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Authors
Kriz, Sarah
Hegarty, Mary

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Constructing and Revising Mental Models of a Mechanical System: The role of domain knowledge in understanding external visualizations

Sarah Kriz (kriz@psych.ucsb.edu)
Department of Psychology, University of California
Santa Barbara, CA 93106 USA

Mary Hegarty (hegarty@psych.ucsb.edu)
Department of Psychology, University of California
Santa Barbara, CA 93106 USA

Abstract

External visualizations such as diagrams and animations are frequently used to teach people about the workings of mechanical systems. The present study considers the types of mental models that can be constructed from visual-spatial (non-verbal) materials alone, and the extent to which people revise their incorrect mental models. Comparing 10 high physics knowledge participants to nine low physics knowledge participants, we assessed how these two groups constructed and revised mental models of a flushing cistern. High domain knowledge participants extracted more meaningful information from the materials, although their initial models of the system were not as accurate as expected. However, after answering comprehension questions and viewing the learning materials again, high domain knowledge participants were more likely to revise their mental models into correct representations of the system, whereas the participants with low domain knowledge continued to rely on incorrect models. The discussion of these findings focuses on how prior knowledge may contribute to understanding visual instructional materials.

External visualizations (e.g., diagrams and computer animations) are often used to inform people about how a complex system behaves. Physical systems such as machines are causally and temporally complex, and understanding these systems depends on an appreciation of the spatial relations between their components and how these change over time. The spatial and temporal aspects of mechanical movements can be illustrated directly via visual-spatial representations, while the same information presented in a verbal format might be more difficult to understand.

It seems plausible that the design of external visualizations could greatly affect one's success at extracting relevant information from the display. For example, adding accompanying text that describes aspects of phenomena presented in the visualizations may help in providing additional information that a diagram alone could not provide. Previous studies researching the integration of text and diagrams have shown that people with low domain knowledge or low spatial ability rely heavily on accompanying textual descriptions (Hegarty & Just, 1993; Kalyuga, Chandler, & Sweller, 1998). These studies also suggest that as a person becomes more familiar with a domain, the reliance on textual explanations decreases. However they have not specifically addressed which types of information are best understood from diagrams and animations by people with different amounts of background knowledge.

The purpose of the present study is to examine how understanding a mechanical system is achieved when visual materials such as diagrams and animations are presented without accompanying textual or verbal explanations. As part of a larger research objective, we analyze how purely visual materials are understood by both high and low physics knowledge participants. By examining how people with varying degrees of domain knowledge interpret visual materials, we can design future materials containing verbal descriptions that supplement informational gaps in the visual displays. We assume that these informational gaps will differ for low and high domain knowledge individuals, therefore, this study focuses on how domain knowledge contributes to the comprehension of visual materials conveying a complex mechanical system.

Constructing Mental Models

Creating a mental model of a complex system requires that a person identify the parts involved, understand their causal relationships, and relate the causal steps to the larger functions of the system. Our cognitive model of how people come to construct mental models from multimedia materials follows that outlined by Narayanan & Hegarty (2002). To summarize, there are five steps that a person must take to understand a machine from multimedia presentations. First, the system must be decomposed into individual components. Second, the learner must make representational connections to prior knowledge. Third, if verbal information is present, a person is required to make further referential connections between the visual media and the verbal explanations. Then, she must determine the causal chain of events. Finally, a dynamic mental model is constructed. In the present experiment, we are particularly interested in the second step-- how prior domain-related knowledge affects the construction and revision of mental models.

We predict that, in accordance with previous studies (Spilich et al., 1979; Chiesi, Spilich, & Voss, 1979; Lowe, 1994; 1999), high domain knowledge individuals will be more likely to construct initial mental models that incorporate high-level functional understanding, whereas people lacking domain-related knowledge will focus on the movements of the parts on a local level. Additionally, we expect the level of domain knowledge to influence the extent to which models are revised. Assuming that learning is an iterative process of understanding (Miyake, 1986), how people move from a state of understanding to a state of non-understanding may depend on their level of domain-related knowledge. As previous studies have shown (Chi, 2000; Chi et al., 1994), it is when conflicts between internal models and external information occur that people are more likely to revise their internal mental models. We propose that conflicts are more likely to be perceived by people with high domain knowledge because they are at an informational advantage for meaningfully evaluating their models.

Three Types of Mental Models

The stimulus used in this experiment was a British model of a toilet tank. While the purpose of the system is the same as an American model (i.e., to flush water into the toilet bowl), the mechanism used to accomplish this function differs vastly from its American counterpart. Thus, we assume that the participants in our experiment (American college students) did not have prior knowledge of the mechanism that they studied in this experiment.

Specifically, the main difference is the manner in which water exits the tank into the bowl. In the British model, water exits the tank through a siphon process. The siphon process begins when two disks (located at the bottom of the bell in the middle of the diagram) are pushed together (by pulling the handle) and push water up through the main siphon pipe. As water flows up the siphon pipe and down into the toilet bowl, the siphon process begins. This enables water to flow through the siphon pipe without the aid of the disks. The process ends when the water level in the tank falls below the siphon bell, and air enters the siphon pipe. This is reflected in Figure 1.

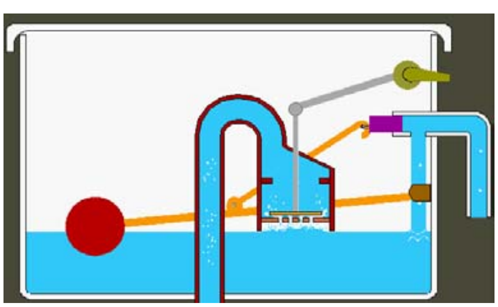

Figure 1: Air enters and stops the siphon process.

Data from this and previous experiments (e.g., Hegarty, Kriz, & Cate, 2003), indicate that people construct one of two types of mental models of the flushing cistern. The first (physically correct) model works according to the physical process of siphoning. As explained above, a siphon occurs when liquid in an enclosed system moves, via a pressure differential, from a point of high pressure to a point of lower pressure. In the case of the British toilet tank shown in Figure 1, a siphon enables water to continuously flow up and back down the large pipe in the middle in order to exit the tank. The siphon is broken when air, which is lighter than water, enters the enclosed system. This breaks the pressure differential, and the water flow out of the pipe stops.

The incorrect model of this system involves the disks as the main stopping agents. Participants with incorrect models may or may not understand the initialization of the siphon process. Their model is characterized, however, by the function of the disks. The incorrect model assumes that the water stops flowing out of the tank because the upper disk falls on the lower disk and creates a water-tight barrier, or seal. As Figure 1 illustrates, the two disks do not touch when the lower disk falls. If they did, air would not be able to enter. Therefore, the visual materials that participants view are in direct conflict with this model.

Many participants do not offer an explanation for how water starts and stops flowing from the tank to the bowl. A possible reason for this omission is that they have an informational "gap" (Chi, 2000) in their mental model. In other words, they are missing the knowledge necessary to explain the causal relationship between activity in the tank and the stopping of exiting water. However, it is quite possible that this process is, in fact, represented in their mental models but was simply not explained during the protocol. Because there was no method for empirically differentiating between these two possibilities, these cases were not considered in analyses.

Method

Participants

Nineteen adults (10 high domain knowledge, 9 low domain knowledge) volunteered for the study as paid participants. The high domain knowledge (HDK) participants were UCSB graduate students from Mechanical Engineering or Material Science, with the exception of one participant, who was the staff lab manager of the undergraduate Mechanical Engineering lab. All experts held Bachelors degrees in engineering or physics and had been studying physics and engineering for a mean of 6.4 years (range 5-8 years). It was assumed that the HDK group had knowledge of pressure differentials and siphoning, as these topics are covered in undergraduate physics and engineering courses.

The low domain knowledge (LDK) participants were UCSB graduate students from Social Sciences, Art, Humanities, or Biology, and all considered themselves physics novices. Four had taken introductory physics in high school and one had taken freshman physics in college. None had taken engineering courses.

Materials and Apparatus

Participants viewed a variety of visual displays depicting a toilet tank either in a resting state or in motion. The *labeled static diagram* showed a color picture of the toilet tank in its resting state and included labels naming the mechanical parts. The *unlabeled static diagram* was identical to the labeled version, but without the labels. The *four phases static diagram* was a series of four diagrams displayed together. Each diagram showed a different phase of the flushing process. The labeled, unlabeled, and four phases diagrams were all viewed as PowerPoint slides.

Three animations were also available to the participants. All of the animations consisted of a series of 134 bitmap images. The *computer-controlled animation* was displayed in Macromedia Flash MX and played at a rate of 6 frames per second. The participant pressed a button with the mouse in order to begin playing, but otherwise had no control over the speed or the direction of the animation. The *participant-controlled animation with arrows* was run in a Quicktime player, which allows one to control the speed and direction in which a video file plays. In both animations, arrows appeared at various points to indicate a part's direction of movement or to signal an important event. The *participant-controlled animation without arrows* was identical to the other participant-controlled animation except it did not contain arrows.

All materials were displayed on a 17" desktop monitor at 1024x768 resolution.

Procedure

Participants sat in front of the computer and were told, "You are going to view diagrams and animations that illustrate a toilet tank, but note that this is not an American model. Please view the materials and learn how the system works. You have as much time as you need to study the materials." They were then shown the six visual learning aids. The researcher briefly explained each learning aid, without mentioning the presence or absence of arrows in the animations, and demonstrated how to manipulate the controls of the Quicktime Player.

After viewing the material, the monitor was turned off and participants were given a booklet of comprehension questions. The first question asked to explain step-by-step what happens in the toilet tank after the handle is pushed. The next four questions were troubleshooting questions, in which novel breakdown scenarios were described. The participants were required to generate as many responses as possible that would account for the breakdown of the system. The final four questions were function questions that asked about the function of specific parts of the mechanical system. Participants were asked to provide written answers at their own pace.

Upon finishing the written portion of the experiment, the participants were then asked to view the visual materials again. The participant-controlled animation without arrows was displayed and participants were asked to orally report to the researcher where events began and ended. An "event" was not predefined by the researcher, and participants were allowed as much time as they needed to formulate their answers before reporting. When they were ready, participants reported what they saw as "events." This portion of the session was video taped for later analysis.

Results

Constructing Initial Mental Models

In order to assess participants' initial mental models of the system, we evaluated the first written question, in which participants described the step-by-step process of a flush. The two groups' responses showed both quantitative and qualitative differences. As Figure 2 shows, the HDK participants reported on average four more steps than the LDK participants, and this difference reached significance: $M = 16.8$ v. $M = 12.8$; $t(17) = 3.176$, $p < .05$. This difference indicates that the HDK individuals were able to extract more information from the visual materials.

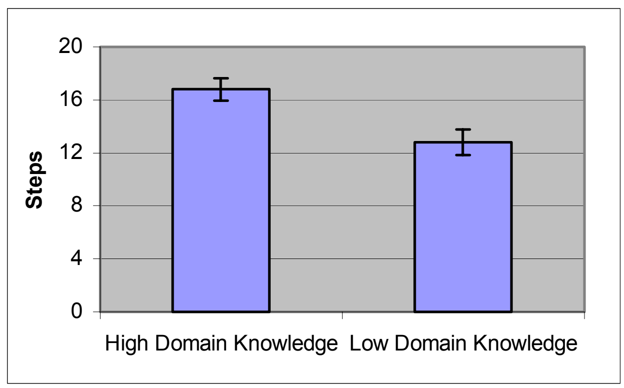

Figure 2: Mean number of steps in written responses.

Furthermore, the types of events that were mentioned by each group differed. The majority of participants (i.e., seven participants or more) in both groups reported eight common steps. However, the HDK participants tended to mention steps that the LDK students did not mention. (See Table 1.) Of note, the HDK participants tended to focus on the rising and falling of the water level, and that focus was not evident in the majority of the LDK participants' written reports.

To evaluate the accuracy of participants' initial mental models, the step-by-step written reports were evaluated for steps that reflected correct, incorrect, or unstated models of the siphon process. If participants mentioned the siphon process beginning when the disks pushed the water up the siphon pipe and ending when air entered the system, their models were considered correct. Incorrect models were those in which the disks were reported as stopping the water from leaving the tank. Finally, a mental model was coded as "not stated" if participants made no mention of the how the water stopped flowing out of the tank. As Table 2 shows, the distribution of initial model types did not differ at all between the two groups.

Table 1: Steps mentioned by at least 7 participants in their step-by-step written responses.

Steps	HDK	LDK
Push down on the handle	x	x
The upper disk moves up	x	x
The lower disk moves up	x	
Water enters siphon pipe	x	x
The upper disk moves down	x	x
The lower disk moves down	x	
Water level falls below siphon bell	x	
Water level lowers in tank	x	
Float lowers	x	x
Inlet valve opens	x	x
Water flows from inlet pipe to tank		x
Water level rises	x	
Float rises	x	x
Inlet valve closes	x	x

Data from the troubleshooting and function question responses reveal, however, that high and low knowledge participants did differ on how strongly they relied on incorrect models in later comprehension questions. Figure 3 reflects the mean number of troubleshooting and function question answers that contained the incorrect model. The data indicate that the LDK participants used incorrect mental models significantly more often than the HDK participants to account for system breakdowns and overall functions of the tank: M= 3.4 v. M=1.6; $t(17)=2.535$, $p<.05$.

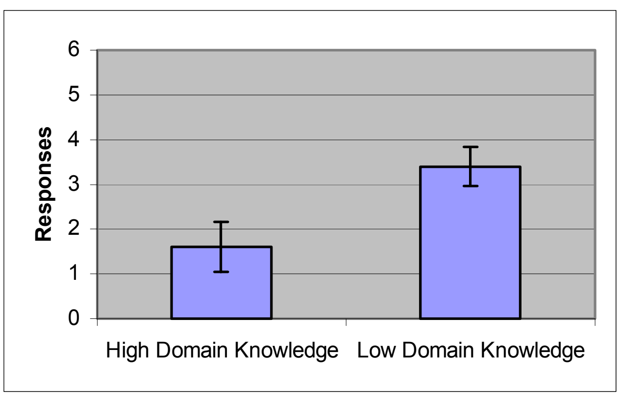

Figure 3: Mean number of troubleshooting and function responses conveying incorrect model.

Revising Mental Models

Although the written step-by-step responses and the orally presented event structure responses resulted from slightly different tasks, a paired samples t-test yielded no significant differences for either group in the number of steps mentioned between the two tasks. Thus, we were able to compare the written and oral reports in order to assess model revisions.

In their oral reports, the majority of participants in each group (at least 7) mentioned three steps that were not in their written reports. For the LDK participants, these included: (1) the lower disk moves up, (2) the lower disk falls down, and (3) water stops flowing into the siphon pipe. The three events that the majority of HDK participants mentioned in their oral reports but not in their written response were: (1) water flows into the toilet bowl, (2) the siphoning process begins, and (3) the siphoning process is broken. The striking difference between the two groups is in the perceptibility of the added steps. The three steps commonly added by the LDK participants are directly perceptible from the animation, which they were allowed to view while giving their reports. On the other hand, the HDK group added steps that were not directly perceptible from the animation, but instead involved higher-level processes and functions.

The number of participants in each group who changed from one model to another is shown in Table 2. As is evidenced in this table, the majority of the HDK participants moved from an incorrect or unstated model to a correct model. Whereas two HDK participants began the study with a physically correct model, eight of the ten finished the study with this model. That is, they orally reported that the siphon phenomenon, not the disks, ends the outflow process. Contrary to this, the LDK participants show no clear pattern of model revision. Many of their final models remain incorrect. In sum, the steps reported in the written response compared to the oral response clearly showed signs of model revision in the HDK sample, whereas no pattern was evident in the LDK data.

Discussion

Initial Models

The results of this study indicate that HDK participants were able to extract more information about the flushing cistern system from the visual materials provided. They not only reported more initial steps than the LDK individuals, but were also better at integrating higher-level causal changes, such the rising and falling of the water level, into their initial reports. As predicted, and following previous findings on reasoning with external visualizations (Lowe, 1994; 1999), the LDK participants' step-by-step reports revolved around small mechanistic movements and did not indicate a functional understanding of the system.

A comparison of HDK and LDK participants' written protocols revealed that the types of models constructed initially were similarly distributed across the two groups. This result was rather surprising, given that we expected the engineers to fully comprehend the siphon process upon viewing the materials. Additionally, we expected reading the label "siphon pipe" to prime this siphon schema. Our findings conflict with previous accounts of experts solving physics problems (Chi, Feltovich, & Glaser, 1981), as well as lay beliefs that people trained in a certain domain are able

Table 2: Summary of Initial and Final Models.

HDK	Initial Model	Final Model	LDK	Initial Model	Final Model
E01	Correct	Correct	N02	Incorrect	Not Stated
E02	Incorrect	Incorrect	N03	Incorrect	Incorrect
E03	Not Stated	Correct	N04	Not Stated	Incorrect
E04	Not Stated	Correct	N05	Correct	Not Stated
E05	Correct	Correct	N06	Incorrect	Incorrect
E06	Incorrect	Incorrect	N07	Incorrect	Incorrect
E07	Incorrect	Integrated[1]	N08	Incorrect	Incorrect
E08	Not Stated	Correct	N09	Not Stated	Not Stated
E09	Incorrect	Correct	N10	Not Stated	Incorrect
E10	Incorrect	Correct			

to understand domain-related phenomena quickly and easily. As evidenced by their later oral reports, the engineers were able to spontaneously report the siphon process, indicating that they had the relevant domain-knowledge, yet they did not grasp the process in their initial viewing of the materials.

Here we offer a possible explanation for why many of the HDK participants did not incorporate the siphon process into their initial mental models. In the initial viewing phase of the experiment, participants were trying to integrate their prior domain-related knowledge with the external visualizations in order to create a cohesive causal model of the system. Because the HDK individuals have a larger body of prior knowledge than the LDK participants, they have more explanations in competition. Two sources of knowledge that may contribute to the understanding or misunderstanding of how water stops exiting the tank are: (1) domain-specific knowledge about a siphon process and pressure differential, as described previously, and (2) domain-general knowledge of "damming." From experience with the real world, we know that flowing liquid can be stopped by solid objects. Integrating the damming principle with the external visualizations leads to the incorrect model of the disks blocking the outgoing water. This integration of domain-general information seems to be how LDK individuals reason about the flushing cistern. Although both explanations were available to the HDK participants, the domain-specific explanation may not have been adequately cued by the visual materials. Thus, the HDK relied on their domain-general knowledge until they had reason to switch to using domain-specific understanding. This explanation is purely speculative, and further studies exploring these issues need to be conducted.

Model Revision

While the distribution of both groups' initial model types were found to be relatively similar, analyses of their final oral reports revealed that the model revision process differed across the groups. Although both groups did, on average, add three steps that were not present in the majority of the initial models, the steps differed qualitatively across the groups. The LDK participants seemed to perform "model addition" after answering the comprehension questions and reviewing the visual materials. They *added* visually salient information that was left out of their initial models. However, the LDK participants did not *change* their model to the correct model. Moreover, the sealing of the disks continued to be the dominant view of how the water stopped exiting the tank, even though this explanation was in direct conflict with what was shown in the visual materials. These findings are consistent with previous findings that LDK individuals do not integrate functional information into their mental models (Spilich et al., 1979; Chiesi, Spilich, & Voss, 1979; Lowe, 1994; 1999) and that they tend to stay at a kinematic/behavioral level of explanation, even after spending additional time with the learning materials (Hale & Barsalou, 1995).

The HDK participants in this study can be described as truly revising their mental models. Rather than simply adding perceptually salient steps to their final models, the majority of HDK participants changed their models to include the beginning siphon process and the correct explanation for the ending of the siphon process. The HDK participants did not tend to rely as heavily on their initial incorrect model while answering the troubleshooting and function questions. This indicates that the HDK group was more flexible in generating other responses to the questions, possibly because they had more prior knowledge available to them.

There are many possible explanations of how the revision process occurred. Because a variety of activities took place between the initial written step-by-step explanations and the final oral reports, we can only speculate on the possible causes of revision. One possibility is that the troubleshooting and function questions lead the HDK group to internal conflicts within their models. Troubleshooting

[1] The participant incorporated both the correct and incorrect models into his final model.

questions can be used to induce causal knowledge of a system (Hale & Barsalou, 1995), and can also be used to judge deep comprehension (Graesser & Olde, 2003). While providing responses to these questions, HDK participants might have become aware of conflicts between their initial mental model and the possible explanations for the breakdown scenarios presented in the troubleshooting questions. Alternatively, viewing the visual materials a second time may have contributed to model revision. As the HDK participants were able to compare their mental models to the information presented in the visual tools, they may have realized inconsistencies in their models.

The LDK group, on the other hand, did not seem to experience conflicts between their models and their troubleshooting and function responses, nor between their models and the external representations. Although their models conflicted with what was shown in the learning materials, none of the participants explicitly identified a conflict. These participants may have refrained from revising their mental models even after re-viewing the materials because they began to rely on their mental models as perceptual evidence (Rozenblit & Keil, 2002). The HDK group, on the other hand, seemed to be more sensitive to conflicts between their mental models and information that did not match.

Conclusion

This study demonstrates the limitations of visual materials such as diagrams and animations for communicating about how machines work. Although the animations showed how the parts of the mechanism move when it is in operation, LDK individuals were unable to construct an accurate mental model from the visual materials, and tended to construct erroneous mental models that were in fact inconsistent with what they viewed. Most HDK individuals were able to construct the correct mental model eventually, but this took some time and occurred only after engaging in other activities such as answering troubleshooting and function questions.

The results of this study suggest that materials designed for low domain knowledge participants must explicitly describe the siphon process (e.g., through language), while materials targeting learners with adequate domain knowledge may need to merely induce these learners to access the relevant domain information they already possess. Thus, examining the mental models constructed from visual materials alone can provide insights into the design of instructional materials for individuals with different amounts of background knowledge, and suggest when and how visual-spatial instruction materials should be supplemented by verbal instruction.

Acknowledgments

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