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Mental Models of Complex Systems: Structure and Function

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Abstract

Interacting with complex systems such as organizations and mechanical devices is an integral part of our lives. Learning them can be a challenge, although they can be described in language and depicted in diagrams. Medium, verbal or graphic, and ability/expertise have had conflicting effects on acquisition. Those effects are clarified by recognizing that complex systems have *structural* organizations, parts and their relations, and *functional* organizations, operations and consequences. Diagrams can convey a variety of functions by the addition of arrows. Diagrams are effective for those with high mechanical ability/expertise but difficult specifically for functional information for those with low ability/expertise. Individuals high in ability/expertise form mental models integrating function and structure; those with low ability/expertise form mental models of structure separate from knowledge of function.

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Mental Models of Complex Systems: Structure and Function

How does a car brake work? How do I register for classes? How does the human heart function? Answering these questions depends on understanding complex systems, mechanical, organizational, or biological. Complex systems, whether concrete or abstract, have two levels of organization: a *structural* organization consisting of parts in a particular configuration and a *functional* organization consisting of a sequence of actions, usually operations of parts, and their consequences. Here is how a car brake works from a functional perspective: "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 the friction along the inside of the brake drum, slowing the rotation of the wheel" (see Figure 1).

Explaining such systems, either to students of politics or sciences or to users of VCRs or cell phones, has proved to be a challenge. A major difficulty is comprehending functional organization. A mental model of function is needed for understanding the operation of a device, for making inferences, and for solving problems (e. g., Kieras and Bovair, 1984). Diagrams are ideal for conveying structural organization, as they use elements and spatial relations in diagrammatic space to convey elements and spatial or conceptual relations in the system thereby capitalizing on people's experience interpreting spatial relations (Tversky 1995, 2001). Language is also effective in conveying structure (e. g., Mani & Johnson-Laird, 1982; Taylor & Tversky, 1992), probably the main reason that well-crafted text is often as good as diagrams in conveying structure (e. g., Taylor & Tversky, 1992; Winn, 1987). Diagrams cannot convey function as directly as they convey structure, simply because depicting function may entail depicting changes of state, movement, and forces, all more difficult to portray in static depictions than structure. Text can convey function, but text loses the natural mapping of diagrams from elements and configurations of a system to elements and configurations on paper. To convey function in diagrams requires other means.

Enriching diagrams with devices that are less iconic to convey ideas not easily depicted is commonplace. Even the most spatial of diagrams, maps, use such devices, for example, elements to signify kinds of sites, archeological, commercial, religious or shading to indicate altitude or colors to denote legal boundaries. One compelling candidate for conveying change over time in a diagram is an arrow. Arrows belong to a class of privileged diagrammatic elements, along with lines, boxes, crosses, and circles (Tversky, in press; Tversky, Lee, Zacks, and Heiser, 2000). These privileged elements are schematic geometric figures that convey meanings related to their Gestalt or geometric properties. For example, lines, as used in route maps, graphs, networks, and flowcharts, associate. They signify that a relationship exists between the entities they link. Arrows can link as well but they are asymmetric, indicating an asymmetric relationship. The arrowhead indicates the direction just as it does in a flying arrow or in the arrowheads formed by rivulets of water converging downstream. Arrows can express many relationships, among them pointing or connecting, change over time, path or manner of movement or forces, and order. In the case of maps, arrows indicate the direction of the route, the order of the actions to reach the destination. In the case of diagrams of complex systems, arrows can be used to indicate temporal sequence, the order of the operation of the components to accomplish the goal. Arrows can also show aspects of motion. It is noteworthy that all of these concepts and more, each requiring separate words, can be expressed by a single graphic device, an arrow. Because diagrams of complex systems readily convey structure but not function, enriching them in order to convey function effectively is desirable.

Diagrams are frequently used to supplement text in teaching complex systems. Illustrations that focus learners on the key elements of devices such as a bike pump or car brake benefit learners; combinations of text and labeled illustrations improved performance on problem solving (Mayer, 1989). To investigate formats that might promote construction of mental models of systems, Mayer & Gallini (1990) compared three types of diagrams, those portraying the parts of the system, the steps of the system, or both the parts and the steps. Benefits of the diagrams depended on the prior knowledge of the learner. For students high in prior knowledge, none of the diagrams improved recall or transfer performance. For students with low prior knowledge, only the diagrams with both parts and steps were helpful. However, the steps diagram used arrows as well as added text to explain the process of the system. Thus, this design cannot isolate the role or aspects of diagrams per se in promoting mental models of the systems. In a study comparing text, diagrams, or both in conveying a pulley system, Hegarty and Just (1993) found that either text or diagram was sufficient to comprehend the configuration of the system, but the conjunction of text and diagram was needed to understand the processes that are involved in a pulley system. Altogether, understanding system process or function or kinematics has proved to be harder than understanding configuration. The studies reviewed found that both text and diagrams are needed, but this could be because function has typically been conveyed only by text (e. g., Hegarty & Just, 1993; Hegarty & Sims, 1994).

How does language convey structure and function? Consider a structural description of a bicycle pump: “The bicycle pump is a tall cylinder with a handle extending from the top that can move up and down. Attached to the bottom of the handle in the middle of the cylinder is the piston. Next to the piston is the inlet valve that can open and close. Below the inlet valve is he chamber. Extending outward from the chamber at the bottom is the outlet hose. Between the chamber and the hose is the outlet valve, which can open and close." Now compare this to the functional description of the car brake above. The major distinction is the verbs. Structural descriptions describe the spatial relations among parts. These are similar to survey descriptions of environments (Taylor and Tversky, 1992, 1996), and like survey descriptions, structural descriptions use intransitive, static verbs, frequently, forms of the verb "to be." Functional descriptions are dynamic; as such, they are similar to route descriptions of environments and tend to use verbs of motion and transitive verbs, such as *enters, travels, accumulates, exerted, push, slow,* and even, *causes.* Not only do these verbs directly describe function, they are also likely to be the verbs used in testing knowledge of systems, so they enjoy verbatim as well as semantic advantages (e. g., Taylor and Tversky, 1992).

Here we investigate how depictions and descriptions convey structure and function of complex systems. From the work of others, we chose three mechanical systems: a car brake, a bicycle pump, and a pulley system (cf. Hegarty, 1992; Mayer, 1998). For the learner, what is critical is the nature of mental models engendered by diagrams with different formats and text with different perspectives. In the first experiment, we ask whether adding arrows to structural diagrams changes the way they are interpreted. In the second experiment, we examine whether the perspective of the text, structural or functional, affects the diagrams participants produce. In the third experiment, we determine the ease with which participants comprehend functional and structural aspects of the systems and make inferences from one to the other when learning from text or diagrams that take structural or functional perspectives.

A parallel issue is the role of individual differences in extracting structural and functional information from text and diagrams. Not surprisingly, people with low mechanical ability have more difficulty understanding complex systems (Hegarty & Just, 1993; Hegarty and Sims, 1994). Diagrams sometimes benefit individuals with low ability, but sometimes present difficulties (Holliday, et al., 1997; Koran & Koran, 1980; Winn, 1980). Larkin and Simon (1987) claimed that if a student does not have the appropriate background knowledge, enough to be able to make inferences from diagrams, the diagrams will be “largely useless” (p.71). In some studies, low ability participants had more difficulty locating the relevant information in diagrams, and were more dependent on accompanying text (Hegarty, et al, 1988; Hegarty & Just. 1989, Hegarty & Just 1993). Participants low in mechanical ability tests encoded only the elementary components of the pulley system depicted in the diagrams, whereas high mechanical participants encoded the configuration of the components as well (Hegarty, Just, & Morrison, 1987). Low ability participants have more difficulty mentally animating the process of a complex system, as some spatial transformations are difficult for inexperienced learners (Just & Carpenter, 1985), These conflicting results suggest that diagrams can either help or hinder participants with low spatial ability depending on format and the information to be extracted**.** Since one of the major difficulties in understanding complex systems is making inferences from structure to function, we were especially interested in the effectiveness of diagrams and text for conveying structure and function to participants of low and high ability or expertise.

In the studies reported here, we used self-reported measures of mechanical ability and prior knowledge of the specific devices. Mechanical ability is relevant because the systems used here are mechanical. Furthermore, mechanical ability has been shown to involve general reasoning ability in addition to knowledge of complex systems and machines. (Hegarty, et al., 1988; Hegarty & Sims, 1994) and to be related to inference-making and comprehension (Hegarty, et al., 1988) In all three studies, self-reports of mechanical ability and expertise correlated highly, so were averaged to a single ability/expertise score. Mechanical ability is highly correlated with spatial ability (Hegarty & Just, 1993). For such domains, self-reported ability is a good predictor of task performance (e. g., Kozlowski and Bryant, 1977).

Experiment 1: Interpreting Diagrams with and Without Arrows

The structure of complex systems can be easily and effectively conveyed in diagrams. Absorbing function from a static diagram requires inferences. Function depends on an ordered sequence of actions and consequences. One natural way to depict order is an arrow, widely used to indicate order. Arrows can also convey direction, path, and manner of motion, all involved in the function of mechanical systems. In this experiment, we ask participants to interpret systems diagrams with or without arrows. The expectation is that diagrams without arrows will elicit structural descriptions and diagrams with arrows will elicit functional descriptions.

Participants and Design

Participants were 80 students in an introductory psychology course at Stanford University fulfilling a course requirement. Thirteen participants did not complete the questionnaire leaving 67 participants. Thirty-four participants described diagrams without arrows. Of those participants, 8 described a car brake, 14 described a bicycle pump, and 12 described a pulley system (see Figures 1-3). Thirty-three participants described diagrams with arrows; 8 described a car brake, 12 described a bicycle pump, and 1

3 described a pulley system.

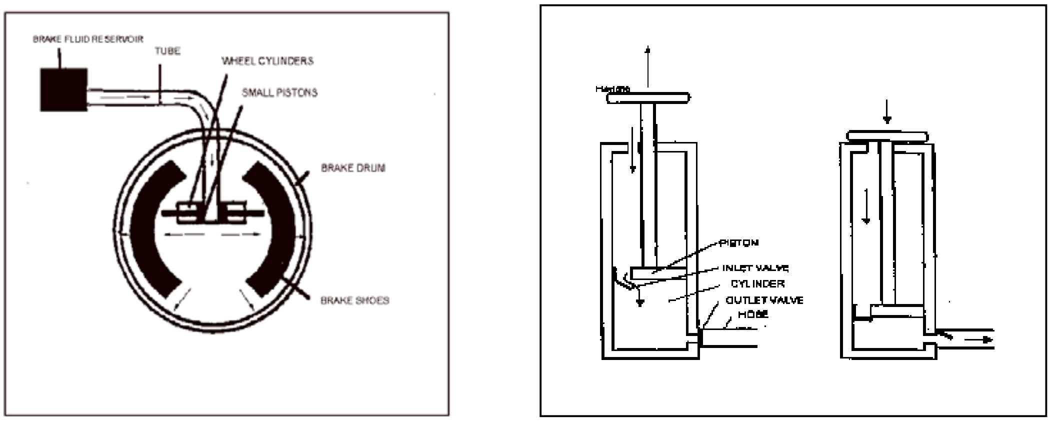

Figure 1& 2. Diagram with arrows of a car brake and bicycle pump used in Experiments 1, 2 and 3. Adapted from Mayer & Gallini (1990).

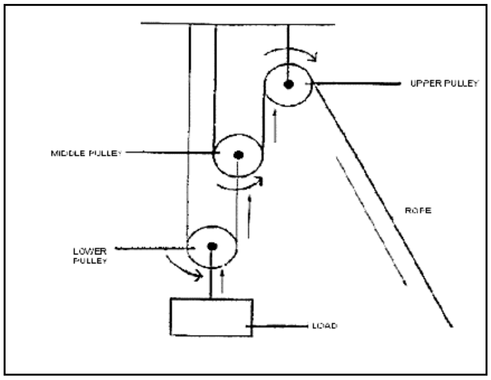

Figure 3. Diagram with arrows of a pulley used in Experiments 1 and 2. Adapted from Hegarty (1993).

Procedure

Participants were given a single piece of paper (8.5 x 11 inches) with one of three diagrams; a car brake, bicycle pump, or a pulley system. These diagrams either included arrows indicating the direction of motion, or did not include arrows. Below the diagram was the instruction, "Please examine the diagram above. On the lines below, write a description of the system in the diagram." Participants were also asked to rate their mechanical ability on a 1 to 7 scale, 1= poor, 7 = excellent. In addition, they were asked to rate their prior specific knowledge of the mechanical system being portrayed in the diagram on the same scale. They were instructed to spend approximately 3-5 minutes on the entire task.

Coding Descriptions

Descriptions of diagrams were coded blindly. Two coders first divided statements into propositions, that is, the smallest unit of meaning in a sentence, and then decided whether those propositions described the structure or the function of the mechanism. Descriptions of the system structure or explanations 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. For example, in the sentence "the liquid brake fluid travels down the tube" there are two propositions: "the brake fluid is liquid" and "the brake fluid travels down the tube." The first is structural and the second, functional. Coders agreed 94%, and the disagreements were settled through discussion.

Results

Self-rated mechanical ability and self-rated system knowledge correlated highly ($\underline{r} = .78$, $\underline{p} < .01$). The numbers were averaged to provide a single ability score.

There were no main effects or interactions of 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 (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 (see Figure 4). 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 (see Figure 4).

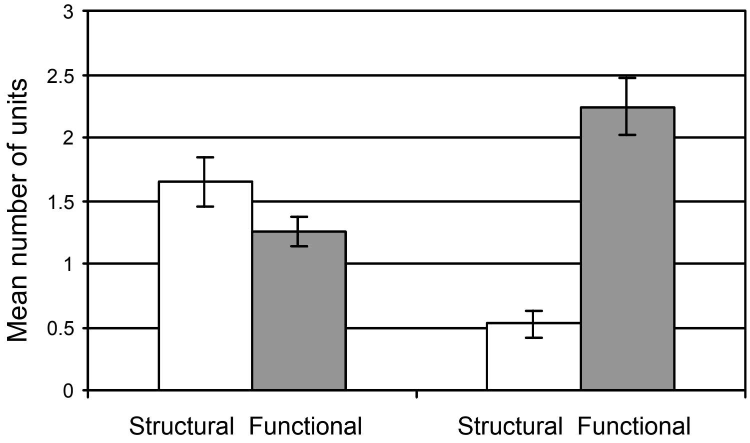

Figure 4. Mean number of structural and functional units per description of diagrams with and without arrows (Experiment 1).

Converging evidence was found in a count of the verbs types that were used in the descriptions. Participants describing diagrams without arrows should use structural predicates, specifically, more forms of the verb "to be," whereas those describing diagrams with arrows should use more action predicates, specifically, verbs of motion and causation, such as "push," "lift," or "travels." This hypothesis was confirmed. Descriptions from the no arrow condition contained significantly more static expressions using forms of the verb "to be" (M = 1.87, SD = 1.86) than descriptions from arrow condition (M = .84, SD = .95), F(1,81) = 10.496, $p < .01$. Furthermore, descriptions from the arrow condition contained significantly more active expressions using motion, action, and cause verbs (M = 3.26, SD = 2.07), than descriptions in the no arrow condition (M = 1.78, SD = 1.35), F(1,81) = 14.66, $p < .01$.

As seen in Figures 1-3, the arrows in the diagrams specify the sequence in which the parts operate to complete the function of the complex systems. They guide the learner through the functional, relations of the system. For each system, there is one correct order of operation, so descriptions were given a "0" if the order was incorrect, or a "1" if the order was correct. There were no significant differences among the complex systems, so the three systems could be included in the same analysis. The correct sequence of operations was used by more participants who described the diagrams with arrows than who described diagrams without arrows, X^2 (1, N = 67) = 4.3, $p < .05$.

Discussion: Comprehending Diagrams

When asked to describe diagrams of a car brake, bike pump, or pulley system, participants' produce primarily structural descriptions. When arrows are added to the diagrams, descriptions are primarily functional. Arrows imposed on the structure of a mechanical system effectively convey the order of operations of the system, and thus the functional relations of the system. Arrows can also signal the direction, path, and manner of motion and hence the operation of the device. Without arrows, diagrams suggest the structural configuration of the device. As expected, the language of structural and functional descriptions differed. Structural descriptions used more static verbs, especially forms of "to be," whereas functional descriptions used more transitive verbs and verbs of motion and cause. Moreover, the diagrams with arrows increased reporting the correct sequence of operations. From structural diagrams, those without arrows, participants form mental models of the structures of the systems. From diagrams with arrows, participants form mental models of the functions of the systems.

Experiment 2: Producing Diagrams from Structural or Functional Descriptions

People interpret diagrams without arrows primarily structurally and diagrams with arrows primarily functionally. Will this correspondence hold for the mirror-image task, producing diagrams from text that is structural or functional? In this experiment, participants read a structural or functional description of one of the three systems. They were asked to sketch a diagram of the described system.

Participants and Design

240 students in an introductory psychology course at Stanford University participated for course credit. 44 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; car brake, bicycle pump, and pulley system. These appear in Table 1. 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

Descriptions used in Experiments 2 & 3

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.

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.

Bike Pump Structural Description

The bicycle pump is a tall cylinder with a handle extending from the top that can move up and down. Attached to the bottom of the handle in the middle of the cylinder is the piston. Next to the piston is the inlet valve that can open and close. Below the inlet valve is he chamber. Extending outward from the chamber at the bottom is the outlet hose. Between the chamber and the hose is the outlet valve, which can open and close.

Bike Pump Functional Description

When the handle is pulled up, it pulls the piston up. The pressure of the upward movement of the piston causes the inlet valve next to the piston at the top of the chamber to open and the outlet valve at the bottom of the chamber of the pump to close. This allows air to enter the lower chamber. When the handle is pushed down, pressure is exerted in the chamber causing the outlet valve to open. The pressure in the chamber and the opening of the outlet valve causes air to exit through the hose.

Pulley System Structural Description

This is a three-pulley system. The right-most pulley is highest and the left-most is lowest. A short rope attaches the highest right pulley to the ceiling. A longer rope extends from the ceiling under the middle pulley over the highest pulley and down to the operator. Another long rope extends from the ceiling under the lowest left-most pulley and to the center of the middle pulley. The load is attached to the lowest pulley by a short rope. All the ropes and pulleys can move around and upwards.

Pulley System Functional Description

As the rope is pulled downward to the right, the upper pulley turns clockwise. The rising of the rope causes the middle pulley that is lower and to the left to turn counterclockwise and to rise. The rising of the middle pulley causes the rope connected to the lower pulley on the left to turn the lower pulley counterclockwise and make it rise. The rising of the lower pulley cause the load attached to it at the bottom to rise.

Procedure

Participants were given a single piece of paper (8.5 x 11 inches) with one of three descriptions, appropriately labeled at the top of the page. Participants were asked to both rate their mechanical ability on a 1 to 7 scale, 1 = poor and 7 = excellent and also rate their specific knowledge of the mechanical system conveyed in the description on the same scale. Participants were then asked to " Please read the following description. In the space provided below the description, please construct a diagram of what you think the description is trying to convey." They were instructed to spend approximately 3-5 minutes on this exercise.

Coding

Diagrams were coded by two people for conventional elements, such as arrows or lines, that might augment depictions of structure or function. There were no disagreements in coding.

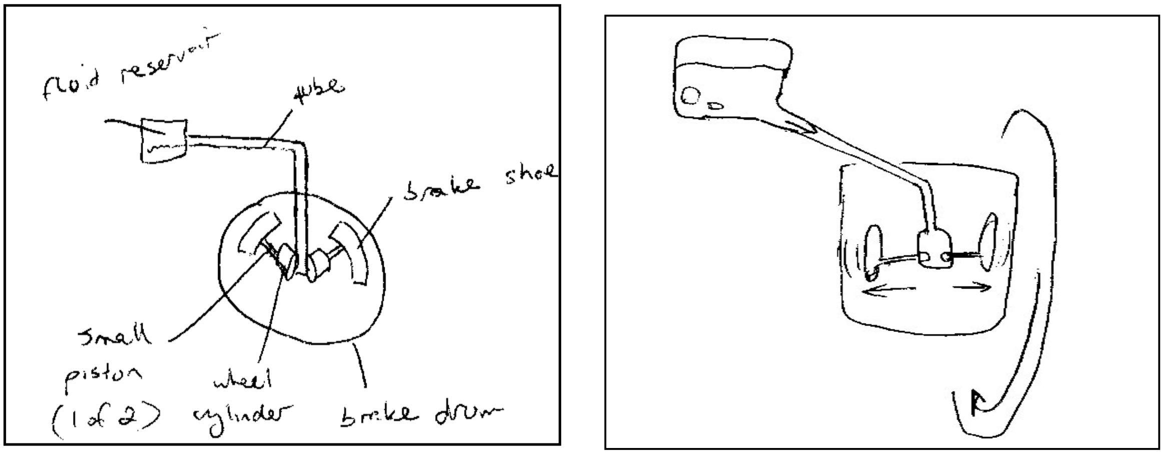

Figure 5a & b. Example of sketches by participants depicting either a structural description or a functional description, respectively (Experiment 2).

Results

Self-rated mechanical ability and self-rated knowledge of the device correlated .72, $p <$ 01. They were averaged to produce a single ability score for each participant.

As before, there were no effects for mechanical system or for self-rated ability. Of the 196 depictions coded, the primary graphical element participants added to depictions were arrows (see Figure 5a & b for examples). The arrows appeared to indicate direction of motion of the mechanical system. As predicted 62/93 (66.7%) of participants who depicted functional descriptions used arrows in their depiction to indicate direction of operation, whereas only 16/103 (15.5%) of participants who depicted structural descriptions included arrows X^2 (1, N = 196) = 9, p < .01, see Figure 6. All 16 who included arrows in depictions from structural descriptions were high ability participants. 68 participants, 38 who read structural descriptions and 30 who read functional descriptions, added lines to their diagrams to label parts, as in Figure 5a.

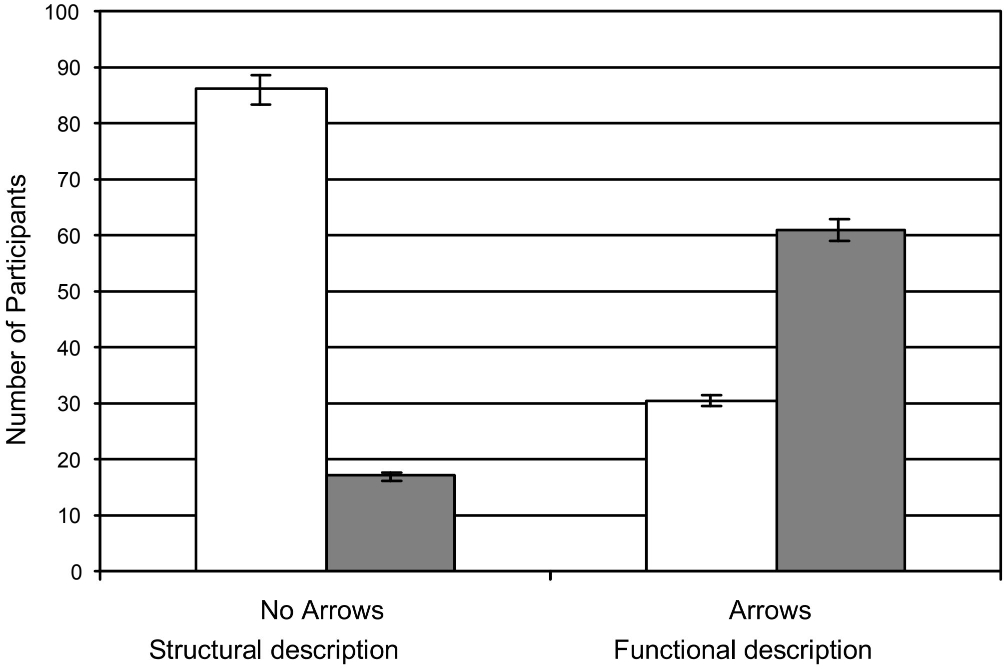

Figure 6. Number of participants producing diagrams with and without arrows for structural and functional descriptions (Experiment 2).

Discussion: Communicating With Diagrams

Diagrams use a mixture of devices to communicate. Effective diagrams map elements and spatial relations from the information to be conveyed to elements and spatial relations in the diagram in a cognitively compelling way. Diagrammatic elements can resemble or be associated with the things they represent as in file folders, trash cans, and scissors in computer interfaces. Proximity in diagrams is used to convey proximity on concrete and on abstract dimensions. Diagrams take advantage of human experience making spatial inferences (e. g., Pinker, 1990; Larkin & Simon, 1987; Hegarty, 1991; Tversky, 1995). But not all information can be portrayed in this way, so diagrams are often supplemented with explanatory text as well as other depictive devices. Some of these, such as lines, bars and arrows have a special status in that their Gestalt and geometric properties suggest constraints on their meanings. Lines link entities, suggesting a relation among them. Arrows are asymmetric lines, indicating an asymmetric relation. Arrows are especially useful as they convey a variety of context sensitive meanings: calling attention, pointing, labeling, direction in space, time, and causality, manner and path of motion and forces.

Diagrams are particularly appropriate for conveying the structure of complex systems, whether concrete, like a car brake, or abstract, like a corporate organization. Function, however, is not readily apparent from a diagram as it depends on a sequence of actions and consequences. Arrows, however, can be added to static structural diagrams to convey function.

Experiment 1 and 2 showed that people readily interpret and produce arrows in diagrams to suggest functional properties of complex systems. For car brakes, bicycle pumps and pulley systems, 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. Similar dualities in descriptions and depictions have been found for other symbolic elements, lines arrows, crosses and blobs in sketch maps (Tversky & Lee, 1998, 1999) and bars and lines in statistical graphs

(Zacks & Tversky, 1999). The communalities suggest that some mental representation more abstract than either is underlies both.

The finding that structural diagrams can be effectively enriched by the simple addition of arrows to convey function 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: Acquiring Structure and Function from Diagrams and Text

Complex systems can be described from structural or functional perspectives. Typically, the structural aspects of a system are easier to describe and comprehend than the functional aspects. However, it is usually understanding of function that allows understanding how the system operates, trouble-shooting, error-recovery and high-level problem solving. The previous experiment showed that a simple enrichment of structural diagrams, an arrow, enables 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 ability participants. This experiment will provide insight into the effects of medium, text or diagram; perspective, structural or functional; and mechanical ability, high or low, on comprehension of structural and functional information about complex systems.

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 participants were in the no arrow diagram condition, 40 participants in the arrows diagram condition, 33 participants in the structural text condition, and 43 in 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 Experiment 3 because it contains fewer parts and actions, and overall is less mechanically complex.

Procedure

As before, participants 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. Next, participants were seated in front of a 15-inch computer monitor where the remainder of the experiment was presented using PsyScope (Cohen, MacWhinney, Flat, and Provost, 1993).

Participants were instructed to either study a description or diagram of either the bike pump or car brake. They were told that they would have to answer questions about what was in the diagram or description. Participants in the text conditions read and studied the description four times. Participants in the diagram condition were told to study the diagrams completely four times. Study time was self-terminating. Readings were separated by a key presses. Immediately after studying text or diagrams, participants answered 16 true/false statements, half structural, half functional. The statements appear in Appendix A. The questions varied in difficulty. Participants were told to respond to the statements quickly and accurately.

Ability measurements

Participants' scores from the self-rated specific device knowledge and mechanical ability scales correlated significantly ($r = .68$, $p < .01$). They were averaged to form a mean ability score.

Study time

On average, participants studied text longer (115 seconds) than diagrams (103 seconds); however the difference was not statistically significant due to the high variance. Study time did not correlate with number of errors made on functional questions ($r = .05$, $p > .1$) or on structural questions ($r = .02$, $p > .1$), nor did study time vary significantly with ability or content (car brake vs. bicycle pump).

Learning Structural Information

Effects of Ability

Participants high in ability/expertise outperformed participants low in ability/expertise on structural questions. Low ability/expertise participants made more errors ($M = 2.5$, $SD = 1.51$) than high ability/expertise participants ($M = 1.59$, $SD = 1.14$), $F(1, 139) = 15.7$, $p < .01$. There were no effects of ability/expertise on response times (high ability, $M = 4.6$s, $SD = 1.5$; low ability, $M = 4.5$s, $SD = 1.3$s), $F(1,137) = .295$, $p > .1$. There were also no significant interactions between ability/expertise, medium, and perspective for errors on structural questions. Although Figure 8 suggests that low ability/expertise participants performed nearly at the level of high ability/expertise participants after studying structural text, the interaction did not reach significance.

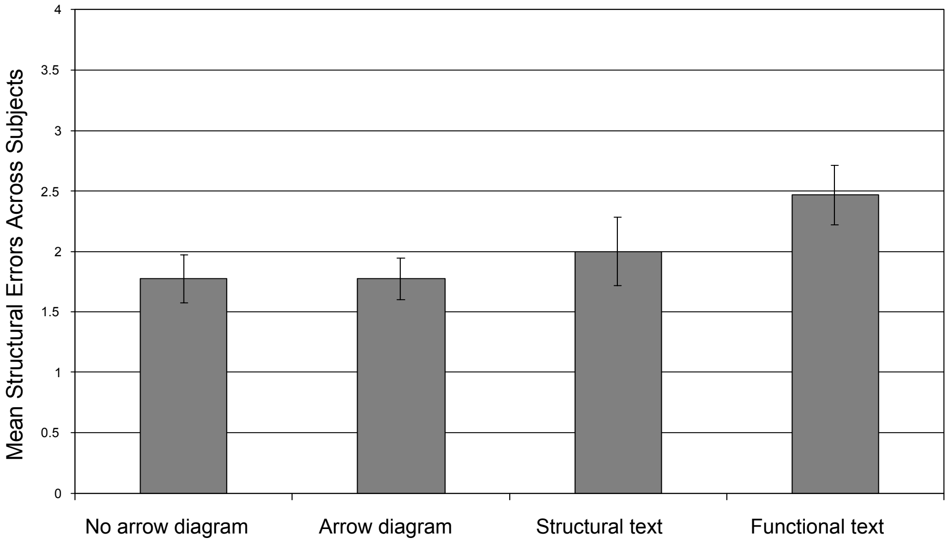

Figure 7. Mean errors on structural questions by perspective and medium (Experiment 3).

Effect of Medium

There were no effects of medium on accuracy answering 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 times, however, were significantly longer on structural questions after studying a diagram (M = 5.1s, SD = 1.4s) than after studying a text (M = 4.2s, SD = 1.3s), F(1, 131) = 13.6, p < .01. This may be due to extra time required to translate a visual representation into a sentential representation in order to answer the verbal questions.

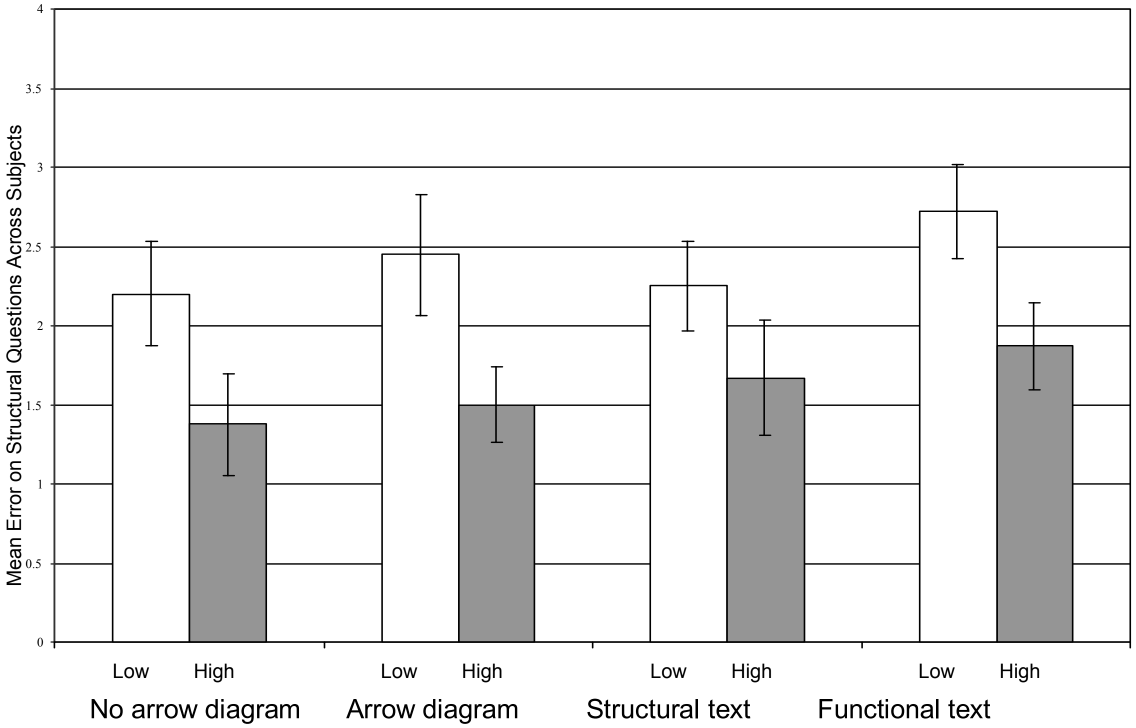

Figure 8. Mean errors on structural questions by perspective, medium and ability (Experiment 3).

Effect of Perspective

There were no effects of perspective (structural or functional) on errors or response times to structural questions. Participants made essentially the same numbers of errors on structural questions following both structural ($\underline{M} = 1.89$, $\underline{SD} = 1.39$) and functional perspectives ($\underline{M} = 2.13$, $\underline{SD} = 1.41$), $\underline{p} > .05$

Similarly, the absence of an effect of medium on structural information adds support to the expanding evidence that language is effective in conveying structure.

Learning Functional Information

Effect of Ability

For functional questions as for structural questions, there was a main effect for ability/expertise, where high mechanical ability/expertise participants made fewer errors (M = 1.44, SD = 1.3) than low ability/expertise 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/expertise (M = 5.2s, SD = 1.9s) and low mechanical ability/expertise (M = 5.3s, SD = 1.8s), $p > .1$. Mechanical ability/expertise interacted with medium, as follows.

Effect of Medium

There were no overall effects of medium on errors or on response times for functional questions. For errors, medium and perspective interacted, F(1, 139) = 8.02, $p < .01$. Functional information was as accurate from diagrams without arrows as from diagrams with arrows. Functional text, however, was more effective than structural text for acquiring function. High ability/expertise participants who studied diagrams made fewer errors on functional questions (M = 1.1, SD = 1.1) than those who studied text, whereas low ability/expertise participants who studied text made fewer errors on functional questions (M = 2.6, SD = 1.6) than those who studied diagrams (M = 3.0, SD = 1.6).

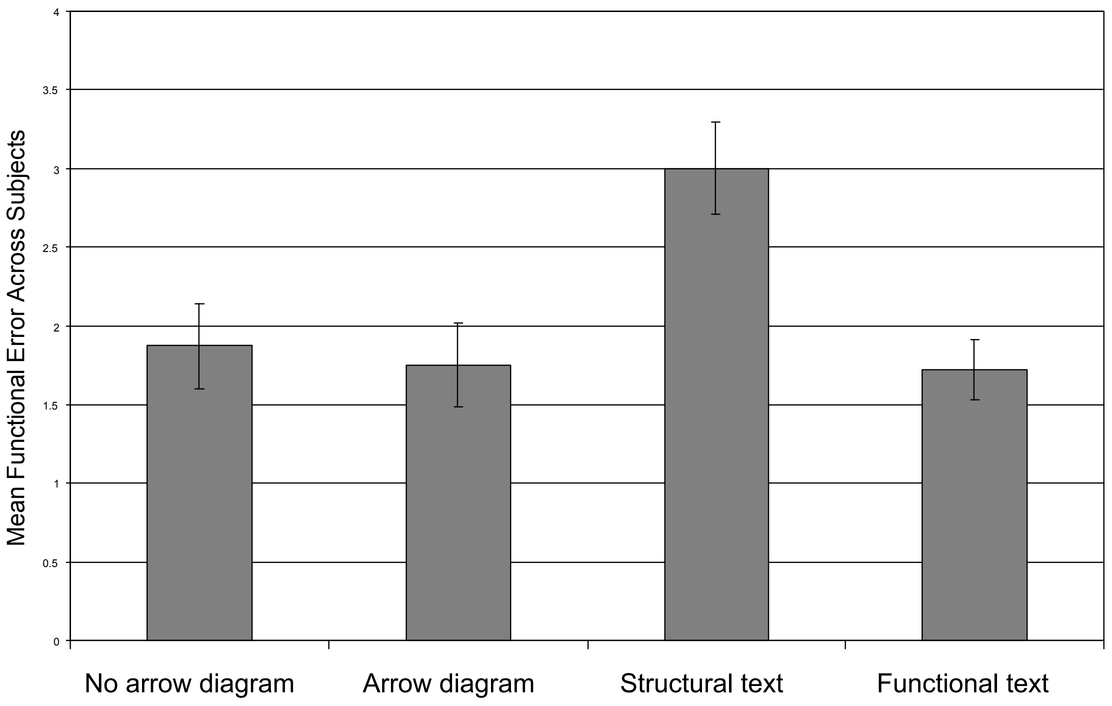

Figure 9. Mean errors on functional questions by perspective and medium (Experiment 3).

Interestingly, high ability/expertise participants outperformed low ability/expertise participants on functional questions in all conditions except when functional text was studied (see Figure 10). These results indicate that low ability/expertise participants have difficulties making functional inferences from structural descriptions and diagrams, with or with out arrows. When functional information is presented verbally, low ability/expertise participants are no longer disadvantaged.

Effect of Perspective

There was a marginally significant benefit for functional questions from studying functional material, 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.

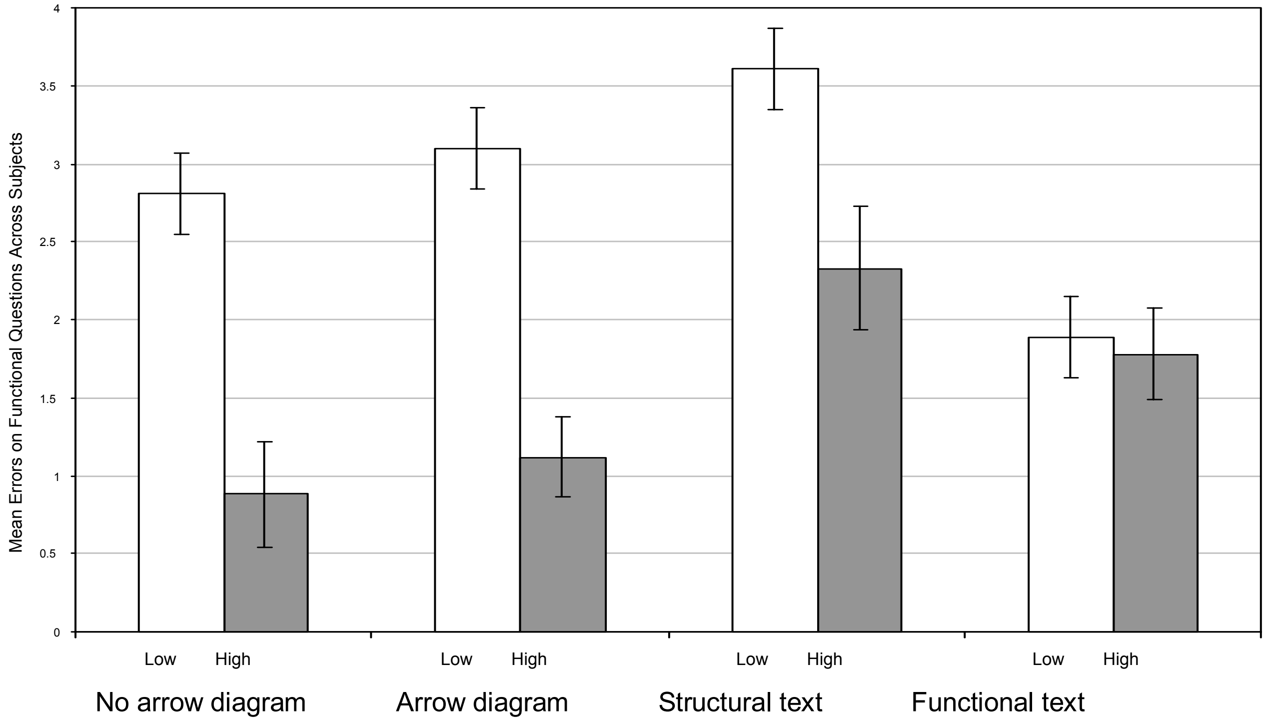

Figure 10. Mean errors on functional questions by perspective, medium and ability (Experiment 3).

Summary of Results: Experiment 3

For structural questions, high ability/expertise participants were more accurate than low ability/expertise participants, but the pattern of findings for each was the same. Neither medium nor perspective affected accuracy on structural questions. Responses were faster after studying text than diagrams; this is probably an effect of close correspondence of the text studied to the questions or, to put it differently, of transforming a diagrammatic mental representation of structure to a linguistic one. The absence of a perspective effect on questions about structure indicates that structure can be effectively inferred from both descriptions and depictions with a functional perspective.

As for structural questions, high ability/expertise participants were more accurate than low ability/expertise on functional questions. However, for functional information, medium had opposing effects for high and low ability/expertise participants. Low ability/expertise participants had particular difficulty acquiring function from diagrams; after studying functional text, they performed as well as high ability/expertise participants. High ability/expertise participants acquired functional information more accurately from diagrams than from text. Overall, participants who studied structural text made more errors on functional questions than those who studied functional text or both kinds of diagrams. Thus, inferring structure from function is easier than inferring function from structure. Overall, diagrams with or without arrows were as effective as functional text at conveying function. This was especially true for high ability participants, where both diagrams were more effective than either text at conveying function.

Discussion: Acquiring Structure and Function from Diagrams and Text

Participants studied diagrams or text of a complex mechanical system. There were two versions of both media: one designed to take a structural perspective and one to take a functional perspective on the systems. In diagrams, that meant depicting system parts and their spatial relations to convey structure, and adding arrows to convey function. In text, that meant using primarily verbs that are static or intransitive to convey structure or verbs that are transitive or describe motion or forces to convey function. Participants were split into high mechanical ability/expertise or low mechanical ability/expertise by their own reports. Accounting for the findings requires all three: medium, perspective, and ability/expertise.

Ability/expertise had global effects on performance; high ability/expertise participants answered both structural and functional questions more accurately than those low in ability/expertise. The effects of ability/expertise were large, more than 50% in most of the conditions testing structural knowledge, and even higher for most of the conditions testing functional knowledge. The only conditions under which there seemed to be no differences between high and low ability/expertise participants were those conditions in which the perspective of the text matched that of the questions. Thus, ability/expertise had specific effects as well. Low ability/expertise participants were particularly disadvantaged in answering functional questions, and especially after studying diagrams. They were as successful as high ability/expertise participants in grasping function from text. Conversely, high ability/expertise participants were particularly adept at interpreting diagrams. For them, diagrams, either without or with arrows, were more effective than text at conveying function. For high ability/expertise participants, the diagrams had at least two cognitive roles: they allowed "reading off" of function; and they organized functional knowledge spatially, that is the spatial connections among the parts as well as the forms of the parts serve to support knowledge of function.

Is there a contradiction between the first study, in which low ability/expertise participants produced functional descriptions of the systems from diagrams with arrows, and the present experiment, in which low ability/expertise participants had special difficulty inferring function from diagrams? There are several explanations for this apparent contradiction, explanations that are not mutually exclusive. First, although low ability/expertise participants in the first experiment produced functional descriptions of the systems from diagrams with arrows, they may not have been able to answer the more demanding questions used in the third experiment. Next, although low ability/expertise participants could produce functional descriptions of the systems diagrammed with arrows in the first experiment when they were asked to do so, they may not have spontaneously done so in the third experiment. This in fact suggests a way to increase the effectiveness of diagrams for low ability/expertise participants: ask them to actively interpret the diagrams. The goal would be to enable low ability/expertise individuals to form mental models that integrate function and structure.

Although diagrams should be especially suited to convey structure as they directly depict parts and their spatial relations, diagrams were not advantaged for either low or high ability/expertise participants in conveying structure. This is probably because language is so effective at conveying spatial relations (e. g., Taylor and Tversky, 1992). Most languages have readily available vocabularies and systems for doing so, so available that spatial language is co-opted to convey time, strength, power, preference, and a variety of other more abstract relations (e. g., Clark and Clark, 1977; Lakoff and Johnson, 1980; Tversky, in press). Diagrams were more effective for functional aspects of the systems, but only for high ability/expertise participants. For high ability/expertise participants, the spatial organization and appearances of the parts facilitates both organizing the functional aspects of the systems and inferring the functional operation of the systems.

For text, inferences from function to structure were easier than inferences from structure to function. This asymmetry could not appear for diagrams because in the present cases, even diagrams with a functional perspective showed structural relations. Less iconic, more abstract functional diagrams would have allowed the possibility of structural inferences, for example, using boxes instead of depictions of parts where the array of boxes and interconnecting arrows do not correspond to the spatial array of parts of the device. Comparing language and relatively iconic diagrams does, however, reveal a profound difference between them. From diagrams with or without arrows, both function and structure could be inferred with equal ease, reinforcing the architectural canon that form follows function. For descriptions of complex systems, knowing the structural arrangements of the parts did not afford inferring the functional organization of the system with ease, yet knowing the functional organization did seem to constrain the possible structural organization. This may have implications for design of complex systems, to begin with function and proceed to structure.

General Discussion

Whenever we attempt to fix a bicycle, to grow vegetables, to obtain a passport, to understand a new scientific finding, to negotiate a transport system, to take advantage of the features of a computer application, to comprehend a political development, or to carry out any number of other tasks that fill our days, we need to learn and use a complex system. Complex systems have two levels of organization. One level is structural, the parts of the system and their relations, which may be spatial, temporal, or abstract. The other level is functional, the sequence of operations and consequences required to accomplish the task. This is the level that is harder to convey, and at the same, the level essential for complex problem solving and trouble-shooting. Instructions for or explanations of complex systems often use both language and diagrams. Many instructions, however, are notorious, the object of jokes, like the now proverbial instructions for a VCR (e. g., Norman, 1988). Inadequate instructions and explanations are not inevitable. Knowing how people mentally represent such systems and how diagrams and language engender them are key to effective design of instructions and explanations. Conversely, knowing how to communicate complex systems can give insight into how they are represented and used in comprehension and inference. In three experiments, we investigated how diagrams and language can convey structural and functional aspects of systems and then evaluated their efficacy in doing so for participants of high and low ability/expertise. There are three interrelated stories to tell, one about conveying information in depictions and descriptions, one about understanding structure and function, and one about individual differences. In the end, the three stories, like a good novel, will come together to say something about mental models.

Diagrammatic Communication. Diagrams are an ancient form of communication, predating written language (e. g., Tversky, 2001). Undoubtedly the most common diagram is a map, which portrays the spatial relations among elements in an environment. Diagrams of function are also ancient. Paintings on the walls of Egyptian tombs portray how wheat is grown and made into bread. Portraying structure in diagrams is straightforward; the spatial relations of the elements or parts in the world are mapped onto spatial relations in the diagram. For maps, the elements themselves may be depicted, as in some tourist maps that show front views of important landmarks in their spatial locations. Depicting landmarks in maps is not usual, however, for a variety of reasons. Depicting landmarks typically violates map scale; landmarks add clutter to maps, making it harder to find the details of interest; depicting landmarks requires mixing perspectives, an overhead perspective for the system of roads and a frontal perspective for the landmarks. In short, the added information has costs that may not be realized in improvements in uses to which maps are put. Depicting parts of functional systems is more common. It does not require mixing perspectives and it may not add clutter. Even more important, the forms of the parts themselves may convey essential information about function. For example, circular things roll, and long, thin things can be used for extension. Functional diagrams are often used together with the actual system, so knowing what the parts look like facilitates their identification as well as inferences to function.

Conveying function in diagrams is not straightforward as it may entail showing movement or forces. The Egyptians solved the problem, as have stained glass windows, comic books, and instructions since, by showing successive stills; the viewer is left to fill in the blanks. Successive stills lose the elegant compactness of single diagrams. Filling in the blanks is not always straightforward. Looking back and forth trying to integrate different depictions is effortful. Another way to add function to structural diagrams is to use non-iconic devices. Non-iconic devices are also ancient, appearing in maps as well as other diagrams. In maps, they include lines for boundaries, names of settlements, indicators of land use.

There is a special class of non-iconic devices added to maps and other diagrams, schematic figures that have meanings suggested by their geometric forms and Gestalt properties, meanings that are general but more refined and interpretable in contexts. These include lines in maps, trees, and statistical graphs. Consider the simple line. Lines are one-dimensional, they connect, suggesting a relationship. Now consider how lines are used. In maps, they can indicate roads between landmarks, in trees, superset/subset relations, and in statistical graphs, functional relations. These graphic devices are similar to words like *line*, *relation*, and *field*. Such words have a multitude of senses, which context disambiguates. An arrow is an asymmetric line, suggesting an asymmetric relation. The arrowhead indicates the direction of the relation, much as an arrowhead used in hunting leads the direction of motion and the "V" formed by water going downstream shows the direction of motion of the water. That arrows are readily interpreted as conveying function was demonstrated in the first two experiments. When arrows were added to structural diagrams of mechanical systems, people interpreted the diagrams functionally. Similarly, when asked to diagram descriptions of functions of systems, people used arrows. What is especially significant in the use of arrows in diagrams of complex systems is that they can convey many different functional relations. They can indicate the sequence of steps in the operation of a system. They can show the path of motion, as in pulleys, or the direction of the consequences of the mechanics, as in the direction of air in the bicycle pump. Arrows can also indicate the direction of forces, as in the car brake or bicycle pump. In other contexts, arrows can show the manner as well as the path of motion and forces, for example, a bumpy ride in a comic strip or a curved path in a map. Significantly, many different words are needed to convey what this compact bundle of meaning, an arrow, conveys. Interpretations of diagrams with arrows used a subset of these, including *rotates*, *pushes*, and *raises*.

Other kinds of diagrams illustrate both these features of mechanical diagrams, that they use abstract schematic elements whose meanings are readily interpretable by their form and context, and that these elements have parallels in language. Bars in graphs are interpreted as discrete comparisons and lines as trends (Zacks and Tversky, 1999). Bars are also produced to portray discrete comparisons and lines to portray trends. Neither of these effects depends on the content of the functions portrayed, discrete or continuous; in fact, the pictorial/meaning correspondences often override the content. In route maps, lines are interpreted as roads, crosses as turns, blobs of generic shapes as landmarks (Tversky and Lee, 1999). Although the angles of turns and shapes of roads and landmarks could be portrayed in sketch maps, they are not. Again, there are parallels in language. People say *take a/make a/turn* right or left without specifying the degree of turn. They say *go down* for straight roads and *follow around* for curved roads.

Diagrammatic elements such as lines, arrows, bars, blobs, and crosses, have other parallels to linguistic elements. They can be categorical rather than analog. They are combinatory. Diagrams enjoy advantages that language does not have. They use space to convey space. They use elements that resemble their referents. But diagrams can be enriched to convey non-spatial information while at the same time retaining their spatial advantages in judgment and inference. Spatial relations may be metaphor as well as literal. And elements may be related to their references associatively through icons of synecdoche and metonymy, and schematically through abstract geometric figures. In sketch maps, they can simultaneously convey an environment and a route. In mechanical systems, they can show structure and function at the same time. Diagrams can integrate the functional with the structural, and convey both compactly.

Perspective. Complex systems have structural organizations, the relations among the parts of the systems, and functional organizations, the operations of the parts and their consequences. Is one perspective transparent from the other? For text, structural information was obtained as well from functional text as from structural text. Inferences from function to structure were readily made. This may be because the functional operations were closely tied to structure, that is, parts and their spatial array. The opposite did not hold; inferences from structural text to function of the systems were not readily made. Apparently, knowing the array of parts is not sufficient to infer much functional information. For diagrams, those without arrows suggest structure and those with arrows suggest function. However, people were able to extract both functional and structural information from both kinds of diagrams. Since the functional diagrams also conveyed structure, there was no need to infer structure from function. Had the functional diagrams been more schematic, for example, flow charts of boxes that were not in the actual spatial array, it is possible that inferences to structure would have been difficult.

That function was inferred equally well from diagrams of both perspectives, with and without arrows, needs explanation, especially as structural text was sufficient to convey structure, but not to infer function. Knowing structure from text is not the same as knowing structure from diagrams, then, with respect to inferring functional information. What is missing from the descriptions that confers knowledge of spatial structure but does not allow inferences to function? Language can effectively describe the spatial relations among the parts, but language is deficient in describing the appearances of the parts of the systems. Knowing the spatial relations among parts is not sufficient to infer function. Information about the appearance of parts appears to be critical to inferring function. For example, the appearance of the brake shoes relative to the brake drum suggests the manner that the shoes interact with the drum to stop the car. Similarly, the appearance of the cylinder and valves of a bike pump suggests exactly how the motion of the cylinder forces air through the valve. The superiority of diagrams to structural text in conveying function is further indication of the utility of diagrams.

Ability/expertise. Participants were split into high and low mechanical ability/expertise on the basis of their self-reports of general mechanical ability and specific knowledge of the specific system. Despite the simplicity of this measure, it revealed dramatic effects in performance. Overall, high ability/expertise participants made fewer errors on both structural and functional information than low ability/expertise participants. For structural information, the performance of low ability participants did not depend on medium. The effect of ability was particularly strong for functional information. Here, there was a strong effect of medium. The only situation in which low ability/expertise participants reached the level of those with high ability/expertise was when the perspective of the text matched that of the information tested for functional information (the same held for structural text but the interaction did not reach significance). Moreover, diagrams, whether with or without arrows, facilitated performance of high ability participants over either text in acquiring functional information. Diagrams had the opposite effect on low ability participants. For them, functional text was superior to diagrams in conveying functional information.

Ability/expertise, then, is especially tied to understanding function and to comprehending diagrams. Diagrams presented no special difficulty for low ability/expertise participants in teaching structural information. Although they did not perform at the level of their high ability/expertise counterparts, low ability/expertise participants acquired structural information as well from diagrams as from text. Low ability/expertise participants were especially disadvantaged acquiring functional information and especially from diagrams. They were notably not disadvantaged acquiring functional information from text, where their performance equaled that of high ability/expertise participants. In contrast, high ability/expertise participants were even better at learning functional information from diagrams than from language. What does this reveal about the mental models of those with high and low mechanical ability/expertise and the nature of mental models of complex systems as a whole?

Mental Models of Complex Systems. Together, these findings suggest that the mental models formed by high and low ability/expertise participants were distinctly different in quality. For high ability/expertise participants, structure and function were tightly coupled so that the spatial configuration and appearance of the parts of the system provided a foundation for functional reasoning. The mental representations of high ability/expertise participants for both aspects of he systems seem close to diagrammatic in format, that is, the spatial configuration of parts and their shapes are preserved. This is supported by the longer reaction times to answer structural questions after learning from diagrams. Not so for low ability/expertise participants. For them, structural knowledge and functional knowledge appear to be separate and distinct in format. Low ability/expertise participants seem to be able to represent structural information diagrammatically. They learned structural information as well from diagrams as from text, yet they responded slower to structural questions when they had learned from diagrams, indicating that their mental representations preserved a diagrammatic format. Yet, for low ability/expertise participants, a diagrammatic mental representation did not serve as a basis for organizing and inferring functional information as it did for high ability/expertise participants. This is another case of multiple routes to knowledge.

Ability/expertise was defined with respect to general and specific knowledge of the mechanics of complex systems, not with respect to either space or to diagrams, yet mechanical knowledge seems tightly tied to visuo-spatial reasoning, to a diagrammatic format. This is consistent with earlier work showing correlations between spatial and mechanical ability. Together, these findings suggest that individuals with high ability/expertise form mental models that integrate structure and function of complex systems, and that the format of these mental representations is diagrammatic, that is, a model of parts and their spatial relations, enriched to include function. Individuals with low ability/expertise do not appear to have mental models that integrate structure and function of complex systems; that is, their understanding of function is separate from their understanding of structure.

In 1984, two volumes were published entitled Mental Models. One, by Johnson-Laird (1984), put forth a theory of deductive inference proposing that to solve inferences, people create mental models of the situations described by the propositions. These are static mental models capturing features and relations of elements. The second book was an edited collection of papers on mental models of a variety of complex systems, buzzers, weather, electricity (Gentner & Stevens, 1984). These were, on the whole, mental models with moving parts, with operations and outcomes, with changes of state. The first kind of mental model captures structure; the second type, function. It seems that mechanical ability/expertise splits people along the same lines. Participants of low ability/expertise form structural mental models. Those of high ability/expertise form mental models that integrate function and structure. Inferring function from structure is critical to the effectiveness of diagrams not just for assembling and operating objects and systems, but also for creative design (e. g., Suwa & Tversky, 1997) and for scientific reasoning. The challenge is to instill mental models combining function and structure for all.

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Appendix A

True/False Statements, Experiment 3

S= Structural, F= Functional

Bicycle Pump

1) The piston is attached to the wall of the cylinder (S).
2) The inlet valve is open when the outlet valve is closed (F).
3) The piston is at the bottom of the handle (S).
4) The inlet valve opens when the handle is pulled up (S).
5) The outlet valve extends outward from the piston (S).
6) Pulling the handle up pulls the inlet valve up (F).
7) Pushing the handle down closes the inlet valve (F).
8) Pressure build up in the chamber opens the outlet valve (F).
9) The downward movement of the piston causes the inlet valve to close (F).
10) The outlet valve opens when the piston is raised (F).
11) The outlet valve allows air to enter the chamber (F).
12) The pump works when the outlet valve stays open (F).
13) Next to the handle is the inlet valve (S).
14) Next to the hose is the outlet valve (S).
15) The outlet valve is between the chamber and the hose (S).
16) The inlet valve is above the chamber (S).

Car Brake

1) Brake fluid can move to the brake shoe (S).
2) The brake drum moves towards the brake shoe (F).
3) The brake fluid reservoir is inside the brake drum (S).
4) The wheel cylinders surround the small pistons (S).
5) The small pistons are adjacent to the brake shoes. (S)
6) The pressure of fluid accumulation is exerted on the small pistons (F).
7) The tube is next to the wheel cylinder (S).
8) The wheel cylinders are next to the tube (S).
9) Brake fluid pushes the brake drum outward (F).
10) The brake shoes are circular devices (S).
11) Next to the brake drum are the wheel cylinders.
12) The tube penetrates the brake shoes (S).
13) The pistons put pressure on the brake shoes (F).
14) The brake fluid stays in the tube (F).
15) The amount of brake fluid released determines time to brake (F).
16) The upward movement of the brake shoe slows the rotation of the wheel (F).