Intelligible Multimedia

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Abstract

Technological advances that facilitate the infusion of intelligence and graphics into interfaces provide an important opportunity for research on cognitive aspects of visual representations to influence the design of smart graphic user interfaces to information-rich applications. In this context, we report on a cognitive model of multimodal comprehension and empirical results on interactive multimedia information presentations developed according to this model. These are preliminary results emerging from an ongoing long-term research program investigating cognitive constraints on multimedia information presentation design.

Introduction

Visual representations are already a major ingredient of the modern graphical user interface. With the advent of the world wide web, graphical representations have also become a pervasive component of Interactive Multimedia Information Presentations (IMIP). We use the term IMIP broadly, to encompass interactive systems designed to convey rich and complex information to the user. Some examples are educational CD-ROMs, hypermedia systems, and commercial as well as educational web sites. Future systems of this kind will not only incorporate advanced graphical capabilities, but also exhibit intelligent and adaptive behaviors. But smart graphics are useless unless these are also effective graphics. In other words, graphics, intelligent or not, must be intelligible. Technological advances that facilitate the infusion of intelligence and graphics into interfaces provide an important opportunity for research on cognitive aspects of visual representations to influence the design and adaptation of graphics in information-rich interfaces.

It is in this context that we embarked in 1996 on a long-term research project to investigate cognitive models of (and constraints on) multimodal comprehension. The term *multimodal comprehension* refers to the process of comprehending information conveyed in multiple formats and sensory modalities, such as diagrams, animation, narratives and text.

In the last three years we have investigated the design of IMIPs to explain mechanical systems and computer algorithms. This has resulted in the design, prototyping and evaluation of several versions of a hypermedia manual explaining the inner workings of a mechanical device, the flushing cistern, and interactive animations of several algorithms. These systems have been empirically studied in experiments involving nearly a thousand participants so far. We have investigated the role of verbal and spatial representations in conveying information about the behaviors of two kinds of dynamic systems: physical devices whose behaviors are governed by causality, and abstract devices whose behaviors are governed by logic. We are currently studying meteorological systems that fall somewhere in-between the two extremes of physicality and abstractness. What follows is a summary of theoretical developments and empirical findings stemming from this research so far.

A cognitive model of multimodal information integration and comprehension

We have developed a cognitive model of how people comprehend multimedia presentations, including text, static diagrams, animations, and aural commentaries, that explain how systems work (Narayanan and Hegarty 1998). This model has been developed and generalized based on our research in the domains of mechanics and algorithms (e.g., Hansen et al., 1998; Hansen, Schrimpsher and Narayanan, 1998; Hegarty et al., 1999). This model can be seen as an extension of constructivist theories of text processing (e.g., Kintsch 1988) that view comprehension as a process in which the comprehender uses his or her prior knowledge of the domain and integrates it with the presented information to construct a mental model of the object or situation described. In addition to text comprehension skills, our model proposes that comprehension is dependent on spatial skills for integrating information in text and graphics, and encoding and inferring information from graphic displays (Hegarty and Sims 1994; Hegarty and Kozhevnikov 1999).

According to this model, people construct a mental model of a dynamic system by first decomposing it into simpler components, retrieving relevant background knowledge about these components, and mentally encoding the relations (spatial and semantic) between components that are evident in the external presentations to construct a static mental model of the situation. They then mentally animate this static mental model, beginning with some initial conditions and inferring the behaviors of components one by one in order of the chain of causality or logic. This mental animation process depends on prior knowledge (e.g., rules that govern the behavior of the system in question) and spatial visualization processes. We postulate that mental model construction under these circumstances requires the following stages.

Stage 1: Decomposition

Graphical representations used in visualizations typically contain several diagrammatic elements such as geometric shapes and icons. These represent elements of the target domain, for example, a geometric shape might represent a mechanical component in a diagram of a machine or an icon might represent a measurement of atmospheric pressure in a meteorological chart. The first step in comprehension is to parse the graphical displays into units that correspond to meaningful elements of the domain. This process might be considered to be analogous to identifying discrete words in a continuous speech sound.

In the mechanical domain, we have found that decomposition is often a hierarchical process in that complex visual units, representing complex elements of the domain, are often made up of sub-units. Decomposition can cause comprehension problems because diagrams are often under-specified in that they do not contain enough information for a user to identify whether two or more connected units represent separate elements or parts of a single element from the target domain (Ferguson and Hegarty 1995). Similarly, in displays of more abstract data, the identification of different data series in a graph, for example, can be problematic if the visual variables used to display the different variables are not visually discriminable, or if too many different data series are displayed (e.g., Kosslyn 1990; Tufte 1983; 1997).

Stage 2: Constructing a Static Mental Model by Making Representational Connections

A second major stage in comprehension involves making memory connections among the visual units identified during decomposition. This stage involves making two types of connections: (a) connections to prior knowledge and (b) connections between the representations of different domain elements.

Connections to Prior Knowledge. First, the comprehender must make connections between the graphical units identified in the previous stage and their real-world referents. This process will be partially based on prior knowledge of both elements of the domain (e.g., atmospheric pressure) and the graphical conventions used to portray the elements visually (e.g., isobars indicating regions experiencing the same pressure). However, for novices, this information will have to be provided in an accompanying text. In addition to helping identify the real-world dimensions to which visual variables refer, prior knowledge can also enable the user to access other conceptual knowledge about typical behaviors of domain elements (Narayanan 1992; Narayanan and Chandrasekaran 1991; Narayanan, Suwa and Motoda 1994a).

There is also experimental evidence that more realistic depictions lead to improved ability to mentally animate systems. Schwartz (1995; Schwartz and Black 1996) studied tasks in which subjects judged whether marks on the top and bottom boards of an open hinge would meet if the hinge was closed, or whether marks on two interlocking gears would meet when the gears rotated. Subjects who viewed more realistic pictures of the hinge or gears tended to solve the problem by mentally animating the depicted system. In contrast, subjects who viewed schematic diagrams solved the problems analytically. Schwartz and Black (1996) argued that information about the surfaces of mechanical components, evident in realistic pictures but not in schematic diagrams, was necessary to construct a mental model of the system behavior.

Connections to the Representations of Other Components. Second, the comprehender must represent the relations between different elements of the system. In a mechanical system, this involves understanding the physical interactions (connections and contact) between components. For more abstract domains such as meteorology, this involves noticing how variables depicted by different graphical elements co-vary in space or time and how they interact to cause some weather pattern.

In understanding how a machine works from graphical depictions, information about the spatial relations between mechanical components forms the basis for inferences of component motion. Thus, people can infer how components move from information about their shape, and connectivity to other components (Hegarty 1992; Narayanan, Suwa and Motoda 1994b). Previous research on mechanical reasoning and comprehension suggests that viewing a diagram is sufficient for constructing a representation of the spatial relations between objects in a diagram (e.g., Hegarty and Just 1993; Hegarty et al. 1999). However, this research focused on "planar" mechanisms in which the important spatial relations are in one plane, so that they can be depicted in two-dimensional diagrams. In more recent research we considered mental animation of "spatial" mechanisms whose linkages are not in a single plane so that they cannot be depicted in a single two-dimensional diagram. We found that ability to mentally animate these spatial mechanisms is selectively related to the ability to take different perspectives in space (Hegarty and Kozhevnikov 1999). This is an important finding, when coupled with recent research indicating that mental representations of objects are viewpoint dependent, i.e., retain the perspective from which an object has been viewed (e.g., Tarr 1995). In the context of this research, Hegarty and Kozhevnikov (1999) developed a psychometric test of perspective-taking ability, which may turn out to be an important predictor of ability to comprehend complex spatial visualizations.

Stage 3: Making Referential Connections

An important component of integrating information from different displays is co-reference resolution: making referential links between elements of the different displays that refer to the same entity. This is similar to the processing of co-references in natural language discourse (e.g., Gordon and Hendrick 1998).

When diagrams are accompanied by text, the reader needs to make referential links between noun phrases in the text and the diagrammatic units that depict their referents (Mayer and Sims 1994; Novak 1995). Visual and verbal information about a common referent must be in working memory at the same time in order to be integrated (Mayer 1989). Thus, people who read a text-and-diagram description of a machine have better comprehension if the text is placed close to the part of the diagram to which it refers (Mayer 1989; Mayer and Gallini 1990) or if an auditory commentary is presented simultaneously with an animation (Mayer and Anderson 1991; 1992; Mayer and Sims 1994). A multimedia visualization can increase the likelihood of this by presenting visual and verbal information close together in space and in time.

By monitoring people's eye fixations as they read text accompanied by diagrams, Hegarty and Just (1989; 1993) observed how people coordinated their processing of a text and diagram to integrate the information in the two media. Interpretation of eye-fixations in this research is based on the empirically validated eye-mind assumption (Just & Carpenter, 1976) that when a person is performing a cognitive task while looking at a visual display, the location of his or her gaze on the display corresponds to the symbol that he/she is currently processing in working memory. People began by reading the text and frequently interrupted their reading to inspect the diagram. On each diagram inspection, they tended to inspect those components in the diagram that they had just read about in the text. This research indicates that information in a text and diagram describing a machine is integrated at the level of individual machine components and that the text plays an important role in directing processing of the diagram and integration of the two media. Similar results were found by Baggett and Graessser (1995) when college students were asked to answer questions that required them to engage in causal reasoning about machines presented in illustrated expository text, and by Schrimpsher (1999) when college students were provided with interactive algorithm visualizations. These results indicate that there needs to be a significant overlap between visual and verbal information.

Making referential connections is also a necessary process when people have to integrate information in visual displays, such as graphs. Carpenter and Shah (1998) studied people's eye fixations as they attempted to understand and make inferences from data graphs. They measured the time spent looking between the different data series and between the data series, the axes and the legend of the graphs. Interestingly, a large proportion of time was spent looking back and forth between data series, the legend, and the graph axes, indicating that a large amount of the time spent comprehending the graphs was spent making referential connections between the lines and bars on the graph and their referents.

Stage 4: Hypothesizing causality

The next stage of comprehension involves identifying the potential causal chains or "lines of action" in the system (Carpenter, Just and Fallside 1988; summarized in Hegarty, Carpenter and Just 1990). Previous studies (Hegarty 1992; Narayanan, Suwa and Motoda 1994b) have shown that subjects tend to reason about machine operation along the direction of causal propagation when presented with labeled schematic diagrams. In complex systems with cyclical operations or branching and merging lines of causality, finding the lines of action depends not only on the spatial structure of the machine but also on the temporal duration and ordering of events in its operation. For example, the flushing cistern device has two causal chains (subsystems) that branch and merge and are temporarily dependent on each other. In our studies of comprehension of this device from multimodal presentations we found that subjects were able to infer the motions of components within each causal chain, but had much more difficulty integrating information between the two causal chains.

In domains such as meteorology and algorithms, there is the additional problem that cause-effect relationships between observable behaviors of components and lines of action in the system are not immediately evident from animated visualizations. For example, Lowe (1994; 1997) has found that novices erroneously ascribe cause-effect relationships to weather phenomena visible in typical meteorological animations based on their temporal relationships alone. This strongly indicates a need for visualization techniques that make causal relationships explicit.

Stage 5: Constructing a Dynamic Mental Model by Mental Animation and Inference

The final stage of comprehension is that of constructing a dynamic mental model by integrating the dynamic behaviors of individual components. Cognitive and computational modeling (Hegarty 1992; Narayanan 1992; Narayanan and Chandrasekaran 1991; Narayanan, Suva and Motoda 1994a; 1994b) suggest that this is often accomplished by considering components individually, inferring their behaviors due to influences from other connected or causally related components, and then inferring how these behaviors will in turn affect other components (causal propagation). Thus, if asked to predict the motion of a machine component from that of another component in the system, people make more errors and take more time if the components are farther apart in the causal chain (Baggett and Graesser 1995; Hegarty 1992; Hegarty and Sims 1994). These processes will cause the static mental model constructed in earlier stages of comprehension to be progressively transformed into a dynamic one. This stage can involve both rule-based inferences that utilize prior conceptual knowledge (Schwartz and Hegarty 1996) and visualization processes for mentally simulating component behaviors (Sims and Hegarty 1997; Narayanan, Suwa and Motoda 1995a; 1995b; Schwartz and Black 1996).

Mental simulation of the behavior of machines has been termed mental animation (Hegarty 1992). Mental animation appears to be constrained by working memory capacity such that people are only able to mentally animate one or two component motions at a given time (Hegarty 1992). Working memory demands are imposed when several mechanical components constrain each other's motions, so that the motion of components cannot be inferred one by one (Hegarty and Kozhevnikov 1999) or if imagining the motion of a component changes the configuration of components so that it no longer corresponds to the external display (Narayanan, Suwa and Motoda 1994b). Furthermore, this type of mechanical reasoning is particularly demanding of spatial working memory processes (Sims and Hegarty 1997).

This five stage comprehension model, when applied to a particular domain such as that of simple mechanical devices, reveals potential sources of comprehension error, which in turn can be used to derive design guidelines for IMIPs in that domain (Narayanan and Hegarty 1998). For instance, the first stage of the model predicts that one potential source of comprehension error is erroneous parsing of graphical depictions of a system or process. Therefore, interactive displays ought to be designed to explicitly support accurately parsing the graphical representations they present. This can be accomplished by hyperlinking graphical components to explanations of the entities that they depict, as in the case of a meteorological display in which moving the cursor over any part of an isobar highlights the entire contour and pops up an explanation that the contour represents a region of equal pressure.

Summary of Findings from Experiments with IMIPs

- In several experiments, IMIPs designed according to this comprehension model have outperformed traditional means of conveying information, such as printed descriptions from books and classroom lectures, in the domains of algorithms and machines.
- IMIPs designed according to this comprehension model have outperformed IMIPs not designed according to guidelines derived from this comprehension model, such as an award-winning commercial CD-ROM explaining how devices work and a typical algorithm animation research prototype. This indicates that our theoretically derived and empirically supported guidelines represent a significant improvement over the conventional wisdom in expository multimedia design.
- We have shown that the effectiveness of animations in IMIPs in the domain of machines can be enhanced by encouraging users to engage in predictive problem solving by mentally animating the system in question before presenting them with an external animation of the system's behaviors.
- We have discovered that a user's ability for mental animation in the mechanical domain is related to his or her ability to take different perspectives in space. This indicates that users with this spatial ability may be able to get more out of both mental and externally presented animations. Whether mental animation remains dependent on spatial visualization abilities as the domain becomes more abstract is an open question.
- Animations of dynamic systems are more effective in conveying information when they are "chunked" and embedded in a context and knowledge providing hypermedia environment, as opposed to one-shot and stand-alone animations.
- Ablation experiments (comparative evaluations of complete versions of an IMIP against versions with features or sections disabled) revealed that in an abstract domain such as algorithms, "bridging analogies" – interactive, animated and real-world examples illustrating the core behaviors of the process being explained – significantly improve learning from subsequent animations.
- In the abstract domain of algorithms, printed static versions of IMIPs are less effective than computer-based, interactive and animated versions, when both were constructed according to the design guidelines derived from the comprehension model. When the paper versions are supplemented with problem solving exercises however, perusing those turns out to be as effective as interacting with a computer-based IMIP.
- Contrary to intuition, in the domain of mechanical systems, printed versions of IMIPs appear to be as effective as computer-based versions, including animations. This was true for manuals designed according to our guidelines as well as commercially available guidelines. This brings up the interesting issue of whether the benefits of interactivity and animation are overstated from the perspective of comprehension, and begins to question widely held beliefs about multimedia.

Conclusion

Our research program seeks to answer the following two fundamental questions: (1) What are the design guidelines for effectively communicating different kinds information that typically characterize a complex and dynamic system through interactive textual, graphical and aural presentations? (2) How can the different media components be coordinated and connected along spatial and temporal dimensions to assist in mental integration and comprehension of the information?

This work adds to a growing body of recent research addressing cognitive constraints on multimedia learning, such as that of Mayer and Moreno (1998) who have proposed the following principles: (1) The multiple representation principle: it is better to present an explanation in words and pictures than solely in words. (2) The contiguity principle: present words and pictures contiguously rather than separately. (3) The split attention principle: present words through the auditory channel when pictures are engaging the visual channel. (4) The individual differences principle: the above principles are more important for novice and low spatial ability users. (5) The coherence principle: use few, rather than many, extraneous words and pictures in explanations.

To this we add the following principles emerging from our research: (1) The decomposition principle: provide clues in verbal and visual representations that help users decompose the system or process being explained into simpler components. (2) The connection principle: use words and pictures that help users invoke and connect their prior knowledge to the external representations. (3) The co-reference principle: use interactive and deictic devices to highlight the common referent when multiple verbal and visual references in different media refer to the same object or component. (4) The propagation principle: use words and pictures that help a user understand the physical, causal and logical connections among parts that determine how the behavior of each part of the system or process influences that of others. (5) The mental animation principle: use graphics and interactivity to encourage users to predict, or mentally animate, the process or system that is being explained before providing an external animation.

The emerging picture from our research supports a variation of the "message is more important than medium" adage: the content and structure of the message are more important than interactivity and graphics, but interactivity and graphics can further enhance communication when properly designed. These principles have the potential to provide a sound theoretical basis as well as design constraints for the adaptive, on-the-fly generation of multimedia information presentations by "Smart Graphics Systems" of the future.

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