UNDERSTANDING MACHINES FROM MULTIMEDIA AND HYPERMEDIA PRESENTATIONS

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What is the best way to communicate to someone how a complex system, such as a mechanical or biological system, works? The traditional way is to produce a printed book that combines textual descriptions with different kinds of illustrations, presented on sequential pages. With the advent of multimedia computers and hypermedia authoring tools however, we no longer need to be confined to this traditional medium. For example, we can now choose to present verbal information as written text or as an audio commentary. Similarly, we can present diagrams as static or animated, and images as still photographs or video clips. *Multimedia* presentations, combining some or all of the above media, are becoming increasingly available as educational CD-ROMs and on the World Wide Web. Furthermore, with the availability of new authoring tools, we do not have to be constrained by the linear format of the printed book, in which information is presented and typically read in a sequential order. In *hypermedia* systems, information is presented in a collection of hyperlinked documents, so that information can be browsed in any order.

These technological advances present a tantalizing spectrum of choices to authors of instructional materials. However, there are few empirically validated guidelines for how to choose among the various capabilities for optimal design of hypermedia presentations. There are some widely held beliefs about the effectiveness of these new developments, for example, that diagrammatic representations are better than sentential representations, three dimensional representations are better than two-dimensional ones, animated diagrams are more effective than static diagrams and interactive graphics are better than non-interactive

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graphics (Scaife & Rogers, 1996). However, most of these beliefs have not been tested systematically.

This chapter describes a research program in which we designed, prototyped and evaluated several versions of a hypermedia presentation explaining how a mechanical system works. Although our prototypes describe a specific mechanical system, the flushing cistern, our approach to the design of hypermedia presentations can be applied to explaining any complex system, for example a biological system such as the human circulatory system. In a parallel research project, we have applied our guidelines to the development of interactive animations of computer algorithms (e.g., Hansen et al. 1998; Hansen, Schrimpsher and Narayanan 1998) and we are currently extending our research to the domain of meteorology.

Our design process (illustrated in Figure 1) begins with a review of research on multimodal comprehension, leading to a preliminary model of this process. An initial design for a hypermedia presentation is derived from this model. Then basic research is conducted to refine and elaborate this model. At the same time, the design principles are used to create an initial presentation, which is evaluated by assessing how people interact with the presentation and how well they understand the mechanical systems it explains. The experimental research and evaluation therefore proceed in parallel. The results of the evaluation can be used to redesign the presentation and to suggest further experimental studies (e.g., to examine the causes of particular comprehension failures). The results of the experiments can refine the model that forms the basis of the next design cycle. This process can be repeated to iteratively improve both the design of the hypermedia manual and the model of comprehension upon which it is based.

This design process makes two types of prescriptions about instruction. First it specifies the content of instruction -- what information should be communicated in the hypermedia presentation and in what order. Second it makes prescriptions about the format of instruction -- the media and modalities in which different types of information should be presented. Many studies of the effects of new media and visualizations in education investigate situations in which a new medium is used in the context of a novel method of instruction, such as discovery or collaborative learning (e.g., Edelson, in press; White, 1993). Effects of instruction are compared to learning from traditional lecture and textbook formats. In these situations it is difficult to evaluate whether differences in learning outcomes are due to the new media used, the instructional method, or instructional goals embodied in different pedagogies. In our research, we attempt to design instructional treatments that systematically vary the content and the format of instruction, so that we can evaluate the separate effects of each.

Our research builds on recent research examining the conditions under which multimedia instruction is most effective (e.g., Mayer & Moreno, 1998; this volume; Mayer, 1997; Faraday & Sutcliffe, 1997a; 1997b; Mousavi, Low & Sweller, 1995). For example, Mayer and his colleagues have shown that students learn better from text and diagrams if related visual and verbal information is presented as close as possible in space (Mayer & Gallini, 1990), that people learn more effectively from animations if they are accompanied by simultanous commentaries (Mayer & Sims, 1994) and that people learn more effectively from multimedia information if visual information and verbal information are presented in different modalities (Mayer & Moreno, 1998). Similarly, Faraday & Sutcliffe (1997a, 1997b) have shown that students learn more effectively from movies accompanied by commentaries, if visual cues such as arrows and highlighting draw their attention to the relevant parts of the display as they are described in the commentary. Our research addresses a different question. We ask whether multimedia presentations, including animations, commentaries and hyperlinks, lead to different learning outcomes, compared to traditional printed media when both contain the same information and when both are designed according to available empirically validated guidelines.

A Model of Machine Comprehension from Text and Diagrams

Explaining how machines work using the printed book is a well-established craft since the 15th century (Ferguson, 1977). This medium consists of written text interspersed with various kinds of illustrations, for example schematic diagrams, cross-sectional views, exploded views and realistic depictions of machines. Popular books like *How Things Work* (George Allen & Unwin Ltd., 1967) and *The Way Things Work* (Macaulay, 1988) are excellent examples of this medium. Readers of such books typically have some specific comprehension goal in mind. For example, a reader might want to understand how the machine operates so that he or she can predict its behavior, operate it, or troubleshoot it.

Our approach to developing a hypermedia manual was to first construct a model (essentially a task analysis) of the process of understanding a machine from text and diagrams (Narayanan and Hegarty 1998; Hegarty, Quilici, Narayanan, Holmquist and Moreno, 1999). This model can be seen as an extension of constructivist theories of text processing (e.g., Kintsch 1988), which 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 to construct a static mental model of the situation. They then mentally animate this static mental model to construct a kinematic/dynamic mental model of the system. We postulate that mental model construction under these circumstances requires the following stages. Although we list them in order, we acknowledge that they are not always accomplished in this order.

A. Machine Decomposition by Diagram Parsing. Diagrams of mechanical systems are made up of elementary shapes, such as rectangles, circles and cylinders, which represent objects such as pistons, gears and tubes. The first step in comprehension is to parse the connected diagram into these elementary shapes, i.e., units in the diagram that correspond to subcomponents of the mechanical system.

B. Constructing a Static Mental Model by Making Representational Connections. The second stage in multi-modal comprehension involves making appropriate connections in memory among the components identified in Stage 1. This stage involves making two types of connections: (1) connections to prior knowledge and (2) connections to the representations of other machine components.

First, the user must identify the components, that is, make connections between the diagrammatic elements identified at Stage 1 and their real-world referents. For example, the user might represent that a rectangle represents a piston or a circle represents a gear. Prior knowledge can also provide additional information about components, such as what they are typically made of and whether they are rigid or flexible. This information is valuable in making inferences about how components move and constrain each other's behaviors.

Second, the user must represent the spatial relations between different machine components by building connections between the representations of these components (Mayer & Sims, 1994). In understanding how a machine works, information about the spatial relations between mechanical components forms the basis for inferences about the motions of components, because these spatial relations determine how components affect and constrain each other's motions.

C. Making Referential Connections. When diagrams are accompanied by text, an additional stage in comprehension is that of resolving coreference between the two media, i.e., making referential links between a noun phrase in the text (e.g., "the piston") and the diagrammatic unit that depicts its referent (e.g., a rectangle) (Novak, 1995). This step is crucial to constructing an integrated representation of the common referent of the text and diagram in memory as opposed to separate surface-level representations of the text and diagram.

D. Determining the Causal Chain of Events. When asked to predict the behavior of machines from static diagrams, people tend to reason about machine operation along the direction of causal propagation in the machine (Hegarty, 1992; Narayanan, Suwa & Motoda, 1994; 1995). Therefore, we hypothesize a fourth stage of comprehension that involves identifying the potential causal chains of events in the operation of the machine, or "lines of action" in the machine.

E. Constructing a Dynamic Mental Model by Mental Simulation and Rule-based Inference. The final stage of comprehension is that of constructing a dynamic mental model of the machine, i.e., a representation of how the components move and constrain each other's motion when the machine is in operation. Our previous research

(Hegarty, 1992; Narayanan, Suwa & Motoda, 1994; 1995) suggests that people can often infer this information from a static diagram by a process which we call mental animation. Computational models and empirical evidence suggest that this is an incremental process in which the reasoner considers the components or subsystems individually, assesses the influences acting on each, infers the resulting behavior of each, and then proceeds to consider how this behavior affects the next component or subsystem in the causal chain. It depends on both prior knowledge (e.g., rules that govern the behavior of the system in question) and spatial visualization processes.

Initial Design of a Hypermedia Manual

In a recent paper (Narayanan & Hegarty, 1998), we identified potential sources of comprehension error that users might encounter in each stage of comprehension, and developed hypermedia design guidelines intended to ameliorate these difficulties. These were applied to develop a prototype hypermedia manual that explains how a toilet tank (a flushing cistern) works. Although this is a familiar device, its inner workings are not intuitively obvious. It is relatively complex, having two main subsystems, a water output system that flushes water into the toilet tank and a water inlet system that refills the tank for the next use. Explaining a flushing cistern presents interesting challenges for our theory because its operation involves two causal chains of events that occur in tandem but are also temporarily dependent on each other. The particular toilet tank explained in our manual (shown in Figure 2) also contains a siphon, raising the interesting question of how to explain a basic physics principle in the context of explaining how a specific machine works.

The initial design for our hypermedia manual contained seven sections designed to guide users through the stages of comprehension in our model. Figure 2 contains an image of a screen from the first section of this manual.

Section 1, "Parts": The primary objectives of this section are to help the user in decomposing the machine into its components and building referential connections between elements of text and diagrams. Previous research has pointed out that diagrams are often underspecified in that they do not contain enough information for a user to identify whether two or more connected units in a diagram represent separate objects or parts of a single object (Novak, 1995). For example, a diagram element, such as a line, might represent the edge of an object, or an object itself (a rope). Furthermore, resolving coreference between text and graphics can be a source of comprehension difficulty (Mayer, 1989; Mayer & Sims, 1994). To facilitate users in these processes, the first section of the manual presents a cross-sectional diagram of the toilet tank, in which decomposition is facilitated by labeling the different functional components, by presenting them in different colors, and by allowing users to click on the label of any component and have the component highlighted in the diagram (see Figure 2).

Section 2, "Subsystems": The decomposition of a mechanical system is often hierarchical, such that the system breaks down into functional subsystems, which can themselves be broken down into more elementary components. The objective of Section 2 is to facilitate identifying the functional subsystems to which the components belong -- the water output system and the water input system. The first presentation in this section is a schematic diagram with accompanying text that outlines the various subsystems of the machine tank. This presentation also allows the user to animate an exploded view of the tank in which the input and output systems are separated in space. In two further presentations, the user views diagrams highlighting the components of first the output system and then the input system, each accompanied by text describing the function of the relevant subsystem.

Section 3, "Connections": The objective of Section 3 is to facilitate construction of a static mental model of the machine. This includes identifying the real-world components to which diagram units refer, and retrieving prior knowledge about these components (what they are made of, their principles of operation, etc.). This information is not included in highly schematized depictions, but is necessary for correct inferences about how the machine works (Schwartz & Black, 1996). In this section, the user is shown a cross-sectional view of the toilet tank and taken on a guided tour of the components. Text describes each of the components in turn, pointing out its linkages to other system components, and other information that is not visible in the diagram, such as its material composition and function. Only the text about one component is visible at a time, and to aid the construction of referential connections, the component in question is highlighted in the diagram concurrently with the presentation of the textual description.

Section 4, “Questions”: This section is designed to encourage the user to reason about the causality and dynamics of the machine. Previous research has shown that the generation of ideas or self-explanations improves learning (Chi, deLeeuw, Chiu & LaVancher, 1994). Therefore one of our guidelines is that users should be encouraged to mentally animate the machine (i.e. attempt to predict its behavior) before they are shown animations of the causal chain and movement of the machine. Section 4 does this by presenting users with the static diagram, and a set of multiple choice questions in which users are asked to imagine that a component of the system is moving in a given way and have to predict how another component of the system will be moving. Users are given feedback on their answers.

Section 5, “Causal Chain”: The purpose of this section is to help the user in understanding the propagation of causality in the entire machine. It contains an audio commentary describing the operation of the toilet tank, explaining causal propagation within and across the water output and water inlet subsystems. Synchronized with the commentary, the corresponding components and paths of causal propagation are highlighted in the static schematic diagram. An “explain siphon principle” button gives users the option to access a description of the fundamental physics principle underlying the operation of the water output system - the siphon (see Section 7).

Section 6 “Movement”: The objective of this section is to convey how the machine actually operates by describing and showing the movements of its components. It includes the same auditory commentary as Section 5. An animation in which all component behaviors are concurrently shown continuously cycles through the operation of the device during this commentary. At the end of this narrated animation, users have the option of replaying it, or viewing a silent animation. An “explain siphon principle” button again gives users the option to access a description of how a siphon works.

Section 7, “The Siphon”: The purpose of this section is to explain a fundamental physics principle underlying the behavior of the toilet tank - the siphon. It contains a schematic diagram of the machine with the siphon bell and pipe highlighted. The text describes how a siphon works and how it applies to the operation of the water output system of the toilet tank. Users can also view a silent animation of the siphon effect. This section is not part of the sequential path through sections of the manual. Instead, it is reached from Sections 5 or 6, in response to a user clicking the “explain siphon principle” button.

Navigation and Guidance. The model of machine comprehension outlined above suggests a sequence of comprehension stages, such that the later stages are at least somewhat dependent on successful completion of the earlier ones. In particular, representation of the spatial relations between device components (Stage B-2) is dependent on first decomposing the system into individual components (Stage A), and the stages of finding lines of action and constructing a kinematic mental model (Stages D and E) are dependent on successful construction of a static model of the machine (Stages B and C). Therefore, in the initial version of the hypermedia presentation, we constrained navigation. Users studied the sections of the manual in order, starting with Section 1 (“Parts”). An exception to this forward traversal was section 7 (“the Siphon”), which could be accessed optionally from Section 5 or 6. Once the user had seen a section, he or she was allowed to return to it at any time. Users proceeded from section to section using an overall “map” of the hypermedia manual, which showed icons for all the sections of the manual and was color coded to show users their current place in the system, the sections that they had already studied, and the sections that they were allowed to move to at any given time (see the upper left corner of Figure 3). Sections of the map were highlighted and became mouse sensitive based on the user’s history, so that clicking on a section was only successful if it was consistent with these navigation constraints.

Empirical Studies of Multimedia and Hypermedia Comprehension

We now summarize the results of several experiments designed to evaluate different aspects of the hypermedia presentation. First, we examine whether people learn differently from hypermedia presentations, including hyperlinks and animations, compared to printed manuals containing the same visual and verbal information. Second we ask whether people learn differently from hypermedia presentations that direct the learner to view the information in a specific order as opposed to those that allow free navigation. Third, we ask whether people learn more from an animation of a mechanical system if they first try to mentally animate the system.

Do people learn differently from hypermedia presentations, compared to printed materials containing the same information?

The initial hypermedia manual design embodied guidelines about both the format and the content of instruction. Therefore it was important to evaluate the separate effects of format differences and content differences between our manual and typical instructional materials. First, the hypermedia manual differed from standard printed manuals in the format of instruction -- it included dynamic elements, i.e., constrained navigation, hyperlinks and animations that are not available in the print medium. In the first experiment that we describe here, we compare the learning outcomes of interacting with the hypermedia manuals to those of studying printed text and diagrams containing the same content.

Experiment 1a.

Hegarty, Quilici, Narayanan, Holmquist & Moreno (1999) compared learning from the hypermedia presentation, described above, to learning from a paper printout of the text and diagrams used in the manual (which we will refer to as the full text condition), and learning from a paper printout of the labeled diagram of the toilet tank accompanied by printed text describing the movement of the components in order of the causal chain (the causal text condition). The main differences between the hypermedia manual and full text conditions were the absence of hyperlinks and animations in the full text condition and the presentation of the verbal description of the causal chain and movement of components, which was presented visually as text rather than auditorally. The main difference between the full text and causal text conditions was that the causal text did not include the sections explicitly pointing out the subsystems of the toilet tank, the connections between components and the material composition of the components.

Twenty undergraduate students studied how a toilet tank works from the manual, 20 more students studied the full text, and 20 more students studied the causal text. All students were timed as they studied the materials. Afterwards, their comprehension was tested with the following types of questions:

Mental animation questions, which required them to predict how a component of the system would be moving, given that another component was moving in a specified way. For example, one question asked “Imagine the connecting rod is moving up. What is happening to the float arm?”.

Function Questions. Questions about the function of a component in the system, e.g., “What is the function of the float and float arm?

“Fault-behavior” questions, which described a particular fault in a component of the system and asked participants to predict how the system would behave, e.g., “How would the tank function be affected if the inlet valve was stuck in the water inlet pipe? (list all possible answers)”.

“Troubleshooting” questions, which described faulty behavior of the system and asked what components might be faulty, e.g. “Suppose that after flushing the toilet, you notice that water is continuously running into the tank. What could be wrong? (list all possible answers).”

A background questionnaire asked participants to list any courses they had taken in physics, mechanics or mechanical engineering, to list any mechanical or electrical items that they had attempted to repair, and specifically whether they had ever tried to fix a toilet, change the oil in a car or unblock a drain. Finally they were asked to rate on a scale of 1 to 7 how interesting they thought the material was (with 1 meaning not interesting at all and 7 meaning very interesting).

Results. The main difference between the three groups was in their study times. The causal group spent the least time studying the materials (4.62 minutes, SD = 1.89) Although the full text and hypermedia manual groups received the same content, the latter group spent longer (14.57 minutes, SD =4.09) than the full text group (10.43 minutes, SD = 3.39). This may reflect time learning and interacting with the computer interface and the fact that participants had to view the whole animations in Sections 5 and 6 of the manual. These animations were played at a constant rate that was probably slower than the time taken to read the relevant text and integrate it with the diagram in the full text condition. It might also reflect higher motivation induced by the hypermedia presentation. However, the type of instruction did not influence participants’ ratings of interest in the materials. The mean rating 4.05 for the hypermedia group, 4.10 for the full text group and 4.30 for the causal text group.

These differences in study times did not lead to differences in comprehension. There were no significant differences between the three groups on any of the comprehension measures. The only effect of prior knowledge was on the mental animation questions -- participants with more practical experience with machines (i.e. those who had attempted to repair more machines) had higher mental animation scores (12.12, SD = 4.26) compared to those with less practical experience (9.73, SD = 2.52; $F(1, 54) = 6.24$, $p < .05$). None of the measures of training or experience had significant interactions with the type of instruction suggesting that the different types of instruction were not differentially effective for individuals with different amounts of prior knowledge or experience.

Discussion. In summary, Experiment 1a showed no differences in learning outcomes between the three groups, despite differences in study times. The similarity in performance between the full text and hypermedia groups indicates that whether people view information on a computer screen or on paper, interact with a hypermedia interface including hyperlinked text and diagrams rather than reading printed material, and view animations with commentaries rather than static text and diagrams does not have significant effects on learning this material. This result suggests that the media and modalities through which information is presented do not affect comprehension, when the instruction is designed according to our comprehension model.

A comparison of the full text and hypermedia groups with the causal text groups also reveals no differences in learning outcomes. This suggests that explicitly describing the functions of the toilet tank subsystems, the connections between components and the material composition of the components does not affect people's ability to understand the causal chain or kinematics of the device. On first glance this appears to contradict the principles of our theoretical model. However, it is possible that the labeled diagram of the device provided to participants in the causal text condition provided sufficient information about the decomposition of the diagram and the spatial relations between components so that the additional text describing these aspects of the system was superfluous. Furthermore, since a toilet tank is a household item, participants might have already been familiar with the functions and material composition of its parts, so that the additional information on these topics in the full text and multimedia conditions (Section 3 of the manual) might have been superfluous. Hegarty et al. (1999) replicated this result in two further experiments, in which students learned about car brakes and a bicycle pump, in addition to the toilet tank, indicating that it generalizes to other relatively familiar devices.

Experiment 1b.

Experiment 1a indicated that that the media and modalities through which information is presented does not affect comprehension, when the instruction is designed according to our comprehension model. In a recent experiment, we compared hypermedia and printed versions of our manual to hypermedia and printed instruction on the same type of flushing cistern from commercially available hypermedia and multimedia presentations -- "The Way Things Work" book and CD-ROM by David Macaulay (Macaulay, 1988; 1998). This experiment also allowed us to compare learning from our materials to learning from materials that were designed according to the intuitions of an award-winning designer, but which were not informed by our comprehension model.

In this experiment, some participants learned from a version of our hypermedia manual, which was revised according to the results found by Hegarty et al., 1999. Because we found that students learned as much from the causal text as from the full text in Experiment 1 above, we omitted Section 3 of the original presentation in the revised manual. The revised manual combined Sections 1 and 2 of the original model, so that students first saw the cross-sectional diagram of the whole system (as in Section 1 of the original manual), then saw it decomposed into the water output and water inlet systems (with all the functionality described in Section 2 of the original manual), and then were allowed to click on individual components and have them highlighted in the diagram (as in Section 1 of the original manual). The revised manual also combined Sections 5 and 6 of the original manual, so that students saw an animation of the system in which successive components in the causal chain were pointed out, using a red arrow, as they were described in the accompanying commentary (the arrow thus performed the same function as the successive highlighting in Section 5 of the original manual). This embodies a design principle suggested by Faraday and Sutcliffe (1997a; 1997b) to direct students' attention to the part of the visual presentation that is being described in the auditory commentary. The manual therefore had 4 sections; an initial section that showed the hierarchical decomposition of the systems, a questions section (identical to Section 4 of the original manual), a movement section, in which successive components in the causal chain were indicated with an arrow, and the siphon section (identical to Section 7 of the original manual).

Other students learned from the description of the toilet tank in *The Way Things Work,* book or CD-ROM (Macaulay, 1988, 1998). The description in the book shows a large labeled diagram of the toilet tank which differed from the diagram in Figure 2 in that it showed the third dimension and is a rather whimsical depiction, showing fish swimming in the tank, and fishermen sitting on the float arm. Several small diagrams are shown as insets to the main diagram. One shows a side view of a toilet showing the location of the tank, two more show the operation of a siphon and are accompanied by text explaining how a siphon works, and three more show different stages in the flushing of the cistern and are accompanied by a description of the flushing process. The CD-ROM version shows the same large labeled diagram on a single screen of text. From this, the user has the option of clicking on two "movie" icons, one of which brings them to another screen showing a schematic diagram of the toilet tank that is animated in response to a mouse click. This animation is very fast (takes no more than a couple of seconds) and is not accompanied by a commentary. Clicking on the other "movie" icon brings the user to a screen describing how a siphon works, which is also accompanied by a diagram that the user can animate.

Method. 15 undergraduate students studied our hypermedia manual, 16 studied a paper printout of the text and diagrams used in the manual, 14 students studied the hypermedia presentation on the toilet tank from "The New Way Thing Work" CD-ROM (Macaulay, 1998) and 16 students studied the corresponding materials from "The Way Things Work" book (Macalulay, 1988).

Afterwards, all students wrote a description of how the device worked. They were instructed to imagine that they push down on the handle of the toilet tank and describe, step by step what happens to each of the other parts of the tank as it flushes. Then they answered function questions and troubleshooting questions as described in Experiment 1a above. Finally they were administered a test of spatial visualization ability – the Paper Folding Text (Ekstrom, French, Harman & Derman, 1976).

Results.

Students spent on average 9.06 minutes studying the hypermedia manual, 6.18 minutes studying the printed version of the manual, 5.32 minutes studying the "Way Things Work" CD-ROM and 4.79 minutes studying the "Way Things Work" book. There was a large effect of instruction on ability to describe how the toilet tank worked, such that the students who learned from the materials developed according to our comprehension model described more steps in the causal chain (12.20 steps for the hypermedia group, 12.25 steps for those who received the printed materials) than students who learned from the "Way Things Work" materials (7.36 steps for the CD-ROM group, 7.81 steps for those who received the printed materials from the book) . However, as the data indicate, there were no significant differences in this measure between the printed and multimedia versions of either presentation.

There were no significant differences between the groups on either the function questions or the troubleshooting questions. Spatial ability was marginally related to ability to describe how the toilet tank worked and had a significant effect on troubleshooting performance. However there were no interactions of the format of instruction with either spatial ability, prior knowledge or practical experience of machines, indicating that the instruction was equally effective for students with different backgrounds and abilities.

Discussion. In summary, the results of this experiment are consistent with those of Experiment 1a above in showing no difference between printed versions of instructional materials and hypermedia versions, including animations and hyperlinks, when the content of the materials is the same. It also showed that for at least one important measure of comprehension, the materials that were designed according to our comprehension model were superior to award-winning commercially available materials, suggesting that our theoretically derived and empirically supported guidelines are a significant improvement over the conventional wisdom in multimedia design. These studies clearly indicate that it is the content and structure of instructional materials, and not the media and modalities in which they are presented that is important for comprehension of complex devices.

Do people learn differently from hypermedia presentations that direct the learner to view the information in a specific order compared to those that allow free navigation?

Our model of machine comprehension suggests that a presentation should provide information about the decomposition of the device, the spatial relations between components, the causal chains of events in the operation of the machine, and the behaviors of the components. In our initial hypermedia design, we constrained navigation in the manual to ensure that users worked through each section. In a sense, this made our hypermedia manual more like a digitized book, in which information is presented on sequential pages, rather than a true hypermedia system that allows information to be viewed in any order.

Our decision to constrain navigation in the initial version of the hypermedia presentation was based on evidence that people, especially novices in the domain of interest, do not search these media optimally. For example, users can search haphazardly, get lost and fail to get an overview of how the information in the different displays is integrated (Hammond & Allinson, 1989; Spoehr, 1994). On the other hand, Shapiro (1998) found that students indicated a deeper level of learning from a less structured hypermedia document, compared to one in which the hierarchical structure was made obvious, and one in which the presentation was linear. She interpreted this results in relation to research on text comprehension showing that more knowledgeable readers learn more from less elaborate and less coherent texts compared to texts that are easier to comprehend (McNamara, Kintsch, Songer & Kintsch, 1996), because the less structured texts promote more active processing. In general, there is no clear consensus in the literature regarding the relative effectiveness of hypermedia systems compared to more linear forms of presentation. For example, in a meta-analysis of 13 studies comparing hypertext to linear text, Chen and Rada (1996) reported that hypertext was more effective in 8 cases and the opposite was true in the other 5 cases.

In Experiment 2, we compared learning outcomes from our initial hypermedia manual that constrained the order of navigation, and a version which contained the same information, but allowed students to view the sections in any order.

Experiment 2.

Method. Thirty six students took part in this experiment. Eighteen learned from the hypermedia presentation described above in which they were restricted to view the sections of the presentation in the order prescribed by our comprehension model. The other 18 students learned from a presentation that contained the same sections and information within the sections, but they were free to view the sections in any order. Afterwards, all students answered the mental animation questions, function questions, fault-behavior questions and troubleshooting questions used in Experiment 1a above.

Results. Participants who learned from the restricted-navigation version of the manual spent more time studying (M = 15.21 minutes, S.D.=03.23) than participants who viewed the free- navigation manual (M=11.39 minutes, SD=02.37). In general, participants viewing the restricted version revisited a section (M=1.82, SD=1.6) more often than did participants viewing the free version (M=1.38, SD=1.2).

The type of presentation studied (free versus restricted navigation) did not affect performance on any of the four categories of comprehension questions. Furthermore, there were no significant effects of the interactions between previous experience or mechanical training with type of manual presented for any of the categories of questions.

Although participants in the free-navigation condition were allowed to view the sections in any order, in fact, most of them viewed them in the order prescribed in the restricted navigation version of the manual. Twelve of the 18 participants in the free navigation condition viewed the sections in the order prescribed in the constrained navigation version of the manual and most of the others did not depart much from this order. This may be because the icons that people clicked to gain access to the sections of the manual were aligned from left to right on the screen (see upper left corner of Figure 2). Therefore most participants did not use the freedom that they were afforded to view sections in any order, a result that has been reported elsewhere (White, 1993).

This study therefore showed no differences in effectiveness of hypermedia presentations with free and restricted navigation. It was a limited test of the differences between free and restricted navigation, given that the number of sections in the presentation (7) was relatively small. Differences may emerge in more complex hypermedia systems, or in systems where the interface used for navigation does not suggest an order in which to view the information. However, as reviewed above, the issue of whether hypermedia are more effective than linear presentations is clearly an open question, and probably depends on many aspects of the design of specific presentations (Shapiro, 1998; Chen and Rada, 1996).

Do People Learn more from an Animation of a Mechanical System if they first Try to Mentally Animate the System?

Experiments 1a and 1b, described above, showed no advantage of learning from animations accompanied by commentaries, compared to learning from text and static diagrams presenting the same information. This result is contrary to many people's intuitions about the effectiveness of computer animations (Scaife & Rogers, 1996). We might expect animations to be more effective than static diagrams, for example, because they portray the temporal changes in the operation of a machine explicitly, rather than relying on the user to visualize these changes, and because they might be closer to a mental model of a mechanical system than a static depiction (Lowe, 1999).

However, there are also several reasons why animations accompanied by commentaries might be less effective than static text and diagrams. First, animations accompanied by commentaries take a specified amount of time to display. In contrast, reading of static diagrams and text is self paced. There is a question, therefore, of whether comprehension processes can keep up with the pace at which an animation is presented (see also, Lowe, 1999).

Second, a realistic animation of a mechanical system shows all components moving simultaneously. In contrast, when people attempt to understand how a machine works, or answer questions about how a device works, they mentally animate the components one by one, in order of a causal chain of events (Baggett & Graesser, 1995; Hegarty, 1992; Hegarty & Sims, 1994, Narayanan, Suwa & Motoda, 1994; 1995). Furthermore in a complex machine such as the flushing cistern, there are two causal chains that operate simultaneously. Therefore, to understand an animation, people need to attend to and relate changes that occur simultaneously in different regions of space (Lowe, 1999). However our visual attention is typically focused on only one location at a time.

Third, viewing an animation is a passive process. Phenomena such as the self-generation effect (Slamecka & Graf, 1978) and the self-explanation effect (Chi, deLeeuw, Chiu & LaVancher, 1994) suggest that people learn more effectively if they are more active in the learning process, and actually generate ideas or explanations. Similarly, people learn more from information presentations if they first participate in activities that activate their knowledge relevant to the topic of the presentation (Britton & Graesser, 1996; Kintsch et al, 1993; McNamara, Kintsch, Songer & Kintsch, 1996) or generate the important distinctions relevant to understanding the topic (Schwartz & Bransford, 1999).

In contrast to passively viewing an animation, previous research has shown that people can be quite successful in mentally animating mechanical systems (Hegarty, 1992; Narayanan, Suwa & Motoda, 1994, 1995), and that people with high spatial ability are more successful than people with low spatial ability (Hegarty & Sims, 1994; Hegarty & Steinhoff, 1997, Hegarty & Kozhevnikov, 1999). Even if people are not successful in mentally animating a machine, if they first attempt to do so before viewing a computer animation, they might discover which mechanical linkages they can easily visualize and which linkages they cannot visualize. The mental animation process might also induce them to articulate their intuitions about how the machine works, so that when they view the animation they can compare these intuitions to the actual physical process shown in the animation. They can then use the animated display to check the accuracy of their mental animations and to encode information about the motions of components that they could not infer from the diagram. We recently tested the effects of learning from computer animations versus learning by mentally animating static diagrams in three experiments.

Experiment 3a.

Method. Ninety-three undergraduate students participated in 4 different conditions of this experiment. Twenty-four studied a static diagram of the flushing cistern, shown in Figure 2 (Diagram Group). Twenty-one students studied the static diagram and then attempted to explain to the experimenter orally how the system worked (Mental Animation Group). Twenty-six students studied the static diagram and then viewed an animation, accompanied by a commentary explaining how the flushing cistern worked (Computer Animation Group). Twenty-two students viewed the static diagram, then attempted to explain to the experimenter how the system worked and finally viewed the computer animation (Combination Group). Afterwards all students answered mental animation questions, function questions, and troubleshooting questions similar to those used in

Experiment 1a, described above. Finally students were given the Paper Folding Test (Ekstrom, French & Harman, 1976) as a test of spatial visualization ability.

Results. Viewing the animation and commentary significantly improved performance on all three types of questions. That is, students in the Computer Animation Group and the Combination group answered more questions correctly than students in the other two groups. Students with high spatial ability also answered more function and troubleshooting questions correctly. For the mental animation questions, there was a trend for students in the mental animation group to have better performance than those in the diagrams group, but this trend did not reach statistical significance.

Experiment 3b.

Experiment 3a indicated that students can learn how a mechanical system works from an animation accompanied by a commentary. No significant effects of first attempting to mentally animate the system were observed. However the participants in Experiment 3a might not have been given enough information to generate an explanation of how the system worked. They were shown a static diagram of the system, and this diagram was not present when they attempted to explain how the system worked, so they had to mentally animate the system from memory. In Experiment 3b, students in the mental animation and combination groups were shown three static diagrams showing different stages in the operation of the device, and these three diagrams were visible while they attempted to explain how the system worked.

We were also concerned that the mental animation questions were not diagnostic of the differences between the groups, because they were multiple choice questions, and therefore students had a good chance of answering them correctly if they could eliminate one or two of the answer choices. Therefore in this experiment, the multiple choice questions were replaced by a task in which the students were asked to describe, step by step, how the flushing cistern works (as in Experiment 1b above).

Method. Eighty students participated in this experiment, 20 in each of the conditions (Diagram only, Mental Animation, Computer Animation and Combination Mental + Computer Animation). The procedure was similar to that of Experiment 3a with the changes noted above.

Results. Students who viewed the animation and commentary wrote more complete descriptions of how the flushing cistern worked, that is they included more steps in the causal chain in their description. Furthermore, students who mentally animated the mechanical system also wrote more complete descriptions than those who did not mentally animate the system. The effects of these two manipulations were additive, such that students in the Combination condition (who first mentally animated the system and then viewed the computer animation) had the best performance of all 4 groups on this measure. This indicates that students learn more from viewing an animation of a mechanical device if they first attempt to mentally animate the device. Students with higher spatial ability also had better performance on this measure.

Students who viewed the animation and commentary also had better performance on the troubleshooting questions. Although there were trends for mental animation and spatial ability to improve performance on this measure, the trends did not reach statistical significance. None of the experimental manipulations had significant effects on the function questions.

Experiment 3c.

Experiments 3a and 3b showed that people are better able to describe how a mechanical system works after viewing an animation accompanied by a commentary than after viewing a static diagram. Experiment 3b also showed that they are better able to describe how a machine works if they attempt to mentally animate the machine before viewing an animation. However Experiments 1a and 1b above indicate that students learn as well from static diagrams accompanied by text as from animations. In this experiment we examined the effects of two factors on students' ability to describe how the flushing cistern works. The first factor was whether they learned how the system worked from an animation accompanied by a commentary or from a static diagram accompanied by text. The second factor was whether they first attempted to mentally animate the mechanical system before receiving an explanation of how it worked.

Method. Ninety-six students participated in this experiment (24 in each group). The first group first studied a diagram of the flushing cistern and then read a text, accompanied by a diagram describing how it worked (Text and Diagram group). The second group viewed a static diagram of the device, then attempted to explain to the experimenter how it worked, and then read a text and diagram description of how it worked (Mental Animation + Text and Diagram group). The third group studied the diagram and then viewed an animation accompanied by a commentary explaining how the device worked (Computer Animation Group). The fourth group studied a static diagram of the device, then attempted to explain to an experimenter how it worked, and then viewed an animation accompanied by a commentary explaining how the device worked (Mental Animation + Computer Animation Group). Afterwards all participants were asked to describe in writing, step by step, how the flushing cistern works (as in Experiment 1b above) and answered the troubleshooting and function questions.

Results. As in Experiment 3b, students who mentally animated the mechanical system (i.e. attempted to explain how it works) before viewing an animation of the mechanical system wrote more complete descriptions of how the device works compared to those who viewed the animation without first mentally animating. This replicates the result (Experiment 3b above) that students learn more from viewing an animation of a mechanical device if they first attempt to mentally animate the device. However, for the text-and-diagram conditions, there were no differences on the outcome measures between those who mentally animated before reading the text and diagram and those who did not. Furthermore there were no differences on the outcome measures between those who viewed animations accompanied by commentaries and those who viewed text and diagrams.

How might we explain these results? First, it is possible that the process of understanding a text accompanied by a static diagram involves mental animation (Hegarty & Just, 1993). That is, when one views a static diagram of a mechanical device and reads a text describing how it operates, the comprehension process involves visualizing how the different parts of the diagram will move to accomplish the function of the machine. In this view, first mentally animating a diagram before reading a text and diagram does not affect comprehension because the comprehension process itself involves mental animation. In contrast, viewing a computer animation does not involve mental animation, and therefore learning from an animation is enhanced if one first mentally animates the device. Second, consistent with Experiments 1a and 1b described above, this experiment indicates that it is the content and structure of instructional materials, and not the media and modalities in which they are presented that is important for comprehension of mechanical systems.

Summary and Conclusions.

In summary, we developed a theoretical model of comprehension of mechanical systems from text and diagrams. From this we derived design guidelines and implemented several versions of a hypermedia presentation that explains how a mechanical device, the flushing cistern works. We described 6 different experiments, some of which evaluated different versions of our hypermedia presentation and some of which were focused on specific aspects of our model.

We obtained support for our theoretical model in that people learned more from materials designed according to this model than from commercially available books and CD-ROMs that explained the same materials. One specific design guideline -- that people should be induced to mentally animate a mechanical system before seeing a computer animation of the device – was also empirically validated. These advantages were primarily evident in participants' ability to describe, step by step, how the machine works. In contrast, differences between conditions were typically not observed for troubleshooting tasks that require the user to reason with the information given in the multimedia presentation.

Our experiments provide no evidence that the <u>format</u> of instruction -- the media and modalities in which different types of information are be presented – has any effect on comprehension and learning. The comprehension measures were not affected by whether information was presented in static text and diagrams or as animations accompanied by commentaries. Furthermore, there we no effects on comprehension of hyperlinking information or allowing participants free rather than restricted navigation of the hypermedia presentations. We have observed similar results in a parallel project on teaching computer algorithms. These results are consistent with a growing body of research showing no significant effects of animations over static media when they present the same information (Morrison, Tversky & Betrancourt, 2000).

What can we conclude about the effectiveness of animations and hypermedia in science instruction? Our research shows no advantages of these new media over traditional print formats. However there have been several excellent demonstrations of the effectiveness of animations in science teaching. Notable examples are White & Frederiksen's studies of teaching mechanics and electrical circuits using interactive microworlds that allow students to run animations of the phenomena being explained (White, 1993; Frederiksen, White and Gutwill, 1999). However, in this case, the animations are embedded in a wider curriculum in which students articulate their intuitions about the phenomena being studied, and are taught basic scientific inquiry skills. Similarly in Edelson's (in press) work on teaching students about climate using an interactive visualization system, successive iterations of the instructional program included more structured activities for students, because it was observed that students did not use much of the functionality of the system if they were not given specific learning goals and supporting conceptual information.

We expect that new media have the potential to be powerful instructional tools in scientific communication and teaching. However, our research has shown that merely translating information from a traditional print medium to a hypermedia system including animations, commentaries and hyperlinks does not affect comprehension and learning when the content of the information is held constant. Basic research is needed to study the conditions under which these powerful new media can be used in the instructional process.

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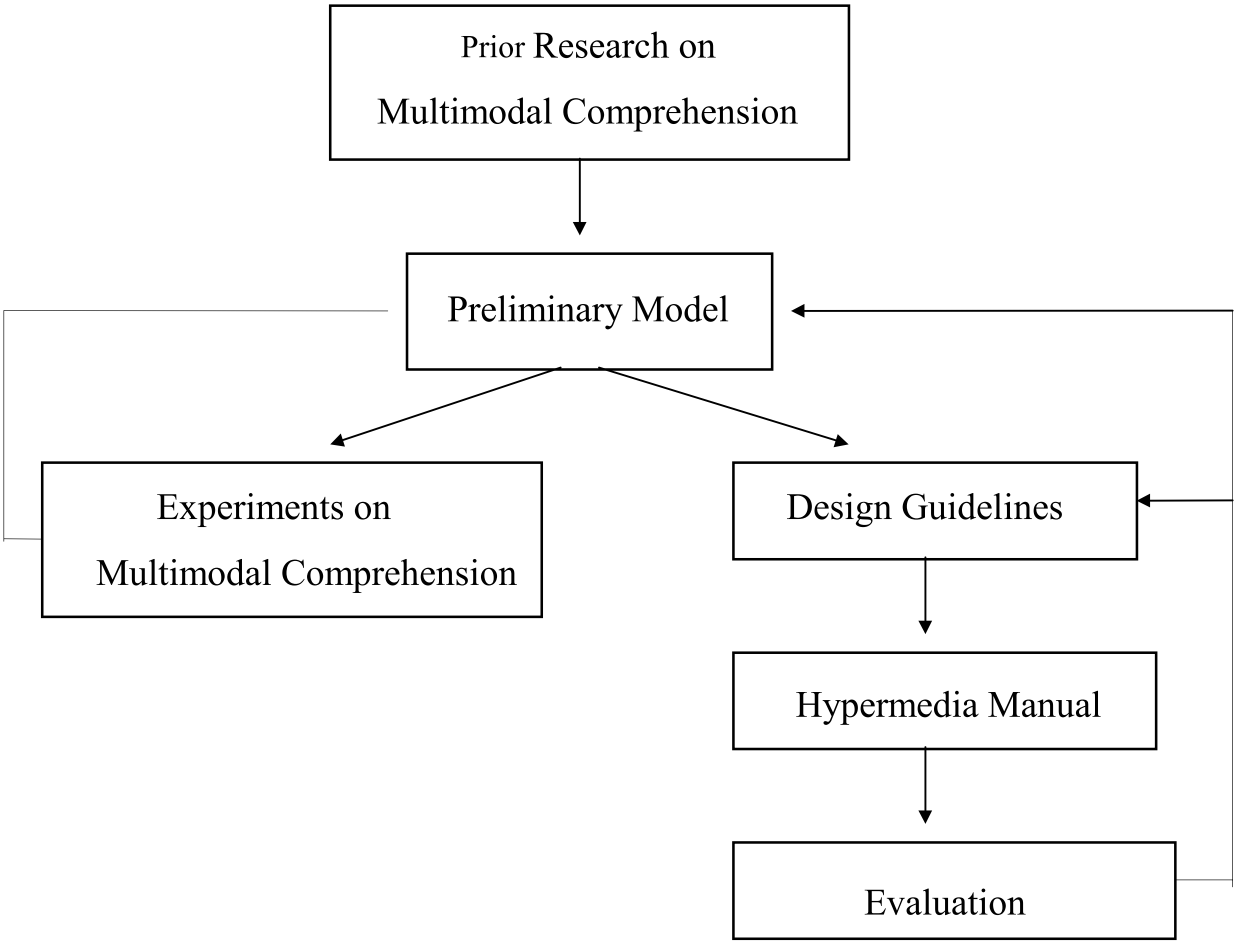
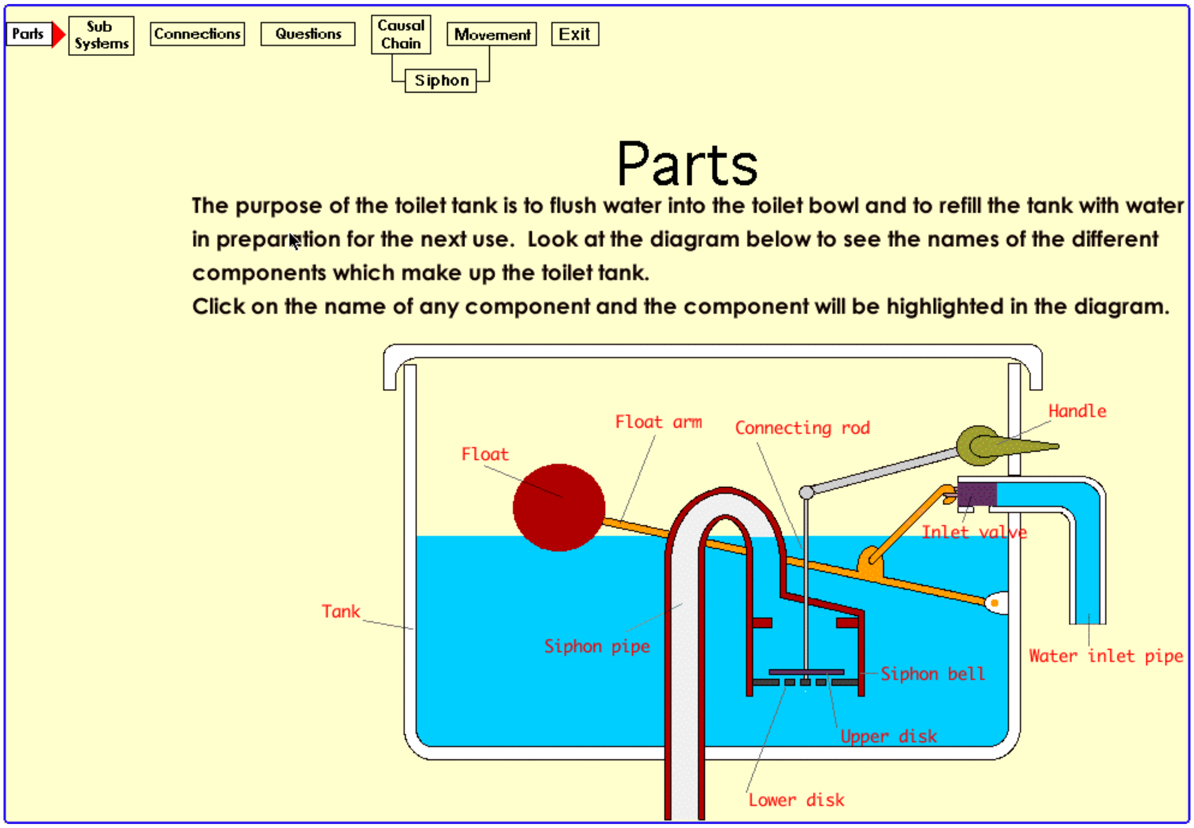


Figure 1. Hypermedia presentation design process.



Parts

The purpose of the toilet tank is to flush water into the toilet bowl and to refill the tank with water in preparation for the next use. Look at the diagram below to see the names of the different components which make up the toilet tank.

Click on the name of any component and the component will be highlighted in the diagram.

Figure 2. A screen of the hypermedia manual.