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Understanding Machines from Text and Diagrams

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Marcel Adam Just

DEPARTMENT
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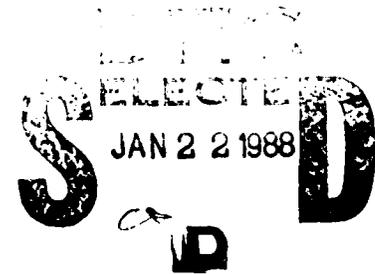
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Abstract

Instructional materials typically use both text and diagrams to explain how machines work. In this paper we give an account of what information is involved in understanding a mechanical device and the role that diagrams might play in communicating this information. We propose a model of how people read a text and inspect an accompanying diagram which states that people inspect diagrams for three reasons: (1) to form a representation of information read in the text, (2) to reactivate information that has already been represented, and (3) to encode information that is absent from the text. Using data from subjects' eye fixations while they read a text and inspected an accompanying diagram, we find that low-ability subjects need to inspect diagrams more often than high-ability subjects while forming a representation of information about which they have read in the text. The data also suggest that knowledge of what is relevant in a diagram might be a prerequisite for encoding new information from a diagram.



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When people read a text explaining a machine, they are usually trying to understand enough about the machine to be able to use it, assemble it, or repair it. Understanding a machine in this way involves knowing what the machine's components are, how they are configured, how they move when the machine is in operation, and the relation between these motions and the forces in the system. This chapter describes some research which examined how people of differing mechanical ability come to gain this kind of understanding of a simple mechanical device, a pulley system, by reading a text accompanied by diagrams. We focused our analysis on the coordinated intake of information from the text and from the diagram, as indicated by the subjects' pattern of eye fixations.

The chapter has three sections. First, we give an account of what information is involved in understanding a machine and the role that diagrams play in communicating this information. Second, we propose a model of how people might read a text and inspect a diagram which explain the workings of a mechanical device. We indicate at which points in the reading of the text people might inspect the diagram, and why they might inspect the diagram. In the third section, we describe a study in which people's eye fixations were recorded while they read a text, and inspected an accompanying diagram, and we interpret the results within the framework of the model.

Diagrams in instructional materials.

We start with an account of the way machines are explained in text and diagrams. This is a useful first step in our research for a number of reasons. First, it tells us what kind of information is probably necessary for understanding a mechanical system. Second, it allows us to specify what cognitive processes might be involved in using this information to construct a mental model of a mechanical system. Finally, it demonstrates that because mechanics is a domain in which many different types of diagrams are used to communicate different types of information, that it is therefore a good domain in which to study text and diagram integration.

We have used the book Basic machines and how they work, prepared by the Bureau

of Naval Personnel, as a test bed for our research. The book describes itself as "written as a reference for the enlisted men in the Navy whose duties require the fundamentals of machinery". It contains material at a suitable level for our readers (high school graduates and college students, both with and without extensive mechanical experience).

One immediately obvious property of the book is the abundance of diagrams in the text. Even though the book is only 150 pages long, it contains over 200 diagrams, approximately one diagram for every 230 words. Each diagram occupies about one third of a page, and so the diagrams occupy about 45% of the space in the book. Most of the diagrams in the book are used to explain the workings of some unfamiliar machine in terms of familiar principles. A small minority of the diagrams are used to help explain a new principle. The diagrams depicting an unfamiliar machine show not only the machine's physical components, but also indicate the dynamic interactions among these components and help to explain how the machine accomplishes its mechanical function.

To understand the kind of task the reader of this book has to perform, it is interesting to follow an excerpt from the book with the intention of understanding the mechanical system. Figure 1 presents a sample passage, entitled Hydraulics aid the Helmsman, and its accompanying diagram.

Insert Figure 1 about here.

This example illustrates several properties of diagrams in a mechanics text. First, the diagram is labeled with arbitrary labels, such as g, R1, R2, etc. The text repeatedly refers to such labels so that it is not possible to understand the text without inspecting the diagram and matching the expressions in the text with their referents in the diagram. Second, the diagram is static, whereas the text describes a dynamic system. Understanding the dynamics described in the text involves frequent looking back and forth between the text and diagram to imagine the sequence of changes in the device's operation that are described in the text.

Figure 1: Sample description from Basic machines and how they work

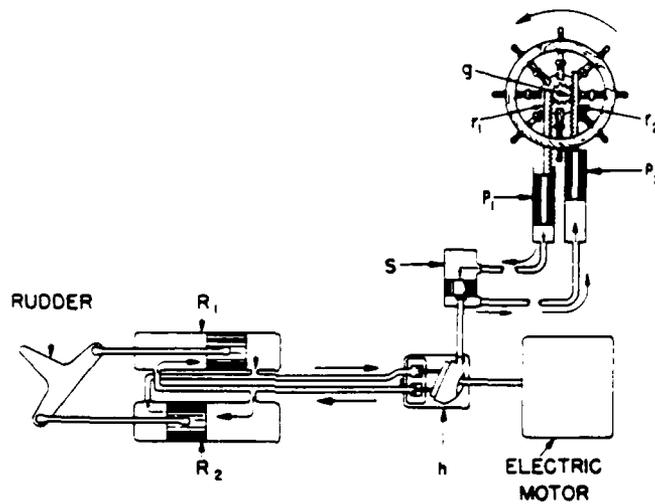


Figure 10-11.—Steering is easy with this machine.

Hydraulics Aid the Helmsman

You've probably seen the helmsman swing a ship weighing thousands of tons about as easily as you turn your car. No, he's not a superman. He does it with machines.

Many of these machines are hydraulic. There are several types of hydraulic and electro-hydraulic steering mechanisms, but the simplified diagram in figure 10-11 will help you to understand the general principles of their operation. As the hand steering wheel is turned in a counterclockwise direction, its motion turns the pinion gear g . This causes the left-hand rack r_1 to move downward, and the right-hand rack r_2 to move upward. Notice that each rack is attached to a piston P_1 or P_2 . The downward motion of rack r_1 moves piston p_1 downward in its cylinder and pushes the oil out of that cylinder through the line. At the same time, piston p_2 moves upward and pulls oil from the right-hand line into the right-hand cylinder.

If you follow these two lines, you see that they enter a hydraulic cylinder S —one line entering above and one below the single piston in that cylinder. In the direction of the oil flow in the diagram, this piston and the attached plunger are pushed down toward the hydraulic pump h . So far, in this operation, you have used hand power to develop enough oil pressure to move the control plunger attached to the hydraulic pump. At this point an electric motor takes over and drives the pump h .

Oil is pumped under pressure to the two big steering rams R_1 and R_2 . You can see that the pistons in these rams are connected directly to the rudder crosshead which controls the position of the rudder. With the pump operating in the direction shown, the ship's rudder is thrown to the left, and the bow will swing to port. This operation demonstrates how a small force applied on the steering wheel sets in motion a series of operations which result in a force of thousands of pounds.

Another important point illustrated by the example is that diagrams communicate information about the configuration of mechanical systems. It is clear from the example that configurational information is essential to understanding how the machine operates because the connections between components determine how they cause and constrain each other's motions to achieve the function of the machine. Yet, in the example in Figure 1, it is the diagram and not the text that indicates the configuration of components. An important function that diagrams serve in descriptions of mechanical devices is to efficiently provide information about configuration.

Our analysis of the diagrams in Basic machines and how they work revealed that there are a number of dimensions along which diagrams differ. Diagrams can be primarily realistic or schematic. In a realistic diagram, the depiction of the device is very similar to the appearance of the real device and preserves many of the details of its appearance. By contrast, in a schematic diagram, the details of the device components are not shown. Diagrams can also differ in their labeling. In some diagrams, all the information in the diagram is pictorial, while in others, symbols such as words and numbers can be used to indicate the names of components and the magnitudes of forces. Third, diagrams can differ in how they relate to the text (i.e., whether the diagram is referred to in the text and whether the diagram is essential to understanding the text). Finally, they can differ in the number of depictions of a device used to explain its functioning.

The type of diagram that should be used in a given text depends on the type of information to be communicated. A realistic diagram is often used to help readers recognize some machine component with which they are familiar, while a schematic diagram is often used to emphasize the configuration of the components of a machine. In Basic machines, schematic diagrams superimposed on pictures are sometimes used to explain the workings of a familiar device in terms of mechanics principles. For example, one illustration demonstrates that a pulley operates as a lever (see Figure 2).

Insert Figure 2 about here.

Labels can communicate a variety of types of information about mechanical systems. The components of the machine can be labeled. Arrows can communicate kinematic information (how the components of the machine move when the machine is in operation) or kinetic information (the direction of forces in the machine). Numerical labels can indicate the sizes of components, the distances between components and the magnitudes of forces. Some examples of labeled diagrams are shown in Figure 3.

Insert Figure 3 about here.

In a description of a machine, the text and diagram have the same referent, namely the machine being described. In this sense they are always related. There are several ways that the relation can be made clear. For example, if the same labels are used to refer to a component in the text and diagram, this will make it easier for the reader to locate that component in the diagram. Arbitrary labels that have no semantic content outside the context of the text, like the labels g , $R1$, $R2$, etc. in the example shown in Figure 1, are often used. When arbitrary labels are used, it is impossible to understand the text without inspecting the diagram.

Explaining some types of information about a machine requires more than one depiction of the machine. For example, if the components of a machine are not all visible when the machine is assembled, an exploded view of the machine shown beside a picture of the assembled machine can depict the individual components and their configurational relations. A set of diagrams that depicts the relative positions of components of a machine in a cycle of the machine's functioning is sometimes used to provide kinematic information. An example of such a set of diagrams is shown in Figure 4. This set of diagrams shows the relationship of the piston, connecting rod and crank on a crankshaft as the crankshaft turns one revolution.

Figure 2: Example of a schematic diagram superimposed on a picture, demonstrating that a pulley operates as a lever.

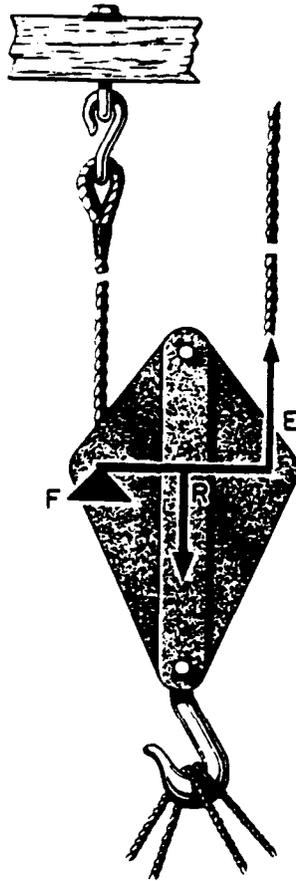
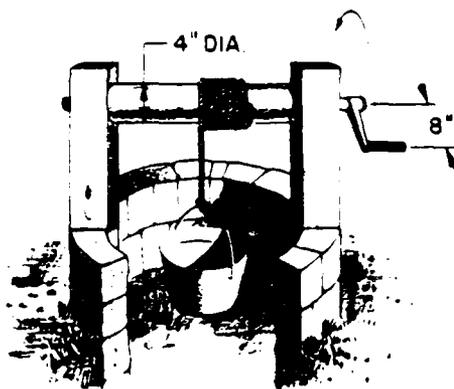
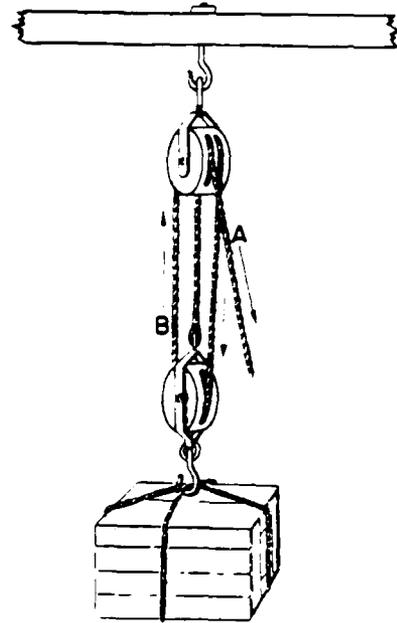
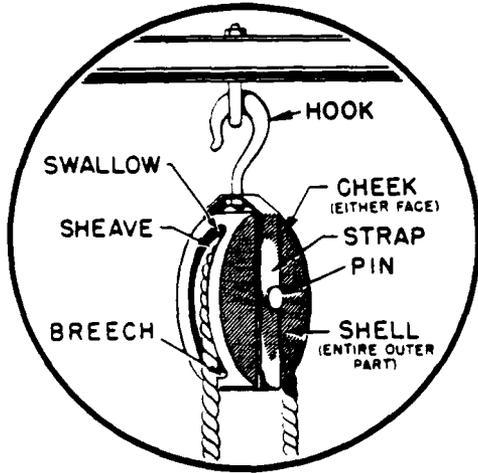


Figure 3: Examples of labeled diagrams.



Insert Figure 4 about here.

Our survey of how machines are explained in text and diagrams suggests several reasons why mechanics is a good domain in which to study how people understand texts accompanied by diagrams. First, diagrams are frequently used in texts that explain how machines work, giving ecological validity to our study. Second, diagrams depict information that is essential to understanding machines (i.e. the configuration of their components). Third, diagrams in mechanics texts differ along a number of dimensions, allowing us to study the effects of these different dimensions on comprehension.

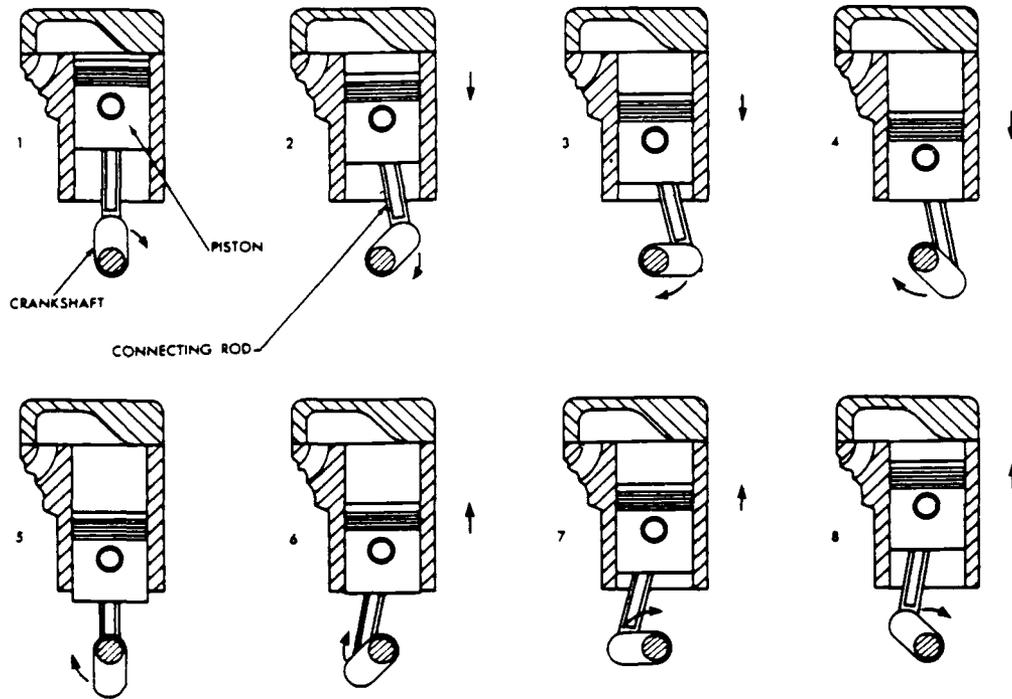
A model of text and diagram processing.

In this section, we suggest how a person might come to understand the workings of a mechanical system by reading a text accompanied by a diagram. We propose a preliminary model of how text and diagrams are integrated, which centers on a number of different purposes that diagram inspection might fulfill. We propose that people inspect diagrams for different reasons and that the characteristics of the text and reader affect the number and length of diagram inspections.

When people read a text, they process it on several different levels, from encoding the individual words and understanding the meaning of sentences, to forming a representation of the object or event that is described in the text (Just & Carpenter, 1987). The result of the comprehension process is a representation of the object or event described in the text, which we will call the referential representation. The referential representation is built up progressively as new information is read, by augmenting the representation of the object being described. Thus, as each proposition is interpreted, the reader decides whether or not it refers to some entity already in the representation, modifying the existing representation if it does, and constructing some new entity if it does not.

A diagram that accompanies a verbal description of a machine usually depicts the

Figure 4: Example of a figure that uses multiple depictions of a machine.



relative spatial locations and connections among the machine's components. The diagram may be particularly useful, therefore, in constructing and accessing the mental representation of these configurational properties of a machine. We have seen that understanding the configuration of the components of a machine is essential to understanding how it operates, because the configuration indicates how the components cause and constrain each other's movements.

We suggest that a diagram can aid in constructing a representation of a mechanical device in the following ways. First, a diagram can depict spatial and visual properties of a device that have also been verbally described in the text. Second, a diagram can act as a memory aid to reactivate the representation of information that has been previously read and represented. Finally, a diagram can be a source of new information that is not given in the text. These three types of uses of a diagram can be elaborated.

First, people might use a diagram as an aid to forming a referential representation of information that they have read in the text. For example, people might inspect the diagram if they have difficulty imagining some configuration of components that they have read about, or to check that their referential representation of some configuration is correct. When people read about how the device moves, they might use image transformation processes, in addition to inspecting the diagram, in order to form the representation. In each of these cases, we would expect people to look in the diagram at the components of the machine that they have just read about. Inspections to aid the initial formation of the referential representation will be called formation inspections.

Second, inspecting a diagram might allow people to reactivate the representation of information that they have read about previously. When people read a text, they not only have to represent each proposition of the text, but they also have to integrate each new proposition with the existing representation. Kintsch and Van Dijk (1978) have suggested that only the most recent and most important propositions are retained in working memory while a person processes a text, so that forming an integrated representation probably involves reactivating parts of the existing representation that are no longer in working

memory. We propose that some inspections of a diagram can serve to reactivate the representation in this way. When people are reactivating an existing representation, we expect them to look at components that they have read about previously (i.e., before the last unit of text read). Inspections to reactivate part of an existing referential representation will be called reactivation inspections.

Finally, people might use a diagram to elaborate the referential representation formed from the text by encoding new information from the diagram that is not stated in the text. This was necessary in reading the sample description given in Figure 1 because the text does not describe the configuration of the machine and so this information has to be encoded from the diagram alone. When people inspect the diagram to encode new information, we expect them to look at components about which they have not yet read. Inspections to encode new information from the diagram will be called elaboration inspections.

There are a number of properties of a text and abilities of a reader that might influence the nature of diagram inspections. In this chapter we focus on one property of the text, information content, and one property of the reader, mechanical ability. These properties were examined in an experiment in which subjects' eye fixations were monitored while they processed a text and accompanying diagram, that described a simple pulley system.

An experimental investigation of text and diagram processing.

Differences in Text Content. In the experiment, the amount of information given in the text about the configuration of components of the pulley system differed between two experimental conditions. In one condition, subjects read a longer text which described the configuration of components of the pulley system, information which was also available in the diagram. In the other condition, the subjects read a shorter text which did not describe the configuration of components so that the diagram was the only source of this information. We expected the information content of the text to affect formation.

reactivation and elaboration inspections as follows.

First, we expected subjects who read the longer text to make more formation inspections. We have suggested that these types of diagram inspections are made primarily when a person has to represent information about configuration. Thus, the number of diagram inspections for this purpose should increase with the amount of information about configuration in the text. Because the longer text contained more information about configuration, subjects who read this text should make more formation inspections.

Second, we expected subjects who read the longer text to make more reactivation inspections. Because only the most recent and most important information is likely to be retained in working memory when a person reads a text (Kintsch & Van Dijk, 1978), older parts of the representation have to be reactivated in order to form an integrated representation of the text. If a diagram is used to reactivate information read previously, it should be inspected more often if it accompanies a text which contains more information that is not recent.

Finally, we expected subjects who read the longer text to make shorter elaboration inspections. The need to extract new information from a diagram depends on how much information is given in the text. If the text gives all the information relevant to understanding the mechanical system, there is no need to extract new information from the diagram. It is only when the text omits relevant information that new information has to be extracted from the diagram. In our experiment, the shorter text omitted information about the configuration of the pulley system so that this information had to be extracted from the diagram. We therefore expected that subjects who read this text would spend more time encoding new information from the diagram to elaborate their representations of the information in the text.

Individual Differences in Mechanical Ability. Abilities of the reader might also influence how diagrams are inspected. In this study we considered the effects of mechanical ability on diagram inspection. We expected subjects with high mechanical ability to have less difficulty forming a representation of configurational information. We also expected high-

ability subjects to form more integrated representations of mechanical systems. Finally, we expected high-ability subjects to be better able to extract new information from a diagram.

These predictions are derived from a previous study of mechanical ability (Hegarty, Just, & Morrison, *ress*). In that study, we found that subjects who had low scores on a test of mechanical ability encoded only the elementary components of pulley systems depicted in a diagram, whereas subjects who had high scores were more likely to encode configurational relations between components. Because high-ability subjects are more attentive to the configuration of components in pulley systems, we infer that they have better knowledge of the possible configurational relations among components and therefore are better able to represent configurational information described in the text. Consequently they should not need to inspect the diagram as often as an aid to representing the configuration of the system (formation inspections).

High-ability subjects take the configuration of pulley systems into account by encoding pulley systems in terms of large chunks of information that include a number of different components and their configurations--for example, a rope going over a pulley that is fixed to the ceiling (Hegarty et al., 1987). In contrast, low scoring subjects encode pulley systems in terms of their elementary components--for example, in the case above, by failing to encode the ceiling attachment in conjunction with the representation of the rope and pulley. People with higher mechanical ability should be able to retain more information in their representations of a mechanical device because this information is chunked more efficiently, and consequently they should have to reactivate information less often.

People with high mechanical ability may be better able to extract information from a diagram selectively. Thus, for example, subjects who score high on tests of mechanical ability typically know which parts of a mechanical system are relevant to its mechanical functioning and which are irrelevant (Hegarty et al., 1987). In contrast, low-scoring subjects are often misled into thinking that an irrelevant property of a mechanical system, such as the height of a pulley system, had some relevance to its mechanical advantage. This implies that if the text does not contain all the information relevant to understanding the

mechanical system, people with high mechanical ability should be better able to encode new information from a diagram than low-ability subjects. We predicted therefore that high-ability subjects would spend more time extracting information from the diagram in this situation than low-ability subjects.

Experimental Materials. The texts that the subjects read in the experiment described the structure and kinematics of a pulley system, and were accompanied by a schematic, unlabeled diagram. We chose to use descriptions of structure and kinematics because these aspects of a mechanical device depend on spatial information and therefore ensure the usefulness of a diagram. We used a schematic diagram because such diagrams seem to emphasize configurational properties of machines, important to understanding structure and kinematics, by omitting details of the appearance of individual components. We chose to use an unlabeled diagram because we wanted to study how people use diagrams spontaneously (without being directed to the diagram by the text).

The texts that the subjects read are shown in Figure 5. Each text was presented in two pages and each page of text was accompanied by the diagram, so that the text and diagram were always visible simultaneously. The first page of text was different in the two experimental conditions while the second page was identical in the two conditions. In the first condition, which we will call the longer text condition, the first page of text described the components of the system, their interconnections, and their relative spatial locations (structure), and the second page described how these components move (kinetics). In the second condition, which we will call the shorter text condition, the first page listed the components of the system but gave minimal information about the structure of the system

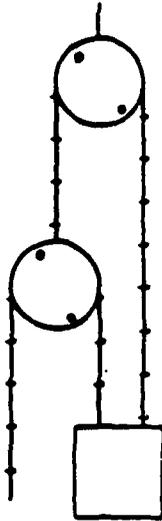
Insert Figure 5 about here.

Experimental Procedure. The stimulus materials were transformed into a computer representation by digitizing a video image, and were displayed to the subjects on a standard video monitor. During the experiment the subject's eye fixations were monitored by a Gulf

Figure 5: The texts used in the experiment

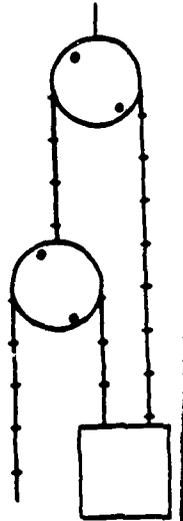
Page 1 of longer text

The system consists of two pulleys, two ropes and one weight. The upper pulley is attached to the ceiling. The upper rope passes over this pulley and is attached to the lower pulley at one end and the weight at the other. The other rope, called the pull rope is free on one end and passes over the lower pulley. The other end of the pull rope is attached to the weight.



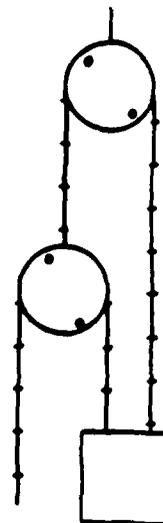
Page 1 of shorter text

The system consists of two pulleys, two ropes and one weight. The upper pulley is attached to the ceiling. Both of the ropes support the weight. The pull rope has a free end.



Page 2 of both texts

When the free end of the pull rope is pulled, the rope moves over the lower pulley and pulls up the weight. Pulling on the free end of the pull rope also pulls down the lower pulley and the rope from which it is suspended. This causes the upper rope to move over the upper pulley and to pull up the weight.



and Western corneal-reflectance and pupil-center eye tracker and were recorded both digitally and on videotape.

The texts were presented as part of the introduction to another experiment which will not be discussed in this chapter. In the other experiment, the subjects viewed computer generated animations of the pulley system described in the texts, and were asked to judge whether the operation of the pulley system in each animation represented how a real pulley system would operate.

The subjects were 16 undergraduate students at Carnegie Mellon University who participated in the experiment for course credit. They were classified as having either high or low mechanical ability on the basis of their scores on a subset of the items in the Bennett Mechanic. Comprehension Test (Bennett, 1969). Based on norms for this test established in previous experiments, subjects were classified as high-ability if they scored in the top third of the distribution while they were classified as low-ability if they scored in the bottom third of the distribution. Five high-ability and 3 low-ability subjects were assigned to the longer text condition while 4 high-ability and 4 low-ability subjects were assigned to the shorter text condition.

When subjects arrived in the laboratory, they were first given 30 minutes to complete the test of mechanical comprehension. They were then given instructions for the experiment involving animations of pulley systems and were told that, as an introduction to the experiment, they would be asked to read a short description of the pulley system in the animations. The texts were then presented.

Data Analysis. Subjects' eye fixations were first aggregated into units called gazes, or uninterrupted sequences of fixations either on the text or on the diagram. This preliminary scoring allowed us to measure the number of diagram inspections, the total gaze duration on the diagram (sum of the durations of all diagram inspections) and the total gaze duration on the text.

In a more precise analysis of the data, subjects' eye fixations were aggregated into gazes on a clause of text or a component of the diagram. These data allowed us to

observe at what points in the text subjects inspected the diagram and what they looked at in the diagram on each inspection. Because of equipment failure and measurement error, this more precise analysis was possible for only twelve subjects, three high-ability subjects and three low-ability subjects in each of the two experimental conditions.

 Insert Figure 6 about here.

The diagram inspections of these 12 subjects were classified according to whether the main purpose of each was to form a referential representation of text just read (formation inspections), to reactivate the representation of previous text (reactivation inspections), or to encode new information in order to elaborate the representation (elaboration inspections).

Figures 6, 7, and 8 give examples of these three types of inspections.

- If subjects looked primarily at the referents of the last sentence of text read, the diagram inspection was classified as a formation inspection. For example, Figure 6 shows a sequence of six fixations on the diagram made by a subject after reading the text printed at the top of the figure. Because most of these fixations (2 to 6) were on components referred to in the last sentence read, i.e., the upper rope and the upper pulley, the inspection was classified as a formation inspection.
- If subjects looked at the referents of previous sentences read, the inspection was classified as a reactivation inspection. The five fixations shown in Figure 7 were on components of the pulley system that were referred to in sentences prior to the last sentence read, while none of these fixations were on the components referred to in the last sentence, i.e., the pull rope and the weight. This inspection was classified as a reactivation inspection.
- Finally, if subjects looked at parts of the diagram that had not been mentioned in the text they had read so far, the inspection was classified as an elaboration inspection. Because the fixations shown in Figure 8 were primarily on points of attachment between components, and these attachments were not described in the text read, this series of fixations was classified as an elaboration inspection.

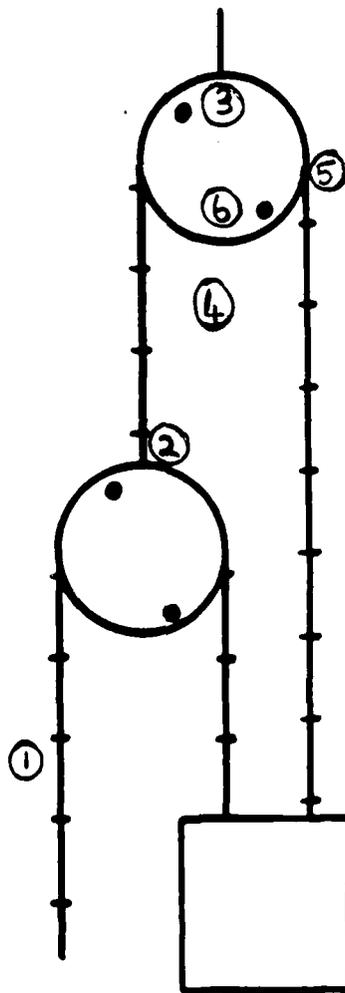
Two independent raters agreed on the classification of 83% of the diagram inspections. Disagreements arose when the raters thought that an inspection had two purposes and disagreed about the primary purpose of the inspection. In these cases, the inspection was classified according to the rating made by one rater.

Figure 6: Example of a diagram inspection to represent information just read.

Text read:

Pulling on the free end of the pull rope also pulls down the lower pulley and the rope from which it is suspended. This causes the upper rope to move over the upper pulley and to pull up the weight

Sequence of Fixations on the Diagram:



 Insert Figure 7 about here.

 Insert Figure 8 about here.

Subjects made an average of 8 inspections of the diagram during the reading of the two pages of text. Of these, 3.2 inspections were made at the end of either page of text while 4.8 were made at other points in reading the text, primarily at linguistic boundaries (see Table 1). Most inspections were classified as either formation inspections (37.2%) or reactivation inspections (52.2%). Few inspections (10.6%) were classified as elaboration inspections.

 Insert Table 1 about here.

Not surprisingly, the subjects in the longer text condition, spent more time reading the text (70.2 seconds) than did subjects in the shorter text condition (46.6 seconds). There were no significant differences in the overall time spent processing the text and diagrams for the different groups.

In reporting the results of the experiment, we will focus on an analysis of the differences in how the subjects inspected the diagram. We will first present the results regarding the total gaze duration on the diagram, and later decompose this into formation inspections, reactivation inspections and elaboration inspections.

Results.

The text content had different effects on the diagram inspections of high-ability and low-ability subjects. As Figure 9 shows, high-ability subjects spent more time inspecting the diagram if they read the shorter text, while low-ability subjects spent more time inspecting the diagram if they read the longer text. With the time spent inspecting the diagram expressed as a percentage of total time on the diagram, this interaction is significant, $F(1, 8) = 5.56, p < .05$. Thus, while all groups of subjects spent approximately equal amounts of

Figure 7: Example of a diagram inspection to reactivate information previously represented.

Text read:

The system consists of two pulleys two ropes and one weight. The upper pulley is attached to the ceiling. The upper rope passes over this pulley and is attached to the lower pulley at one end and the weight at the other. The other rope, called the pull rope, is free on one end and passes over the lower pulley. The other end of the pull rope is attached to the weight.

Sequence of Fixations on the Diagram:

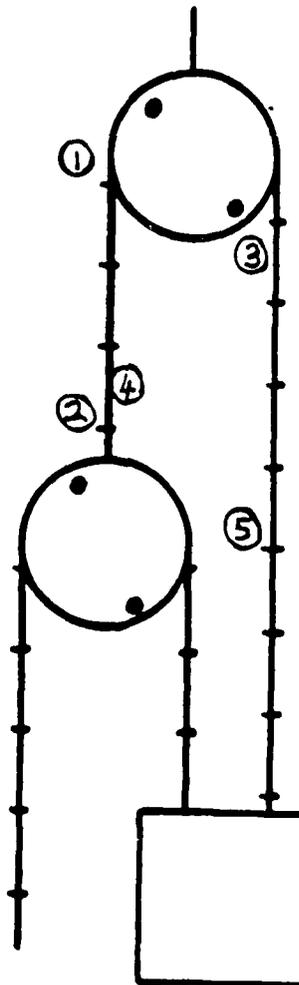


Figure 8: Example of a diagram inspection to encode new information.

Text read:

The system consists of two pulleys, two ropes and one weight.
The upper pulley is attached to the ceiling. Both of the ropes
support the weight. The pull rope has a free end.

Sequence of Fixations on the Diagram:

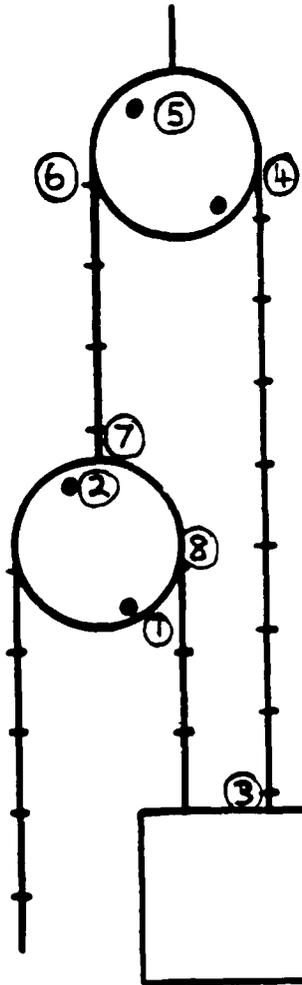


Table 1: Locations in the Text at which Subjects inspected the Diagram

<u>Location in Text</u>	<u>Number of Diagram Inspections</u>	
	Longer text	Shorter text
End of page (paragraph)	16 (27.1%)	15 (42.9%)
End of sentence	15 (25.4%)	3 (8.6%)
End of clause	7 (11.9%)	2 (5.7%)
End of noun phrase	4 (6.8%)	1 (2.9%)
Other	17 (28.8%)	14 (40.0%)

time processing the texts and diagrams together, the groups differed in how they divided their processing time between the text and diagram.

 Insert Figure 9 about here.

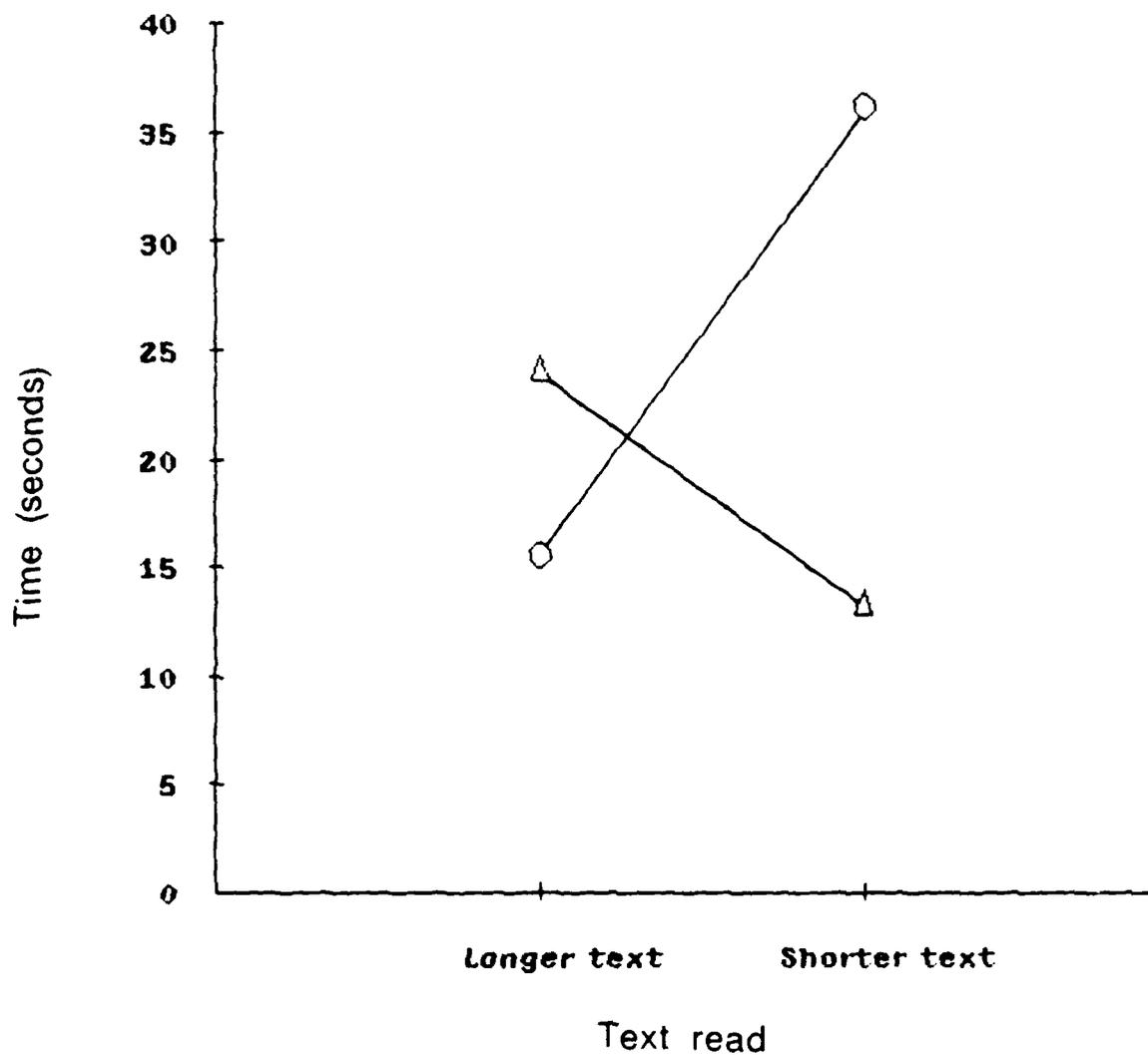
In order to further examine why the text content had different effects on the diagram inspections of high-ability and low-ability subjects, we now consider how text content and mechanical ability affected different types of diagram inspections (i.e., formation, reactivation, and elaboration inspections). These results support our prediction that more formation inspections will be made when subjects read a text containing more information about configuration. They also suggest, as predicted, that high-ability subjects may be better able to encode new information from a diagram than low-ability subjects.

Formation Inspections. Subjects who read the longer text made more formation inspections than did subjects who read the shorter text. $F(1, 8) = 7.35, p < .05$. This result is depicted by the white bars in Figure 10. These subjects also spent considerably more time inspecting the diagram to form a representation of text they had read (6.5 seconds) than did subjects who read the shorter text (0.5 seconds). $F(1, 8) = 9.15, p < .05$. Thus, as expected, the number of formation inspections increased with the amount of information that the text contained about configuration.

 Insert Figure 10 about here.

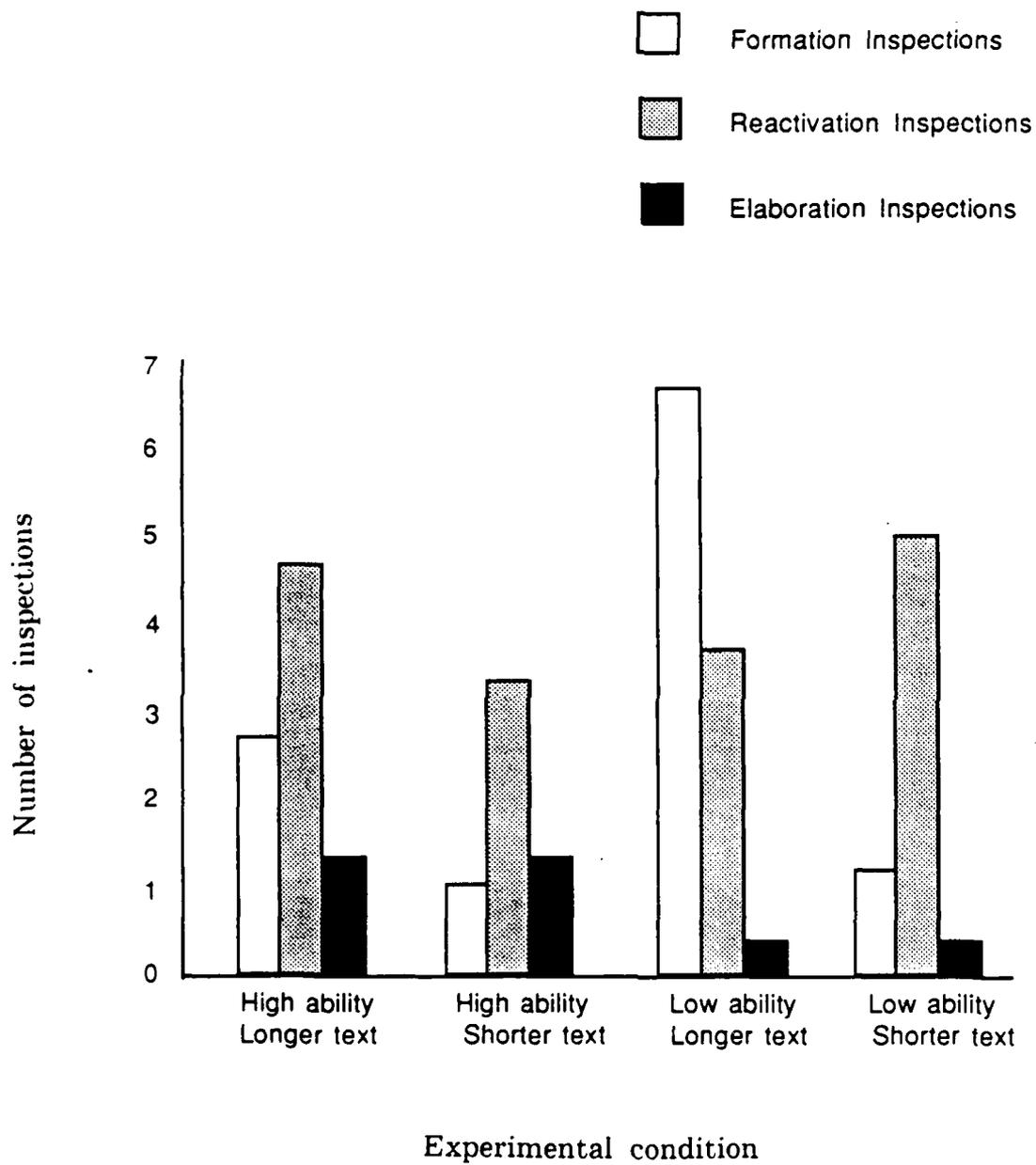
The data add support to the view that the referential representation is built up progressively as each unit of text is read, and that the diagram is sometimes used to check this representation. Most (77.1%) formation inspections were made in mid-text rather than at the end of a page of text, suggesting a progressive construction of the representation. Furthermore, as Table 1 shows, diagram inspections were made primarily at linguistic boundaries in the text, suggesting that people attempt to fully interpret a sentence or clause of text before checking the representation of this unit of text against

Figure 9: Total gaze duration on the diagram



Key	
○	High ability
△	Low ability

Figure 10: Mean Number of Each Type of Diagram Inspection



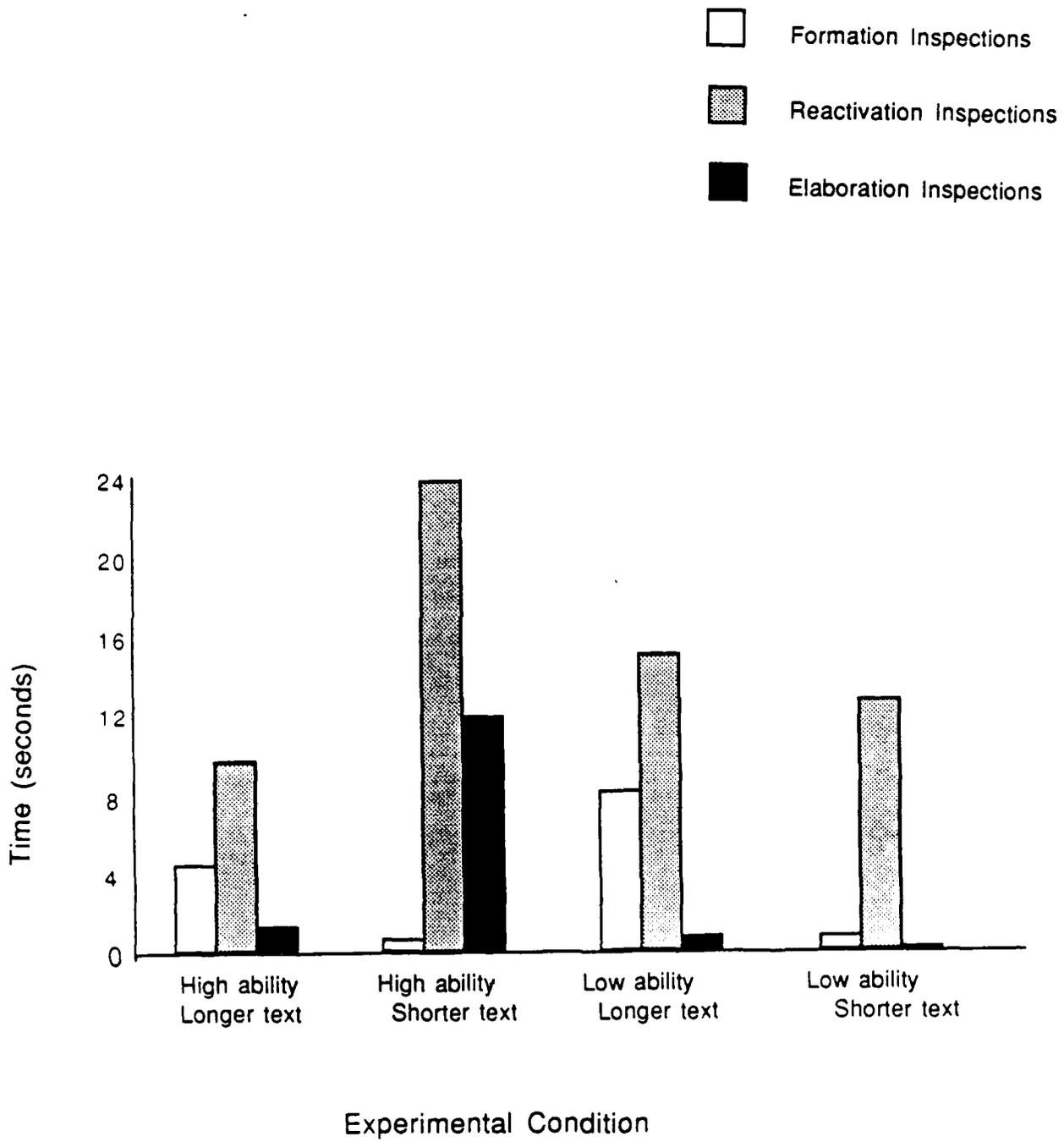
the diagram. Thus, the data are consistent with the view that one purpose of a diagram is to help a person form a representation of the referent described in the text.

We predicted that low-ability subjects should have more difficulty representing configuration, and hence make more formation inspections. A comparison of the white bars for the two longer text conditions in Figure 10 shows that among subjects who read the longer text, low-ability subjects did make more formation inspections. However the difference between high-ability and low-ability subjects was not significant. There was also a nonsignificant trend for low-ability subjects to spend more time (8.3 seconds) inspecting the diagram to form a representation of text they had read than high-ability subjects (4.7 seconds). These statistically nonsignificant results tentatively suggest that low-ability subjects had more difficulty imagining the configuration of components that they had read about in the text, or that they lacked confidence in their representation of configurational properties of the pulley systems so that they checked this representation against the diagram more often.

Reactivation Inspections. The data regarding the number and length of reactivation inspections failed to show the effects that we predicted. There were no significant differences in the number of reactivation inspections across the four conditions of the experiment. A comparison of the grey bars in Figure 11 shows that high-ability subjects who read the shorter text spent more time inspecting components of the pulley systems that they had read about previously, but because of large variance in the data, this difference was not significant. Furthermore, it is inconsistent with our predictions which suggested that both high-ability subjects and subjects who read the shorter text should have to reactivate less information. In order to suggest possible reasons for these inconsistencies, we considered some other reasons why subjects might inspect parts of a diagram that they have already inspected.

Insert Figure 11 about here.

Figure 11: Time spent inspecting the Diagram for each Purpose (seconds).



It is possible that when subjects inspect parts of a diagram that they have already inspected, they are not just reactivating an existing representation. We expected the process of reactivating an existing representation to take a shorter amount of time than the process of forming a representation. However, reactivate inspections were considerably longer (3.4 seconds) than formation inspections (1.2 seconds). When people reinspect parts of a diagram, they may be encoding new information, such as a connection between the fixated component and some other component. They may also be integrating information about different parts of the pulley system. Inspections that were classified as reactivation inspections sometimes involved looking back and forth between components of the pulley system, suggesting that subjects were attempting to integrate their representation of these components. This view is consistent with the evidence that most reactivate inspections (65.9%) were made at the end of the text when subjects had already read about the individual components of the pulley system. Thus, the inconsistency between our predictions and the data concerning reactivation inspections may be due to the fact that reactivation inspections have several different purposes that we did not consider when making our predictions.

Elaboration Inspections. Very few diagram inspections were classified as elaboration inspections, and so these data do not provide a basis for drawing any strong conclusions about the ability to encode new information from a diagram. However, the data did show effects in the directions that we predicted. A comparison of the black bars in Figure 10 shows that the majority of elaboration inspections were made by high-ability subjects. High-ability subjects also spent more time inspecting the diagram (6.7 seconds) than did low-ability subjects (0.4 seconds), $F(1, 8) = 6.29$, $p < .05$, suggesting that high-ability subjects are more able to encode new information from a diagram than low-ability subjects. Furthermore, high-ability subjects who read the shorter text spent considerably more time (12.2 seconds) extracting new information from the diagram than did high-ability subjects who read the longer text (1.3 seconds), suggesting that high-ability subjects spend more time encoding new information from a diagram when the text fails to provide information

that is relevant to understanding the mechanical system.

The interaction shown in Figure 9 can be illuminated by a consideration of the types of diagram inspections that different subjects made. Low-ability subjects need to use the diagram to form representations of information that they read in the text, so the amount of time that they spend inspecting the diagram is positively related to the amount of information in the text. High-ability subjects, in contrast, have less need to use the diagram to represent information in the text, but can use the diagram as a source of new information which is not presented in the text. Consequently, the amount of time that they spend inspecting the diagram is negatively related to how much information the text contains.

In sum, the results suggested that people low in mechanical ability have difficulty forming a representation of configurational properties of mechanical systems from text alone, and use diagrams to help them represent this information. Also, people high in mechanical ability seem better able to encode new information from a diagram when the text does not describe all the information relevant to understanding a mechanical system. Both of these findings were consistent with our predictions. Contrary to prediction, ability and information content of the text did not affect the time spent inspecting the diagram to reactivate the representation of information that was already read about. These types of inspections, which make up the majority of time on the diagram, may be important for integrating representations of different parts of the mechanical system. They may also involve encoding new information about components (i.e. information that is not encoded on the first inspection of a component).

Discussion of experimental findings.

We suggested three purposes of a diagram in a mechanics text: to aid the formation of a referential representation of information in the text, to act as a memory aid for information that has already been read, and to communicate new information not given in the text. By examining where in the text subjects inspected the diagram, and what they

looked at in the diagram, we found differences in the way people inspect diagrams under different conditions, suggesting that inspecting a diagram for each of these purposes is an important component of the process of integrating text and diagrams.

One purpose of a diagram is to aid the representation of information presented in the text by presenting this information in another medium. We found that subjects frequently inspected the depiction of components of the pulley system that they had just read about, suggesting that they were using the diagram as an aid to forming a representation of information that they had read. Because a diagram depicts the relative spatial locations and connections between components, it is particularly useful in representing information about configuration. Thus subjects who read a text including a description of the configuration of components of a pulley system inspected the diagram more for this purpose than subjects who read a text that did not include information about configuration. Diagrams may be particularly helpful for subjects of low mechanical ability who appear to have difficulty forming a referential representation of this type of information from the text alone.

For the most part, when subjects inspected the diagram, they looked at components that they had either read about or inspected previously. We originally suggested that when subjects reexamine parts of a diagram, they are reactivating the representation of information that is no longer in an activated state. However, because of the frequency and length of these types of diagram inspections, we now suspect that these types of inspections may have other purposes as well. It is possible that when subjects refixate parts of a diagram, they are encoding new information (e.g., about a relation of the fixated component to some other component in the system). They may also be integrating information which was presented at different places in a text. Forming a representation of a mechanical system requires an integration of information about components which affect each other's motions. A diagram may be particularly useful for this integration because components which affect each other are always connected and therefore spatially contiguous in a diagram.

A third purpose of a diagram is to provide information that is not given in the text.

The results of our study are consistent with results of previous research (Hegarty et al., 1987; Larkin & Simon, 1987) which suggest that knowledge of what is relevant is a prerequisite for encoding new information from a diagram. While relatively few diagram inspections were classified as being primarily to encode new information, the majority of these were made by high-ability subjects. Furthermore, in the shorter text condition where the diagram contained more new information not stated in the text, high-ability subjects spent more time looking at the diagram while low-ability subjects did not spend any more time on the diagram than in the longer text condition. Thus, it seems that high-ability subjects are more able to encode information from a diagram alone than are low-ability subjects.

The encoding of information from a diagram by high-ability subjects can be characterized as instantiation of a schema for a mechanical device. Studies of text processing have indicated that experts have better comprehension of text in their domain of expertise because they have more elaborate schemata (Chiesi, Spilich, & Voss, 1979; Spilich, Vesonder, Chiesi, & Voss, 1979). These results may be generalized to extracting information from a diagram. It is likely that people with high mechanical ability have more elaborate schemata for mechanical devices, containing more slots for connections between components. If this were the case, a high-ability subject would encode information about connections between components from the diagram even if no information about connections is provided in the text, while a low-ability subject would pay less attention to connections.

Directions for Future Research. One limitation of the experimental study reported here was that it did not include a measure of comprehension of the text and diagram. Our analysis of how the different groups of subjects read the texts suggested that comprehension of the text for some groups should be better than others. In particular, low-ability subjects in the shorter text condition should have formed a poorer representation of the pulley system than other subjects because the text did not direct their attention to the relevant parts of the diagram, and because they had little prior knowledge of what is relevant in the diagram. It is important that future studies examine not only how texts and

diagrams are processed, but also what people learn from processing texts and diagrams.

Another likely direction for the future is to examine other potential sources of individual differences in diagram inspection besides mechanical ability. There are many other potentially relevant factors, such as spatial ability, reading ability, and motivation. For example, in an ongoing experiment we find that subjects with high spatial ability spend less time looking at the diagram than do subjects with low spatial ability ($r = -.56$). This suggests that high spatial people may be more efficient at extracting information from a diagram, possibly because they can process spatial information faster, or possibly because they are better able to translate verbal information into a spatial format, so that the diagram contains less new information for these subjects.

Working memory capacity might also affect the use of diagrams in reading text. People have been found to differ in the amount of information that they can hold in working memory when they are reading text (Daneman & Carpenter, 1980). Subjects with a high working memory capacity during reading might need to inspect a diagram less often to reactivate the representation of information previously read. By the same token, a diagram might be a useful memory aid for subjects with a lower capacity.

Instructional Implications. The finding that low-ability subjects typically inspect those parts of a diagram that are referred to in the text has promising educational implications, because it suggests that the text can be used to direct people's attention to the relevant parts of a diagram. A diagram of a pulley system contains both non-critical information, such as the length of the ropes, and critical information, such as how the components are connected. Our studies of individual differences in mechanical ability (Hegarty et al., 1987) suggest that low-ability people, who have little previous knowledge of machines, might not correctly discriminate between the relevant and irrelevant information. However, our observations of how low-ability people process text and diagrams have indicated that these people look at components of a diagram that have been referred to in the text. Thus, by describing only the relevant information about a mechanical system in the text, it may be possible to direct a person's attention to the relevant information in a diagram, even if the

person has no prior knowledge of what is relevant.

Our results also suggest that labeled diagrams may improve comprehension of instructional materials by helping a person to match components of the diagram with the expressions used in the text to refer to these components. The subjects in our shorter text condition may have had difficulty reading the second page of text because they had not matched some components of the diagram with the labels used to refer to these components in the text. The eye fixations of subjects also indicated that subjects occasionally had difficulty finding components in the diagram that were referred to in the text, in spite of the unambiguous labels used (upper pulley, lower pulley, etc.). Thus, the matching of referents in text and diagram seems to be a source of difficulty in processing texts accompanied by diagrams. The use of identical labels for components in the text and diagram may help people to overcome this difficulty.

Conclusion

An important aspect of understanding machines is representing the configuration of their components, which indicates how the components interact to achieve the function of the machine. Information about configuration is easily communicated in a diagram, so that a diagram can be used to construct a representation of a machine described in text, to access the representation, and to elaborate the representation. We found that the extent to which a diagram is used for each of these purposes depends on both the content of the text that it accompanies and the ability of the reader. Our observations suggest that knowledge of what is relevant in a diagram might be a prerequisite for encoding new information from a diagram. Our observations also have promising instructional implications because they suggest that when a person lacks prior knowledge of what is relevant in a diagram, the text can direct the person's attention to the relevant information.

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Author Notes.

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