Pergamon

Learning and Instruction 9 (1999) 419–425

Learning and
Instruction

Commentary

What is different about interactive graphical representations?

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1. Introduction

The cognitive benefits of reasoning with *static* diagrams have received much interest (e.g., Glasgow, Narayanan & Chandrasekaran, 1995; Larkin & Simon, 1987). Several models have been proposed to account for the cognitive processing that occurs when diagrams are used as an input for problem-solving (e.g., Larkin, 1989; Hegarty, 1992). In contrast, there has been much less theoretical treatment of the cognitive benefits of *interactive* graphical representations, i.e., those that are computer-based and which exploit the computational functionality provided by computers. I was interested to see, therefore, what new claims were being made in this collection of papers about the added value of learning with interactive graphical representations as opposed to just static graphical representations.

As a baseline many of the papers refer to the benefits of using static diagrams during learning compared with using other kinds of static representations (e.g., sentential, algebraic), drawing on well-known arguments about their cognitive effects. Examples include the ability of diagrams to reduce search and working memory load by acting as place holders and through organising information spatially. At a general level, the theorising of Larkin and Simon (1987) is now widely accepted, such as their proposal that the effectiveness of an external representation depends on how easy it is to extract the information that is explicit in it. Thus, static diagrams are thought to provide a more effective way of solving problems than other kinds of representations because their perceptual properties enable solutions to be more easily derived. More specifically, Dobson (this volume) claims that some graphical forms are better than others for problem-solving because of their inherent structure and the language used to describe them. For example, he argues that cubes are more effective than Venn diagrams in helping people solve logic problems because: “the symmetry

PII: S0959-4752(98)00055-3

enables an efficiency for the problem solver and a computational ease in processing the representation. The cube has a rich language of description much richer than the Venn diagram and because of the familiarity of the language used to describe the components computations are simplified." With respect to the learning process itself, Cox (this volume) discusses how the semantic properties of graphical representations may force the learner to become aware of their poor problem comprehension since to construct the correct solution requires them to be determinate. With language, on the other hand, learners can translate a given problem in terms which are somewhat vague, concealing from themselves a complete understanding of it.

By outlining the properties and benefits of static graphical representations an implicit assumption is often made that the same holds true for interactive graphical representations. But what I really want to know is whether there are any additional benefits that can be derived from making graphical representations interactive. Is it possible that they offer more scope for making problem-solving even easier? Can interactivity enable the information required to solve problems to be more readily available and usable to the learner? If so how?

When considering what the added value is of making graphics interactive we should also consider what the added costs might be if learning is made *easier*. In particular, what will someone's understanding of a domain be like when they no longer have to do much of the problem-solving, themselves, but instead can rely on the representation to do it for them? A critical question, therefore, is determining how much computation to "hand over" to the representation and how much to leave for the learners to do themselves. This requires developing interactive graphical representations in combination with appropriate cognitive tasks for the learner to do during the learning process, so that they can develop the right kind of computational skills. To achieve this balance, however, needs a better understanding of how internal and external representations are integrated during learning. It is this set of concerns that I reflected upon when reading this collection of papers.

2. How do interactive graphics facilitate learning?

In the introduction, Dobson suggests that one of the main benefits of interactive graphic representations is that they can be constructed so that the user may actively manipulate them in ways which reflect the underlying behaviour of the subject material. More specifically, Cheng (this volume) argues that they can make the underlying relations of a domain more accessible than can static representations. By "accessible" Cheng refers to the facilities that a computer system can provide to help visualise the various forms of the relations that need to be understood to solve problems in that domain. Thus one of the main benefits is the flexibility and plasticity provided by the computer to display and dynamically transform representations — something which static displays are unable to do.

So how does this work? At one level, the computer can act as a drawing and editing aid, allowing learners to rapidly construct diagrams and make changes to them — something that is extremely tedious to achieve with paper-based versions.

Thus, instead of having to laboriously draw by hand a Venn diagram or an electric circuit, and then start all over again when the learners realise that the configuration they have just drawn is wrong, the computer can do it instantaneously for them. The computer can also generate alternative diagrams in response to minimum input from the learners, allowing them effortlessly to visualise a range of different representations or possible solutions.

Clearly, one of the main benefits provided by interactivity is that it can greatly reduce the amount of effort required by the learner to construct and manipulate the graphical representations used when problem-solving. A question this raises, though, is to what extent does this ability make the problem-solving component of a task easier to solve and if so, how does it do so?

The authors who address this issue do so again by extending the arguments made about the benefits of static diagrams. In particular, one suggestion is that solutions can be more easily read off from interactive diagrams compared with static versions, meaning fewer inferencing steps are required to come to a conclusion. Take Cheng's research on law enforcing diagrams (LEDs) as an example. One instantiation of the LEDs is the AVOW diagrams that he has developed as an alternative representation for the conventional electrical circuit diagram. The main difference between the two kinds of diagram is that the former allows more information to be interdependently represented and manipulated in the same perceptual space. Cheng claims that this property makes it easier to use the AVOW diagram compared with the conventional one, because it transposes the problem to be solved from one of circuit decomposition and algebra to one that is more perceptually oriented, involving the use of simple geometry. In essence, interacting with the AVOW diagram entails fitting shapes together in a particular configuration. Cheng further argues that the act of manipulating the various parts of the AVOW representation enables immediate perception of whether the resulting diagram is the right shape or size. For example, if the AVOW diagram turns out to be squat in shape rather than oblong then this indicates a short circuit. Hence, it is generally easier to spot mistakes in the manipulations of LEDs than it is to find errors in informationally equivalent electric circuit diagrams.

This line of reasoning is redolent of the arguments put forward by Bauer and Johnson-Laird (1993) on the effects of using different kinds of static diagrams for solving logic problems. In one of their studies, they provided subjects with various kinds of diagrams to solve double disjunctive logic problems. One of these was a jigsaw representation: the subjects were required to solve the logic problem by completing a path from one side of the figure to the other, by inserting shapes corresponding to people specified in the reasoning problem into slots in the paths corresponding to particular places. Instead of having to make inferences from sentential descriptions of the logic problem (as is the case with the conventional procedure), the subjects were required to solve a much simpler problem that was essentially a perceptual task (Scaife, & Rogers, 1996). As Bauer and Johnson-Laird (1993) explain:

> in the case of the diagrammatic problems, the subjects form a visual representation of the diagram, and in their mind's eye they can imagine moving the pieces (i.e., they carry out visual transformations of images). Bypassing the construction of

> the meanings of verbal premises and manipulating visual images appears to reduce the load on working memory and to speed up the process of inference. (p. 373)

What appears to be happening in these situations, therefore, is that the problem space is being heavily constrained. Subjects are not required to generate alternative solutions by themselves before deciding which of the possible solutions is the correct one, but instead can quickly work out the answer to the problem through carrying out a perceptual task. Instead of having to make explicit what is implicit in the representation, they need only read off what is already largely explicit in the representation. Which brings me back to the concern raised in the introduction: in making the problem-solving task easier to solve in this way what are the knock-on effects in terms of how the learner will understand the domain? Could it be that learning in this simplified problem-solving context could transform what was previously about making systematic deductions when using abstract representations to one that is more about solving perceptual puzzles? Whilst none of the authors explicitly proposes that we should be moving towards introducing simplified forms of problem-solving as a learning strategy, one is left wondering about the pedagogical value of developing graphical representations that are geared towards making problem-solving easy.

Another argument put forward about the benefits of interactive graphics is that they can reduce the amount of low level computational "number-crunching" that the learner has to do and, in so doing, release more mental effort which can be spent doing other things. By greatly reducing the amount of "low-level" cognitive activities (e.g., drawing and redrawing diagrams) normally required when learning, it is assumed that students can focus their attention instead on more "higher-level" cognitive tasks (e.g., exploring more of the problem space). As suggested by Cheng: "the medium of computers allows routine computations to be off-loaded enabling learning to be more compact and enriched".

But what exactly do "enriched" and "more compact" mean with respect to learning in this context? It is not obvious other than perhaps suggesting that through obviating the need to do low level tasks, learning can be channelled towards developing higher level cognitive skills and in so doing enable a deeper understanding of the domain. Such an idea is indeed very attractive. But is it possible? Can learners simply switch from one mode of working to another at the click of a button? After reading the paper by Cox (this volume) on the pedagogical value of constructing graphical representations, I was struck by the possibility that the opposite may be true: that it could actually be detrimental to learning if too much computational offloading of "low-level" tasks is handed over to the computer. As Cox points out, the process of externalising a representation — like drawing a diagram of a cube — greatly assists the learner in turning an initial mental representation into an external representation, which in turn facilitates problem-solving. In particular, constructing graphical representations can allow the learner to represent information explicitly, make missing information explicit and enable them to lay out information in ways that will help them come to a solution and know what to do next. Having this part of the problem-solving done for them by the computer may actually transform what is usually an integral part of learning into a "black box" mechanical process. In doing so, it may make it too difficult for the learner to carry out "higher level" cognitive tasks and, importantly, understand what they are doing when interacting with ready-made representations — not having had the opportunity to go through the process of constructing them themselves.

This is not to say that there isn't any benefit from interacting with pre-constructed graphical representations. Certainly, as indicated by Cheng's research, they can be effective, especially for trying out alternative solutions. However, we need to have a better understanding of how they work and when and how to use them in the learning process. As suggested in the introduction, more leverage may be gained in tackling this issue if we start to consider how internal representations are developed, used and integrated in combination with the way external representations are used and manipulated during learning tasks. To this end, a conceptual framework that takes on board the notion of multiple representations is needed.

3. Integrating internal and external representations: a way forward?

One of the main properties of interactive graphics which static graphics do not have is their ability to allow multiple representations to be combined and to dynamically change in relation to each other in various ways. For example, moving a slider representing the amount of oxygen at an abstract level can be shown to have consequences for a given ecosystem in another representation. This process of linking and manipulating representations at the interface is what we have called "dynalinking" (Rogers, & Scaife, 1998). One of the benefits of dynalinking is that it can help learners visualise mappings between representations at different levels of abstraction. In our own research we have investigated how dynalinking can facilitate better the integration of abstract and concrete representations. We looked at how the abstract formalisms that are an integral part of ecology (e.g., food webs, cycle diagrams) can be more explicitly linked with more familiar concrete representations. In particular, we aimed to allow the child to see the mapping between "real" events and abstract representations of them. For example, in one of our projects we built a suite of interactive software modules of a simple familiar ecosystem — a pond. A concrete simulation of the pond was shown (and could be interacted with) which was dynamically linked to a variety of diagrammatic interfaces. Altering aspects of the diagram (e.g., removing the tadpoles) caused changes in the pond simulation (dying of the tadpoles) and vice versa. We predicted that providing this configuration of multiple interconnected dynamic representations would support better understanding and the ability to make generalisations from the diagrams — something that children find difficult to do when taught using existing learning methods. Preliminary empirical testing has shown how children (aged 8–10 years) have been able to learn more effectively from this form of interactive graphical representation (Rogers, Scaife & Jones, in preparation). In one post test there was a significant improvement in the children's ability to reason with abstract food web diagrams and to explain what would happen when various organisms were removed from the ecosystem.

In conjunction with dynalinking, computer-based interactive graphics can be used to focus the learner's attention more effectively on key aspects of the domain that are relevant to a given stage of a problem-solving task. With static diagrams various coding conventions are typically used to draw a person's attention to salient aspects (e.g., the use of bold and underlining to highlight core features). Abstract symbols are also used to show relations between related aspects (e.g., the use of arrows to show relationships between entities). With interactive graphics, additional forms of temporal and graphical constraining are available. For example, parts of a display may be concealed or exposed as and when needed; symbols may change colour or flash to show a connection that is relevant between two kinds of representations (or parts within one) and so on.

One of the main cognitive benefits of interactive graphical representations compared with static representations, therefore, is their ability to explicitly support the integration of multiple representations. As discussed by Cox, the ability to translate and integrate new and stored knowledge is critical to understanding and being able to reason about a domain. Supporting that process more effectively can allow people to capitalise on the complementary properties of different modalities, using them concurrently or switching between them. Systems like Hyperproof (which is discussed by four of the authors), which have been shown to significantly help students solve first order logic problems, may be facilitating learning partially through the provision of multiple linked representations.

A central question for anyone who is in the business of explaining and designing interactive graphics therefore is: how can we determine the most effective way of displaying and coordinating multiple representations at the interface whilst at the same time supporting the interactions and activities which the user should be able to control and do for themselves? And finally, a personal plea: why does everyone interested in how graphical representations work nearly always select logic as their domain of study? What about investigating how interactive graphical representations can be designed to aid the learning of more open-ended topics in domains such as chemistry, biology and economics — for concepts and problems that students equally struggle to get to grips with.

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