of particular visualizations, and their effectiveness, can provide insights into the nature of students' mental representations (e.g., their mental models of the concepts; Rapp, 2005), the construction and updating processes of those representations, and the most effective techniques for revising misinformation. In other words, this research can inform theories about the processes and products of memory and comprehension.

Consider a second case example intended to highlight the importance of visualizations for conceptual change under different circumstances. Visualizations are often used by scientists to analyze information and consider existing data sets, maps, and object arrays in different ways. Geoscientists who discover novel findings through the use of such visualizations are indeed going through a similar process of conceptual change. That is, their existing knowledge about a topic area is now being informed, and potentially revised, as a function of their experiences. Thus, the question of how visualizations might best offer opportunities for engaging in processes of conceptual change need not be limited to student experiences. Instead, they may underlie a variety of situations for which visualizations provide new perspectives on data.

Clearly then, this area of research holds much potential for addressing issues of interest to cognitive scientists and geoscientists. Evaluating how visualizations can promote conceptual

change can help outline the appropriate design features for developing visualization lessons, the conceptual frameworks that define mental representations, and the underlying cognitive processes that guide the construction and application of knowledge. Based on these two examples, from the research areas of symbolic understanding and conceptual change, it is readily apparent that reciprocal, collaborative research can benefit our understanding of geoscience visualization comprehension at a variety of levels and for a variety of questions.

CONCLUSION

Earth science visualization, and science visualization in general, has progressed steadily in a relatively short time (particularly from a geologic viewpoint). Researchers, theorists, and instructors from a variety of areas have become intrigued at the prospect of presenting data from novel perspectives, and implementing graphics and animation to illustrate complex ideas. The field is now at a critically important stage; researchers in core domains (cognitive science, the natural sciences, educational technology, etc.) are moving beyond pure visualization development, as they begin to address how visualizations work and whether they have any educational impact. In this chapter, we have focused on frameworks of collaboration as a prime concern for accomplishing these goals. We have attempted to describe two models of collaboration, detailing the types of questions that each model most effectively addresses. In addition, we have made a case for relying on the reciprocal model as a framework for establishing collaboration between earth scientists and cognitive scientists. We have described the reciprocal model to support ongoing, effective research programs that directly inform the study of geovisualizations, as well as informing theories of human cognition. Of course, we do not simply dismiss the types of questions that fit into the advisory framework; we simply contend that those questions are less likely to promote long-term collaboration that informs theory across disciplines at the intersection of earth and mind.

We remain optimistic for the future of visualization research. The potential for using visualizations both to understand how we process information and for developing valid techniques that facilitate learning are well worth the effort of establishing strategic collaborative programs. We must make sure not to squander the opportunities that visualization research potentially affords for assessing a variety of questions beyond “does this look good.” Visualization research has much to tell us about how the mind works, how people learn, how we understand geoscientific data, and how to build more effective educational experiences in the geosciences.

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