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Diagrams and Descriptions in Acquiring Complex Systems

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Abstract

Complex systems such as a car brake, circulatory system, or legislative system can be conveyed by language or diagrams. Such systems can be presented from structural or functional perspectives. In three experiments, we examine communicating structure and function of mechanical systems (bike pump, car brake, pulley system) by text and diagrams in relation to mechanical ability. By adding arrows, structural diagrams can be enriched to convey functional information. Inferring structure from function was easier than inferring function from structure. Participants high in mechanical ability outperformed low participants except when text perspective matched question perspective. Those with low mechanical ability are at a disadvantage, especially for inferring function from diagrams. Comprehension of complex systems depends in sensible ways on perspective, medium, and ability.

Conveying Complex Systems

When we learn about a new digital camera, attempt to troubleshoot a broken-down car, or try to understand a new finding in neuroscience, we need to understand a complex system. Despite the ubiquity of contact with complex systems, understanding them or interacting with them can be frustrating. The frustrations are due not only to the complexity of the systems but also to the inadequacy of instructions and explanations.

Effective explanations of complex systems have a complexity of their own. Effectiveness depends on the perspective of the information to be conveyed, on the medium of conveying the information, and on the ability and expertise of the learner. Some of these complex interactions have been examined in previous work, though finding generality in the conclusions has been elusive (e.g., Hegarty, et al., 1990; Hegarty, et al., 1993; Mayer & Gallini, 1990; Morrison and Tversky, 2000). More clarity may be achieved by an analysis of the information to be conveyed relative to characteristics of the media and to qualities of individual differences.

Information about complex systems is of two types: structural information, the configuration of parts or topology of the system, and functional information, the sequence of operations and outcomes. The configuration of parts has a spatial or metaphorically spatial structure, and the sequence of operations has a temporal, causal structure. The primary media for conveying complex systems are language and diagrams. With an increasing emphasis on visual displays of information, we found it important to investigate the success that diagrams have in comparison to text in communicating this information. Structural information should be effectively conveyed in diagrams because diagrams use elements and relations in space to convey actual topology. Furthermore, arrows indicating the sequence of operations can be added to a diagram to convey functional information.

There are conflicting results on the relations between medium and ability. Some studies show that people with low ability benefit from diagrams and others show that people with low ability have difficulties extracting information from diagrams (Hegarty 1992; Larkin & Simon, 1987; Mayer, 1989) An analysis of information perspective may reconcile these conflicting findings. In particular, low ability participants or novices may be able to extract structural but not functional information from diagrams. Functional information must be inferred from diagrams, in contrast to structural information, which is explicit.

Three experiments examine the interactions of medium, content, and ability in the comprehension of complex systems. We use three systems that have been used with success in previous literature, a pulley system (adapted from Hegarty & Just, 1993), car brake and bicycle pump (both adapted from Mayer & Gallini, 1990).

Experiment 1: Descriptions from Diagrams

Diagrams of complex systems are excellent for conveying structural information as they use space and the elements in it to convey real or conceptual elements and the relations among them. Adding arrows may facilitate conveying functional information as arrows indicate the temporal sequence of operations. Participants were asked to describe what is depicted in a diagram of a complex system, without and with arrows.

Method

Participants

Participants were 67 psychology students fulfilling a course requirement. Thirty-four participants described diagrams without arrows; 8 a car brake, 14 a bicycle pump, and 12 a pulley system (see Figure 1 for example of car brake diagram with arrows). Thirty-three participants described diagrams with arrows; 8 a car brake, 12 a bicycle pump, and 13 a pulley system.

Procedure

Participants were first asked to rate their mechanical ability and prior knowledge of the device given to them on a 1 to 7 scale, 1 = poor, 7 = excellent. In the 3 experiments reported here, participants self-rated their mechanical ability and their prior knowledge of the complex system presented. We chose a self-rated measure as it has been found to correlate with actual mechanical ability and spatial ability (Hegarty & Just, 1993; Heiser & Tversky, in prep).

Participants were shown one of three diagrams: a car brake (Figure 1), bicycle pump, or a pulley system, either without or with arrows and asked to "Please examine the diagram above. On the lines below, write a description of the system in the diagram."

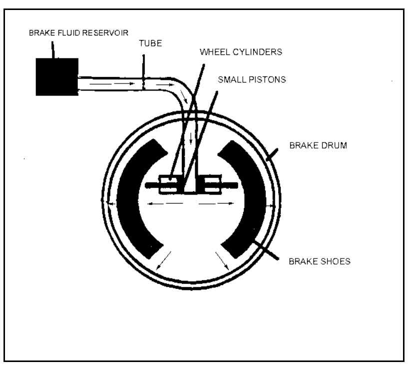

Figure 1: Car brake diagram with arrows (adapted from Mayer & Gallini (1990))

Coding

Self-rated mechanical ability and self-rated prior knowledge of system correlated highly ($r = .78$, $p < 01$). They were averaged to provide a single ability score, ranging from 1-7 (poor-excellent).

Descriptions of diagrams were coded blindly. Two coders divided each description into propositions. Coders were told that a proposition is the smallest unit of meaning in a sentence. For example, in the sentence "the liquid brake fluid travels down the tube," there are two propositions. First, "the brake fluid is liquid" and second, "the brake fluid travels down the tube."

Coders categorized each proposition as structural or functional. Descriptions of the system structure or of the features of the components (i.e. the shape of a part) counted as structural information. Descriptions of the function of the system, the function of individual parts or the way the parts work together, counted as functional information. In the previous example, the first proposition, "the brake fluid is liquid" was coded as structural. The second proposition, " the brake fluid travels down the tube" was coded as functional. Coders agreed 94%, and disagreements were settled through discussion.

Results and Discussion

There were no main effects for diagram content, self-rated ability or total number of propositions across conditions.

As predicted, participants who described diagrams with arrows produced significantly more functional units of information ($M = 2.24$, $SD = 1.3$) than participants who described diagrams without arrows ($M = 1.26$, $SD = 1.1$), $F(1,61) = 10.9$, $p < .01$. Similarly, participants who described diagrams without arrows generated significantly more structural units ($M = 1.65$, $SD = 1.65$), than those who described diagrams with arrows ($M = .52$, $SD = .62$), $F(1,61) = 13.67$, $p < .01$.

The presence of arrows in a diagram of a mechanical system indicates the sequence of operations of the system. From the temporal sequence, participants readily made inferences to the function of the system, and described it in those terms.

Experiment 2: Diagrams from Descriptions

Is the use of arrows to convey temporal, causal sequence so established that producers of diagrams will comply? Participants read either a structural or a functional description of a complex system, and produced a diagram.

Method

Participants

240 students in an introductory psychology course at Stanford University participated for course credit. Forty-four participants either did not draw a diagram or did not complete the questionnaire, leaving 93 participants in the functional description group and 103 in the structural description group, distributed fairly evenly across the three systems.

Stimuli

Structural and functional descriptions were written for each of the three systems, the car brake, bicycle pump, and pulley system. Those for the car brake appear in Table 1 and 2. Structural descriptions contain details of parts and their spatial relations, primarily using forms if the verb "to be" or verbs of fictive motion. Functional descriptions contain actions and consequences primarily using active verbs of motion.

Table 1: Car brake structural description

"The brake or brake drum is a circular structure. Directly inside the sides of the brake drum are two thick semicircular structures called the brake shoes. The brake fluid reservoir is located above and to the side of the brake drum. From the brake fluid reservoir, a tube runs down sideways and then down to the middle of the brake drum. Extending from both sides of the tube in the middle of the brake drum are wheel cylinders surrounding small pistons. Brake fluid can move from the reservoir through the tube to the pistons. The small pistons can move outward toward the brake shoes. The brake shoes can move outward toward the brake drum."

Table 2: Car brake functional description

"From the brake fluid reservoir, brake fluid enters and travels sideways and down the tube. As the brake fluid accumulates at the bottom of the tube, pressure is exerted on the small pistons inside the wheel cylinders. This causes the pistons to push outward toward the brake drum. The outward movement of the shoes causes friction along the inside of the brake drum, slowing the rotation of the wheel."

Procedure

Participants first rated their mechanical ability on a 1 to 7 scale, 1 = poor and 7 = excellent and their specific knowledge of the depicted mechanical system on the same scale. Participants then read a description of one of three labeled systems (car brake, bicycle pump, or pulley) and were asked: "In the space provided below the description, please construct a diagram of what you think the description is trying to convey."

Coding

Self-rated mechanical ability and self-rated prior knowledge of the device were highly correlated, $r = .72$, $p < 01$. They were averaged to produce a single ability score for each participant. Diagrams were coded blindly by two coders for conventional elements, such as arrows or lines, that conveyed either structure or function. There were no disagreements in coding.

Results

As before, there were no effects of mechanical system or for self-rated ability. Of the 196 depictions coded, the only graphical element added was arrows. The arrows were to indicate direction of motion of the mechanical system. As predicted 62/93 (66.7%) who depicted functional descriptions used arrows in their depiction to indicate sequence of operation, whereas 16/103 (15.5%) participants who depicted structural descriptions included arrows, X^2 (N = 196) = 9, $p <.01$. All 16 who included arrows in depictions from structural descriptions were high mechanical ability participants (see Figure 2 for examples).

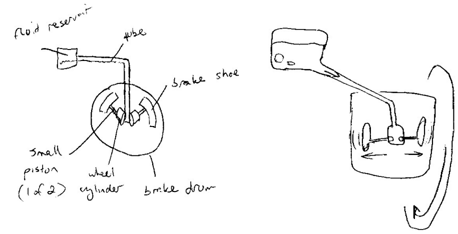

Figure 2. Drawing from structural description (left) and functional description (right) of car brake.

Discussion: Communicating With Diagrams

Experiment 1 and 2 showed that people readily interpret and produce arrows in diagrams to suggest functional properties of complex systems. For a car brake, bicycle pump and pulley system, diagrams without arrows elicited structural descriptions. Conversely, for structural descriptions participants drew diagrams without arrows but for functional descriptions they drew diagrams with arrows. Moreover, low ability participants were as likely as high ability participants to comprehend and produce arrows to convey function.

The finding that structural diagrams can be effectively enriched by the simple addition of arrows is important, as making inferences from structure to function is one of the major difficulties of understanding complex systems. The next study will examine the roles of structural and functional descriptions and diagrams with and without arrows in comprehending and making inferences about complex systems.

Experiment 3: Learning structure and function from diagrams and text

Complex systems can be described from structural or functional perspectives. The structural aspects of a system are typically easier to convey. However, it is often the functional aspects that are critical for understanding how the system operates and for trouble-shooting, error-recovery and high-level problem solving. The previous experiment showed that a simple enrichment of structural diagrams, an arrow, enable functional inferences. Here we examine directly and in detail the relative efficiency of structural and functional text and of diagrams with and without arrows in conveying structural and functional aspects of complex systems. We do this for both high and low mechanical ability participants. This experiment will provide insight into the effects of medium, text or diagram; perspective, structural or functional; and ability, high or low, on transmission of structural and functional information about complex systems.

Method

Participants and design

Participants were 147 students in an introductory psychology course at Stanford University participating for course credit. Each participant was randomly assigned to one of 8 conditions. 31 to the no arrow diagram condition, 40 to the arrows diagram condition, 33 to the structural text condition, and 43 to the function text condition. Approximately equal proportions of the participants studied the car brake and the bicycle pump. The pulley system was not used in this study. Study time was recorded for all subjects; however, timing was inaccurate for 34 subjects (in random conditions) leaving 113 study times in the analysis.

Procedure

As in Experiments 1 and 2, participants first rated their general mechanical ability and prior knowledge of the specific device (car brake or bicycle pump) on a scale from 1 to 7, 1 = poor, 7 = excellent.

Participants studied a description or diagram of either the bike pump or car brake. In the text conditions, participants read and studied the description four times. In the diagram condition, participants studied the diagrams completely four times. Study time was self-terminating. Immediately after study, participants answered 16 true/false statements, half structural, half functional. The questions varied in difficulty. An example of a structural T/F statement is "The small pistons are adjacent to the brake shoes." An example of a functional T/F statement is "The pistons put pressure on the brake shoes." Participants were told to respond quickly and accurately.

Ability measurements

Participants' scores from the self-rated prior knowledge of device and mechanical ability scales correlated significantly ($r = .68$, $p < .01$) and were averaged to form a mechanical ability score. A median split gave low and high ability students.

Results

Does the medium, text or diagram, or perspective, structural/no arrow or functional/arrow affect performance on structural and functional questions? How does ability affect performance? Because of their natural mapping to space, it is predicted that diagrams will be superior to text for structural questions. In regards to conveying structural or functional perspectives of complex systems, it is predicted that structural descriptions or diagrams should facilitate structural questions and functional presentations should facilitate functional questions. Finally, which is easier, making inferences from structure to function or from function to structure? To assess these effects and others, we performed four analyses of variance on errors and response times for structural and functional questions. Each ANOVA had medium, text or diagrams; perspective, structural or functional; and mechanical ability, high or low, as factors.

Study time

There was wide variability in study time, but it did not correlate with any of the measures of interest-medium, perspective, or ability.

Learning Structural Information

Effect of Ability

High mechanical ability participants outperformed low ability participants on structural questions. Low ability participants made more errors ($M = 2.5$, $SD = 1.51$) than high ability participants ($M = 1.59$, $SD = 1.14$), $F(1, 139) = 15.7$, $p < .01$. There were no significant differences in response times between high ($M = 4.6$s, $SD = 1.5$) and low mechanical ability ($M = 4.5$s, $SD = 1.3$s). There were also no significant interactions between ability, medium, and perspective for errors on structural questions. Figure 3 illustrates that low ability participants perform close to that of high ability participants when structural text was studied, however this did not elicit a significant interaction.

Effect of Medium

There were no effects of medium for structural questions. Fewer errors were made after a diagram was studied ($M = 1.76$ out of 8, $SD = 1.08$) than after text was studied ($M = 2.28$, $SD = 1.62$), however this difference was not significant, $p > .1$ (see Figure 3). Structure was conveyed equally well by text and diagrams. Response time, however, was significantly longer on structural questions after studying a diagram ($M = 5.1$s, $SD = 1.4$s) than after studying a text ($M = 4.2$s, $SD = 1.3$s), $F(1, 131) = 13.6$, $p < .01$. This effect may be due to extra time required to translate a visual representation into a sentential representation in order to answer the verbal questions.

Effect of Perspective

There were no effects of perspective (structural or functional) on errors or response time on structural questions. Participants made similar numbers of errors on structural questions if a structural perspective was studied ($M = 1.89$, $SD = 1.39$) than if a functional perspective was studied ($M = 2.13$, $SD = 1.41$), $p > .05$ Though in this analysis, diagrams have a clear advantage because structure remains explicit in the diagram with arrows, the interaction between presentation and perspective was not significant, $p > .1$.

The finding that both high and low mechanical ability participants did not differ significantly on structural errors regardless of study perspective indicates that they were able to efficiently make inferences from function to structure.

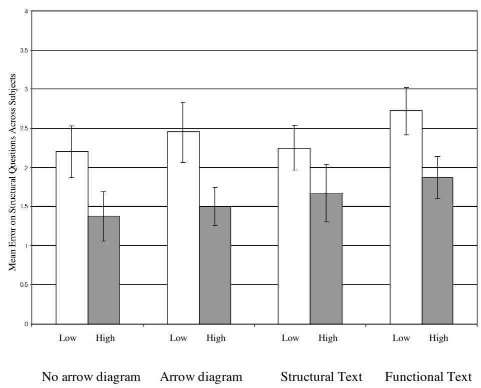

Figure 3. Errors on structural questions by ability, perspective and medium.

Learning Functional Information

Effect of Ability

For functional questions there was a main effect for ability, where high mechanical ability participants made fewer errors ($M = 1.44$, $SD = 1.3$) than low ability participants ($M= 2.75$ $SD= 1.6$), $F(1, 145) = 29.6$, $p<.01$. There were no significant differences in response times between high mechanical ability ($M = 5.2s$, $SD = 1.9s$) and low mechanical ability ($M = 5.3s$, $SD = 1.8s$), $p >.1$.

Mechanical ability interacted with medium. See the following section for details.

Effect of Medium

There were no overall effects of medium on errors and response times on functional questions. However, medium and perspective interacted, $F(1, 139) = 8.02$, $p < .01$. High ability participants made fewer errors on functional questions when diagrams were studied ($M = 1.1$, $SD = 1.1$) than when text was studied, whereas low ability participants made fewer errors when text was studied ($M = 2.6$, $SD = 1.6$) than when diagrams were studied ($M = 3.0$, $SD = 1.6$). This effect however, could be driven by interaction between perspective of study and medium, where participants performed extremely well if functional text was studied, but not structural text. This is further discussed in the next section.

Interestingly, high ability participants outperformed low ability participants on functional questions in all conditions except when functional text was studied (see Figure 4). These results indicate that low ability participants have difficulties making functional inferences from structural descriptions and diagrams, with or with out arrows. When functional information is presented verbally, low ability participants are no longer disadvantaged.

Effect of Perspective

There was a slight benefit for functional questions from studying functional material, however this effect was only marginally significant, $F (1,139) = 3.5$, $p = .06$. Performance was higher on functional questions after studying functional text or diagrams with arrows ($M = 1.73$, $SD = 1.48$), than after studying structural text or diagrams ($M = 2.45$, $SD = 1.69$). There were no differences in response times.

There was an interaction between perspective and medium. Errors on functional questions were higher after studying a structural text ($M=3.0$, $SD=1.7$) than after studying a diagram without arrows ($M=1.87$, $SD=1.5$), functional text ($M = 1.71$, $SD = 1.27$) or diagram with arrows ($M = 1.75$, $SD = 1.68$), $F(1, 139) = 17.48$, $p < .01$. In general, participants were better at making functional inferences from diagrams, than from structural text.

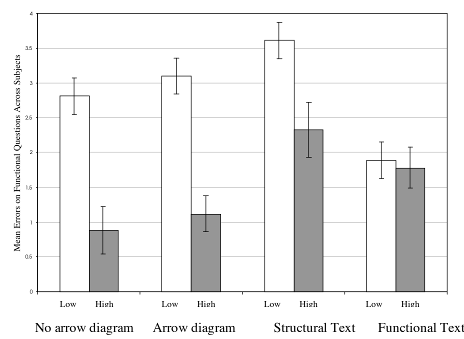

Figure 4: Errors on functional questions by ability, perspective and medium.

Experiment 3 Discussion

Structural information was effectively conveyed by well-constructed diagrams and text, from the perspective of the system's structure or function. Mechanical ability of the participant, however, is important for predicting errors on structural questions.

The results for functional information were quite different. Again, high mechanical ability participants outperformed low ability participants. This result was conditional upon presentation, however, where low ability participants performed as well as high ability participants when functional text was studied. Low ability participants were at their worst when functional inferences had to be made from diagrams.

The results from Experiment 3 help to clarify the relationship between ability and comprehension of diagrams, illustrating the importance of the information to be conveyed. Low mechanical ability participants were able to learn structure from both diagrams and text, but needed functional text to aid learning functional information.

General discussion

Complex systems consist of structural information, a configuration of parts, and functional information, a sequence of operations and outcomes. The present research investigated the effects of medium, text and diagram, perspective of presentation, structural or functional, and ability on acquisition of complex systems.

Diagrams use elements and relations in space to convey elements and relations in real or conceptual space. Thus, diagrams are especially suited to convey structural information. Experiment 1 and 2 showed that a simple addition to diagrams, arrows, enables a static diagram to convey functional information effectively. Participants spontaneously interpreted diagrams with arrows functionally, and produced diagrams with arrows for functional descriptions. In global acquisition of complex systems, however, arrows were sufficient for participants with high mechanical ability but not for those with low mechanical ability.

In Experiment 3, participants were more adept at inferring structural information from functional than functional from structural. Apparently, function imposes more constraints on structure than structure imposes on function, in accordance with the design adage that form follows function. This means that function is not necessarily transparent from form. This fact is substantiated by the performance of low ability participants, who, in contrast to high ability participants, had trouble making functional inferences from diagrams. Similarly, Suwa and Tversky (2001) found that experienced architects were more likely to extract functional information from their sketches than novices. Low ability participants reached the level of high ability participants when the perspective of the questions matched that of the studied text. This suggests that the text guides the learner in forming a mental model of that information, especially for low ability learners. For this type of complex systems, including car brakes and bicycle pumps, the disadvantages of low ability can be overcome by the addition of explicit functional information.

These results have implications for theories of diagrammatic reasoning. The findings indicate that learners of all abilities are able to extract essential parts and their interrelations from diagrams; however the advantage of diagrams disappears when learners with low mechanical ability are asked to make inferences beyond what is conveyed explicitly in the diagram.

In addition, these results have implications for design of instructions and explanations as well as comprehension of complex systems. Instructions and texts depending solely on diagrams will be ineffective for some users, especially for functional information. Instructional illustrations of mechanical, scientific, or abstract systems such as governmental legislation need to include explanatory text. Taking into account the ability of the learner, the perspective of the information, and the medium in which it is portrayed, will dramatically increase the accuracy and amount of information that can be acquired from a portrayal of a complex system.

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