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Commentary

Dynamic visualizations and learning: getting to the difficult questions

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1. Introduction

Recent advances in information technology and graphics have made it possible to produce powerful visualizations of scientific phenomena and more abstract information (Card, Mackinlay, & Schneiderman, 1999; Spence, 2001). With these developments, we can easily present diagrams as static or animated, and we can present images as still photographs or video clips. Furthermore, with developments in hypermedia systems and interactive interfaces, we can create documents that allow students to browse the information in any order, rather than being constrained by the linear ordering of information in printed books. Computer microworlds, in which students can make predictions and evaluate hypotheses by interacting with powerful simulations of scientific phenomena, are becoming more prevalent in educational programs.

There has been much excitement about the potential of these new dynamic visualizations for improving education and training. This is perhaps not surprising, because the same claims have been made about every new technology developed in the last century. For example, when the motion picture, radio, and television were invented, each was hailed as the answer to solving educational problems (Cuban, 1986; Mayer, 1999). The following quote from Thomas Edison about the development of the motion picture could just as likely be made by many proponents of dynamic visualization today.

> I believe that the motion picture is destined to revolutionize our educational system and that in a few years it will supplant largely, if not entirely, the use of textbooks (cited in Cuban, 1986, p: 9).

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It makes intuitive sense that there should be an advantage of dynamic over static media, especially for teaching students about dynamic phenomena. As Lowe (1999) has pointed out, dynamic media allow us to show processes explicitly such that there is an isomorphism between the process being represented in a dynamic medium and the medium being used to represent it. However, the first phase of research examining differences between dynamic and static displays failed to show a clear advantage for dynamic displays. Although some studies found positive effects of animated displays, for example, on student motivation and in implicit learning (Rieber, 1991), there have been few studies that have shown an advantage of static over animated displays in conceptual learning. Tversky, Morrison, and Betrancourt (2002) reviewed over 20 studies that compared learning from static and animated graphics. In the majority of these studies, there was no advantage of animations over static graphics. A small number of studies showed such an advantage, but in these studies, more information was presented in the animated graphics than in the static graphics, i.e., they were not informationally equivalent (cf. Larkin & Simon, 1987).

It is clear from this first phase of research on static versus dynamic displays that there is not a simple advantage of dynamic over static media. Just as in the case of the motion picture, radio, and TV (Cuban, 1986; Mayer, 1999) we have learned that improving education is not a simple matter of adopting a new technology. Yet most educators and researchers in this field continue to believe that dynamic media have enormous potential for instruction and training. This leads us to the much more interesting and challenging issues of understanding what conditions must be in place for dynamic visualizations to be effective in learning and how educational practice must be changed to capitalize on these new media. In this second phase of research on dynamic media, we have to reject the assumption that dynamic media are always better, in order to understand how to best use these new media in the educational process.

The papers in this special issue are clearly in the second phase of research on dynamic visualizations in education. Rather than assuming that dynamic visualizations are always better than static representations, these papers acknowledge that the effectiveness of dynamic visualization is not a simple issue and begin to address some of the complex factors that must be taken into account in evaluating their effectiveness. In my commentary I will first summarize some of the important factors that have been identified by the authors of this special issue, and then raise some other issues that also need to be addressed, but are perhaps receiving less emphasis in the literature at present.

2. Types of dynamic displays

One important insight represented in the papers in this special issue is that we need to go beyond making a simple distinction between static and dynamic displays, because there are in fact many different types of dynamic displays. Perhaps the prototypical example of a dynamic display is an animation of some visible phenomenon, such as a machine in motion. These displays are often characterized as very realistic, because they portray a visible sequence of events in real time, or at least proportional to real time. In this type of visualization, one state of the system is visible at a time, as it is in the real world.

As Ainsworth and Van Labeke (2004) point out, however, a realistic animation of a visible phenomenon is just one type of dynamic display. In addition to portraying processes that are visible in the real world (such as a machine in motion), dynamic represntations can "visualize" entities that are not visible, but are spatially distributed, such as changes in pressure or temperature on a weather map (studied by Lowe in this special issue). Dynamic displays can also portray more abstract information, such as statistical concepts (as studied by Bodemer, Ploetzner, Feuerlein, & Spada, 2004) changes in population over time (as studied by Ainsworth & Van Labeke, 2004) or computer algorithms (Narayanan & Hegarty, 2002). In these cases, space is used as a metaphor for some more abstract information. Finally, in addition to showing objects in real time or space, dynamic displays can distort reality in various ways, such as slowing down some processes and speeding up others, showing an object or phenomenon from different or changing viewpoints, augmenting the display with cues to draw viewers' attention to the most relevant parts, or having moving objects leave a trace or wake, as in the time persistent representations considered by Ainsworth and Van Labeke. Given that the mapping between the dynamic display and its referent is very different in these situations, it is probably simplistic to think that results from studies with one type of dynamic display will necessarily generalize to the others. Therefore, studies need to go beyond simple comparisons between static and dynamic displays, to examine the relative effectiveness of different types of dynamic displays compared to other types of dynamic displays as well as to static displays.

People often assume that more realistic dynamic displays will always be more effective than less realistic displays (Scaife & Rogers, 1996). But as several authors in this special issue point out, the power of media often comes from their ability to abstract from reality, or distort reality in different ways, as Schwan and Riempp put it, to optimize the experience provided to the learner. Good examples of the limitations of realistic simulations come from Rieber's (1991; Rieber, Tzeng, & Trible, 2004) work on learning of Newtonian mechanics and Lowe's (1999) research on learning from animations. Rieber et al. (2004) found that realistic simulations of Newtonian physics promote implicit learning, that enables students to learn to play a video game encompassing Newton's laws, but that this experience must be augmented with verbal explanations in order promote conceptual understanding. Lowe (1999, 2004) found that in viewing realistic dynamic displays, novices are distracted by perceptually salient aspects of the displays that are not necessarily thematically relevant. The papers presented in this volume suggest several ways in which a visualization might distort reality to improve understanding, such as augmenting displays to make boundaries between events more obvious (Schwan, Garsoffky, & Hesse, 2000), using cues to draw students attention to parts of a display that are thematically relevant but perhaps not perceptually salient (Lowe), adding visualizations of entities that are usually invisible in nature

(Ainsworth and Van Labeke), or showing different types of dynamic displays of the same phenomena (Ainsworth and Van Labeke).

3. Cognitive demands of learning from dynamic displays

Another important insight that is shared by the authors in this volume is an appreciation of the fact that dynamic displays are not always easy to understand, and impose demands on human cognition that are not present with static displays. These demands are somewhat different for non-interactive and interactive-dynamic displays, so I will first discuss the difficulties that have been identified with non-interactive-dynamic displays and later discuss how these are affected by making displays more interactive.

3.1. Non-interactive-dynamic displays

Non-interactive-dynamic displays include animations or videos that play at a constant rate and for a set length of time that cannot be altered by the viewer. One important characteristic of these types of dynamic displays, pointed out by Ainsworth and Van Labeke (2004) is their transience. When one views an animation or video, one views one frame at a time, and once the animation or video has advanced beyond a given frame, it is no longer available to the viewer. This places heavy demands on working memory if information presented earlier in the animation or video must be integrated with information that is presented later. In contrast, when viewing a static display, viewers can re-inspect parts of the display as frequently as they wish and eye-movement research has suggested that viewers re-inspect parts of a graphic or visualization many times in the process of comprehension (Carpenter & Shah, 1998; Hegarty, 1992). One possible function of these multiple eye fixations is to relieve working memory by using the external display as an external memory aid.

A related characteristic of non-interactive-dynamic displays is that they play at a constant rate. We know from classic models of human cognition that basic cognitive processes such as encoding and comparing stimuli take in the order of tens to hundreds of milliseconds (e.g., Newell & Simon, 1972). Since these cognitive processes are clearly involved in understanding dynamic displays, there is a question of whether students comprehension processes can keep up with the rapidly changing stimuli shown in dynamic displays. This is an even greater problem when several changes are shown at once in the display and these changes need to be mentally integrated, for example, to understand how a machine works or how weather patterns change. With static media such as text, people can speed up or slow down their intake of information from the external display as a function of difficulty of comprehension (Just & Carpenter, 1986) but this is not possible with dynamic displays because of their transitive nature.

Finally, in non-interactive-dynamic displays, the author rather than the viewer determines the sequence of frames. For this and the reasons discussed above, the viewer may be much less active in learning from dynamic displays than from static displays, a type of "couch potato" as characterized by Schwan and Riempp (2004). For example, in my own research I have pointed out that when learners read text and static diagrams describing dynamic processes, they are often induced to mentally animate the static diagrams (Hegarty, Kriz, & Cate, 2003). This may be a much more active learning process than passively viewing an external animation, and if successful, may lead to more enduring understanding. Similarly, Bodemer et al. (2004) found that asking students to actively integrate the text and diagrams in a display lead to more learning than giving them a display in which these media were already integrated.

3.2. Advantages and disadvantages of interactive-dynamic displays

Many of the cognitive demands of dynamic displays just described are limited to non-interactive displays. Is it possible to reduce these demands by making displays more interactive?

With the right interactivity, viewers can speed up or slow down the display to match their comprehension speed, and can view and review different parts of the dynamic displays in any sequence, which relieves them of the need to keep earlier presented information in working memory. Thus, as Schwan and Riempp point out, the instruction can be tailored by the learner to his or her needs. Furthermore, when interacting with dynamic displays, viewers are much more active in the learning process.

It is tempting to assume, therefore, that making dynamic visualizations more effective in learning is merely a question of making them more interactive. However, then we fall into the trap of assuming that "interactive-dynamic visualization" and not just "dynamic visualization" is the technology that will solve all of our educational problems. Luckily the authors of the papers in this volume have not fallen into this trap and point out that interactive-dynamic visualizations, while having several advantages, also impose their own demands on the human learner.

First, interactive-dynamic displays must have an interface. As several of the authors in this issue point out, using an interface to a dynamic visualization can be a source of extraneous cognitive load (cf., Sweller, van Merrienboer, & Pass, 1998) that can take the viewer's attention away from the task of understanding and learning from the dynamic visualization. The design of effective interactive-dynamic visualizations must therefore be informed by the research on interface design. In this regard, research in human computer interaction (e.g., Hutchins, Hollan, & Norman, 1986) can provide some prescriptions for how to design natural interfaces that will reduce extraneous cognitive load. However, when the information to be presented is complex, it is not always easy to reconcile principles from human computer interaction with those from educational theory, as experienced by Zahn, Barquero, and Schwan (2004). Therefore, questions of how to create effective natural interfaces that facilitate learning do not have simple answers.

Second, to be effective, interactive displays assume a learner who is not just motivated, but has the metacognitive skills to use the interactivity provided. This is an important issue raised by several of the authors of this volume. For example, in the discussion section of their paper Rieber et al. describe a study in which students were given interactive control over whether to view conceptual messages as well as a simulation of Newton's laws of motion. Although their research has shown that students learn more from simulations that include conceptual messages, when given a choice of whether to read these messages, most students did not, and focused on the simulation alone. Similarly both Lowe's paper and Zahn et al.'s paper in this volume provided evidence that individual differences in use of interactive visualizations were highly predictive of amount of learning, and in fact that these individual differences influenced learning more than differences between the media or interfaces in their studies.

An important methodology used by several of the papers in this volume is to trace how students actually interact with interactive-dynamic visualizations. Too often, researchers compare learning outcomes from interactive and non-interactive displays and just assume that people are using the interactive displays differently, and in a productive manner. But the research presented in this issue and elsewhere (Hegarty, Narayanan, & Freitas, 2002; Spoehr, 1994) indicates that this is not necessarily true. It is not difficult to track user interactions with interactive computer displays and by doing so we can gain valuable insights about how well students with different backgrounds and abilities can use the various interactive functions that they afford. Since it is clear that not all students have the necessary metacognitive skills to learn effectively from interactive media, teaching students to use interactive media effectively may lead to greater improvements in learning outcomes than changing the medium of instruction. Studies of how learners actually search interactive media might enable us to discover effective strategies of good learners that could in turn be taught to poor learners.

4. Other concerns

Comparing and contrasting the papers in this volume also raises some other issues that perhaps need more attention in the literature on learning from dynamic displays. The first issue is the type of material to be learned. Papers in this volume have examined learning of learning about meteorology (Lowe), knot tying (Schwann & Riempp), population dynamics (Ainsworth & Van Labeke), lakes as ecosystems (Zahn et al.), basic Newtonian physics (Rieber et al.), how mechanical systems work (Bodemer et al.), and statistics concepts (Bodemer et al.). It is unlikely that the same types of dynamic media will be equally effective for learning about such disparate topics. Indeed, this is evident in the papers in this special issue. For example, people in Schwann's study were able to use interactive video very effectively when learning how to tie knots, and in Bodemer et al.'s study, students were able to use the interactivity effectively to create integrated displays. In contrast, students in Lowe's study on learning meteorology learning and Zahn et al.'s study of learning about ecosystems were less effective in using dynamic media. One thing that is often missing from studies of learning from media is an analysis of what is to be learned (i.e., a task analysis) and how a dynamic environment might be structured to facilitate that learning. By starting with such a task analysis, Narayanan and Hegarty (2002) were able to develop interactive visualizations in two different domains (mechanics and computer algorithms) that were more effective than those currently available. Therefore, instead of looking for types of dynamic display that will facilitate all types of learning, we might make more progress if we consider the affordances of different types of visualizations for different types of learning and content.

Second, in addition to studying how to improve external visualizations, we need to focus more attention on students' internal visualization abilities. In my own work, I have argued that one possible reason that animations may not always be more effective than static diagrams is that people are able to mentally animate static diagrams (Hegarty et al., in press). Dynamic media are expensive to produce, so it is important to understand what students can visualize internally, to avoid producing media in situations where they provide no added value. Furthermore, ability to visualize internally is an important aspect of many types of expertise. Recent studies have shown that even when dynamic visualizations are available to experts such as meteorologists forecasting weather or scientists analyzing data, the experts continue to rely extensively on their internal visualization skills and in fact manipulate internal visualizations more often than they use the computer interface to manipulate the external display (Bogacz & Trafton, 2002; Trafton, Tricket, & Mintz, in press; Trickett & Trafton, 2002). It is clear therefore that external visualizations do not always substitute for internal visualizations, and perhaps the development of internal visualization skills should be an important educational goal as well as the development of effective external visualizations.

In summary, the papers in this volume indicate a significant forward step in our understanding of learning from dynamic and interactive media. In particular, they move beyond a simplistic view of dynamic displays as realistic simulations of visible events, and consider the ways in which distortions, augmentations and visualizations of non-visual phenomena can be instructive. Second, they address some of the challenges as well as the advantages of learning from dynamic displays. Third, they address some of the cognitive abilities and skills that might come into play in learning from interactive displays. Finally, the papers in this volume report relevant data, including process data on how people learn from media, which can provide important new insights. In addition to these important steps, we need more attention to what is to be learned in a given situation and the abilities (especially internal visualization abilities) that learners bring to the situation in order to improve our understanding of how dynamic media can be best used in the educational process and how the educational process itself must adapt to the availability of new media.

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