Commentary

Learning in complex domains: when and why do multiple representations help?

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1. Introduction

For some time, work in cognitive science has been attempting to understand learning in complex domains that involve multiple variables and processes. All of the papers in this volume deal with learning in complex domains, e.g., chemical reactions, weather phenomena, functional relationships in economics, optics, and metabolism. Frequently, the variables and processes in these domains seem to operate in ways that appear random, with nondeterministic outcomes—unless of course you are an expert in the domain. A mark of that expertise is being able to see the patterns that are meaningful in the domain and that portend effects in relatively deterministic ways. How is it that one comes to understand these complex domains? What sorts of representations do experts use to help them understand the patterns and relationships among variables? How do nonexperts in the domain gain access to these patterns and relationships? The papers in this special issue are united around the common theme of attempting to understand the impact of verbal and nonverbal representations in acquiring greater expertise in a variety of complex domains. In other words, the researchers are all concerned with how learners make sense of important concepts and relationships in complex domains based on verbal and visual input information.

Efforts to understand how learners integrate and capitalize on verbal and visual information are not new (e.g., Levie & Lentz, 1982; Mandl & Levin, 1989; Willows & Houghton, 1987). However, the advent of ubiquitous multimedia resources stimulated renewed interest in the role of nonverbal representations, especially those that convey dynamic relationships. At first blush it seemed that multimedia resources

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would ‘solve the problems’ of learning in complex domains because they could show learners how variables interacted and related to one another. But as has happened any number of times with new technologies, research undertaken to demonstrate an advantage for multimedia systems soon found that learners could fail to learn what the designers intended just as easily from multimedia as they could from unimedia (see for discussion Cognition and Technology Group at Vanderbilt, 1996; Kozma, 1994). That is, merely showing the learner a dynamic process did not miraculously produce understanding of that process. The papers by Mayer and Kozma discuss some of these ‘first generation’ efforts and contrast them with their own later efforts to more precisely understand the impact of multiple forms of information representation on learning. Such ‘second generation’ interests characterize the five other papers in this issue.

2. Lessons from first generation work

Summarizing this first generation of work, Mayer proposes that there are three processes in which the learner needs to engage if learning is to occur, whether from visuals (static or dynamic), verbal information, or both. Learners need to select, organize, and integrate the information before them. But how do they know what to select, how to organize it, and what forms of integration make sense? These three processes are difficult to carry out when learners are novices in a complex domain, because they often have no experiences or prior knowledge that could guide selecting, organizing, or integrating. This dilemma is not unique to multimedia. There is a long history in text processing literature of efforts to use a variety of structural cues (headings, typography, paragraphing) to cue learners to important information and the relationships among elements in the text (see for reviews Lorch, 1989, and Goldman & Rakestraw, 2000). Such efforts are successful in improving learning from text to the degree that learners are able to interpret the cues. A parallel effort has occurred in research on multimedia insofar as researchers have arranged verbal and visual information in ways designed to help learners see connections. Mayer’s research is an excellent example of this strategy. He and his colleagues have found that arrangements of verbal and visual information that highlight important relationships, remove irrelevant information, and manage the information so that learners’ working memory resources are not overloaded, tend to produce better learning. These effects override the static-dynamic dimension of visual information: Mayer found no benefit of dynamic visuals, at least in the domains that he investigated (physical devices, lightning storms). In other domains, such as that of chemical reactions, the dynamic properties of visual displays may be more powerful because they convey information that is much harder to access from static visuals or from verbal descriptions of dynamic processes (Kozma, 1994).

The work of Mayer and colleagues, plus the formulation presented in this issue, help us understand some of the consistencies in the processing of verbal and visual information. What Mayer’s work has not done is capitalize on potential differences in the information, and relationships that might be made accessible to learners.
through different media. That is, computer-based media present affordances for information presentation not available in traditional paper and pencil. Efforts to grapple with these issues more deeply constitutes what might be called ‘second’ generation efforts to understand the impact of multiple forms of representation on learning. The remaining papers in the issue begin to address these second generation issues.

3. Issues for second generation research

There are four second generation issues that the work reported in this issue addresses: Media-enabled affordances and computational efficiency, Active processing, Support for processing, and Limits set by prior knowledge.

3.1. Media-enabled affordances and computational efficiency

The key to understanding the effective and facilitative effects of multimedia environments is to examine media-enabled affordances and the kinds of relationships that they can depict, rather than media per se. Furthermore, it is critical that the affordances match the task demands, i.e., the purpose for which learners are processing the information. Schnotz and Bannert refer to this match as computational efficiency. That is, some representations may be very well suited to certain learning tasks, but to use the information for other tasks the learner may need to transform the representation to match the task demands. Having to transform the representation places additional processing demands on the learner, and the learner may not make the transformation. Schnotz and Bannert’s work optimizes the results of active processing by fitting the representation to the kind of relationship learners need to focus on in order to be successful at the outcome task. Consistent with this line of thinking, Kozma points out that one design consideration in the use of multiple representations and media is careful analysis of the requirements of the task, and the kinds of representations that will best meet these requirements.

3.2. Active processing

Even if there are different affordances of different media and these are well-matched to the task demands, none of this careful design is likely to matter unless learners are actively processing the information and trying to make sense of it. Efforts to understand how to foster active processing and how to optimize the results of that active processing are another important second generation issue. Several of the papers investigate various means of support. Kozma’s work suggests that student discourse around linked representations is a very effective means of supporting active processing of the representations. Student discourse around representations also has the added benefit of engaging learners in scientifically authentic ways because such discussions mirror the kinds of scientific discussions that take place among bench scientists.
3.3. Support for processing

Other papers in this issue indicate that the effectiveness of various kinds of support is mediated both by the kind of task and the knowledge level of the learner. Different forms of help encourage different kinds of processing, and care needs to be taken to make sure that the kind of processing, being supported, is consistent with the demands of the outcome task performance. For example, with respect to task, Seufert obtained different effects of her help conditions, depending on whether learners had to recall material or answer comprehension questions. This result is consistent with a long tradition of research on transfer-appropriate processing (Morris, Bransford, & Franks, 1977). Support for processing needs to help learners generate representations and ways of thinking about the information that are consistent with those needed for the target task. The Stern, Aprea, and Ebner paper and the Lowe paper confront learners with tasks that are consistent with the processing of the visual representations per se. That is, learners are asked to construct a graphic representation as part of the outcome task. The graphic representation task, as compared to producing a verbal description, should encourage learners to attend to key elements of the visual representations in the learning material. Graphic representation tasks might also encourage learners to convert verbally presented information to a depictive mode. However, based on the individual differences in the Stern et al. and in the Lowe results, success at extracting the dimensions critical to the construction of depictive representations is highly variable. A very nice finding in the Stern et al. paper is that those who did extract the critical dimensions and construct higher quality graphs also performed better on other tests of learning.

3.4. Limits set by prior knowledge

Prior knowledge effects on the success of active processing and efforts to support it are pervasive. Lack of knowledge usually places limiting conditions on learners’ success. Overcoming learners’ ‘novice’ status in complex domains is often not simply a matter of presenting the right material, or instructing learners to use a particular strategy. Lowe’s detailed analyses of the processing strategies of novices examining meteorological patterns clearly illustrates the magnitude of the issue. Novice learners in his study were captured by the perceptually salient features of the displays and often missed the underlying principles and relationships. Likewise, novices in Kozma’s work focused on surface features, rather than underlying principles, when comparing multiple representations of chemical reactions. A focus on the surface level rather than the deep, underlying principle or concept is a classic distinction between domain experts and novices (Glaser & Chi, 1988).

Nevertheless, or perhaps because of this classic difference, a number of the efforts reported in the papers in this issue are precisely targeted at supporting learners to engage in deeper, sense-making activities by manipulating the instructional conditions. The papers reflect a variety of instructional conditions to foster novices looking beneath the surface and engaging in active processing. For example, as previously mentioned, Kozma had students engage in discourse about four linked representations.
of chemical reactions. In another example, Lewalter encouraged students to engage in active processing through the generation of think-aloud protocols. She was interested in the strategies learners adopted for interpreting and understanding dynamic animations versus static, sequenced frames that illustrated the path of the light and object distortions that occur as a result of gravitational lensing. The think-alouds of the learners revealed that rehearsal of the information was the overwhelmingly dominant strategy, regardless of the kind of visual (dynamic animation, static) that was presented. In the case of optics, learners had so little knowledge that could help them understand the new information that they did not have the option of using different strategies for the two kinds of presentations. In both cases they repeated what they saw, possibly in an effort to accurately encode exceedingly unfamiliar information. With greater familiarity/experience with the topic, there might be evidence that learners processed the dynamic and static differently. As it was, there were very slight differences in what was learned as a result of essentially similar processing of the information.

The limiting effects of prior knowledge are also clearly illustrated in the Stern paper. In that work, learners with varying levels of knowledge of economics were differentially able to take advantage of graphs showing relationships among economic variables. For the low knowledge learners, the lack of understanding of fundamental concepts of graphing and economics prevented them from noticing the relationships that those of higher knowledge were able to notice. However, when lower knowledge learners were presented with graphs that scaffolded more of the underlying concepts, they were better able to process and understand the economics principles that were at issue. Stern’s work is an excellent example of pushing for deeper understanding of the conditions needed to support learning on the part of differentially prepared students. Knowledge differences demand different forms of support for student learning.

4. Directions for the future

What stands out as a theme in the papers in this issue are the efforts to push for deeper understanding of the dynamics of learning by trying to characterize in detail the role that different forms of representations play in facilitating learning, and why they play that role. Although the theory is emergent, the seeds of it are present in models such as that of Schnotz and Bannert. In their model they emphasize the precise mapping of depictive and verbal representations—where they overlap and where they complement one another. They propose that learners engage in analogical processing to determine similarities and differences across multiple representational forms, thereby tying their model of multimedia learning to the broader class of analogical models of learning (e.g., Gentner & Markmann, 1997). Efforts to make learners’ thinking visible through think aloud techniques and through peer dialogue are critical to knowing whether processes such as analogical reasoning are indeed at work, as learners attempt to work from what they do know to learning in complex domains where they know little. As well, the effort to engage in discourse (either
with self or with peers) can facilitate new insights, connections, and noticings. Careful study of externalized thinking, in conjunction with comparisons of learning outcomes that result from different juxtapositions of multiple representations, will provide the information needed to advance our understanding of learning in complex domains. The papers in this issue have charted some very promising directions for this further work.

References


