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COMPREHENSION PROCESSES IN MECHANICAL REASONING

FINAL REPORT

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Several lines of research investigated how people reason about mechanical devices. One avenue explored the use of diagrams in conjunction with texts to understand a particular machine. Another project investigated the psychological processes that distinguish people who score high or low in a psychometric test of mechanical ability. A third project examined the visual scanning and decision processes that are used to evaluate a kinematic display of a machine in motion. A fourth project was a simulation model of how a person might generate the kinematic imagery to represent a machine in motion. A fifth project examined the cognitive processes in a visually-based test of pure reasoning (Raven Progressive Matrices). A sixth project examined the use of kinematic computer displays in understanding a complex device. These projects together provide an overview of the psychological processes used in mechanical comprehension, as well as indicating why some people are better at mechanical comprehension than others.

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INTRODUCTION

This is the final report for ONR contract NOOO14-85K-0584 between the Office of Naval Research (Personnel and Training program) and Carnegie-Mellon University. Patricia A. Carpenter and Marcel Adam Just were the principle investigators. This contract covers work from May 31, 1985 through June 1, 1988.

The purpose of the research is to build psychological models of the technical thinking that constitutes understanding mechanical systems. These processes occur when a person reads about a mechanical device to understand its operation in preparation for operating, assembling, or repairing it. The fundamental cognitive processes involve comprehending language and graphic information to construct a representation of the mechanical and physical properties of the device. One focus of the research are the processes in comprehending texts that describe mechanical devices and the diagrams that often accompany them.

A second goal of this research is to analyze the differences between people who are good at spatial and mechanical reasoning from those who are not. Some of the research examines the performance of individuals of varying levels of ability as they try to understand mechanical devices of varying complexity. Differences among individuals in their ability to reason and retain spatial information is of obvious practical and scientific significance. An important facet of completeness is the ability to account not only for typical processes, but also to provide a systematic account of the variation among individuals.

The research approach is to develop fine-grained analyses of the reasoning and visual-perceptual processes in spatial problem solving. The project utilizes data-intensive methodologies, such as eye fixations and verbal protocols, that us to monitor the cognitive processes as they occur. Thus, these investigations seek to analyze the micro-structure of the comprehension of technical information.

The following sections briefly summarize the research associated with the project and provide references to more complete published descriptions of the work.

I. Individual differences in mechanical and spatial knowledge

A cognitive analysis of a test of mechanical ability provides a fine-grained characterization of the individual differences that traditional psychometric tests characterize as a unitary entity. The cognitive analysis specifies the differences in knowledge among individuals and the types of strategies used by different individuals. These analyses permit us to account for the nature of the errors that individuals make when solving mechanical problems. Based on this analysis, test problems can be constructed that will elicit specific types of errors from individuals with different types of knowledge. We have used this approach to analyze the types of knowledge underlying mechanical skill and the processes in spatial skill.

To study differences in mechanical ability, we began our research (Hegarty, Just, & Morrison, 1988) using problems of the type found in a widely used psychometric test of mechanical ability, the Bennett Test of Mechanical Comprehension Test (Bennett, 1969). A typical item is shown in Figure 1. In this problem, the subject must decide which of two pulleys will require more force to lift a weight. (The test instructions state that the pulleys are weightless and frictionless). To solve the problem based on a correct understanding, a subject must know how the forces balance in the two pulley systems. If the system is in equilibrium, the force is equal throughout the rope and the sum of the upward forces at any point in the system is equal to the sum of the downward forces. If the person using pulley system B exerts a unit force on the pull rope, there will be a force equal to two units acting on the movable pulley. We will refer to the amount of force required to lift a weight with a pulley system as the effort. The ratio of the weight to be lifted to the effort is the *mechanical advantage* of the system. In this case, pulley system B has less mechanical advantage and requires more force than pulley system A.

Figure 1 - pulley system

People who understand mechanical devices can infer the principles of operation of an unfamiliar device from their knowledge of the device's components and their mechanical interactions. A general characterization of how individuals solve the test items is as follows. Individuals decide which attributes of pulley systems are relevant to reducing the effort required to lift a weight. They compare the depicted pulley systems by applying rules that relate these attributes to the effort that must be exerted. When several different rules are applicable in a given situation, preferences among these rules determine which rule is used to generate an answer to the problem. Based on subjects' retrospective protocols and response patterns, it was possible to identify rules that accounted for the performance of subjects of different levels of mechanical ability (Hegarty, Just, & Morrison, 1988). The rules are explicitly stated in a simulation model which demonstrates the sufficiency of the rules by producing the kinds of responses observed in the subjects.

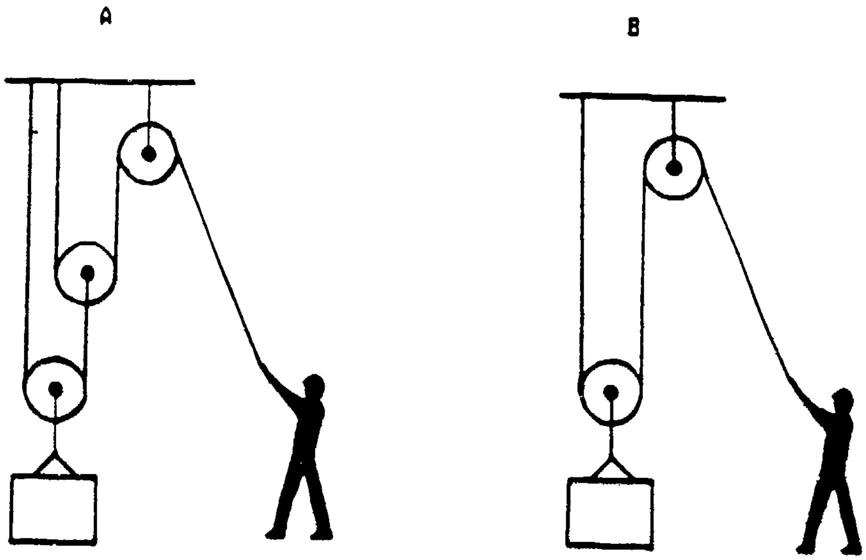
Three abilities are proposed as the sources of individual differences in performance: (1) ability to correctly identify which attributes of a system are relevant to its mechanical function, (2) ability to use rules consistently, and (3) ability to quantitatively combine information about two or more relevant attributes.

First, individuals 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. Low-scoring subjects are often misled into thinking that an irrelevant property of a mechanical system, such as the height of a pulley system is relevant to its mechanical advantage. For example, in problems in which the depicted pulley systems differed on height, high-scoring subjects had a higher proportion of correct responses (.90) than low-scoring subjects (.44).

Second, high-scoring subjects were more consistent in their rule use. Thus, high-scoring subjects typically used the same rule to answer problems of a given type (problems in which the pulley systems differed on the same attributes) while low-scoring subjects used different rules on different problems of the same type. We interpreted this result to mean that high-scoring subjects have a clear set of preferences among rules which are applicable in a given situation while low-scoring subjects do not.

Third, high-scoring subjects were more likely than low-scoring subjects to quantitatively combine information about two relevant attributes in a single rule. In problems that required the quantitative combination of two relevant attributes (weight and mechanical advantage) subjects used one of three strategies to solve the problems. One strategy was to

Figure 1: A typical pulley problem.



With which pulley syster does the man have to pu with more force to lift the weight?

A
B
If no difference. mark C.

compute the effort directly by computing a ratio of the weight to some attribute, such as the mechanical advantage or the number of pulleys. The second strategy was to use a principle whereby differences in mechanical advantage are considered to compensate for differences in weight. The third was to use only one of the applicable rules to solve the problem. The first strategy was used by the highest scoring subjects while the third strategy was used by the lowest scoring subjects.

Figure 2 presents a schematic description of the range of individual differences that we found. According to the description presented in the figure, low-scoring subjects are characterized as using rules based on visible attributes of pulley systems. These rules are qualitative, the attributes on which they are based can be either relevant or irrelevant. Also, low scoring subjects have no clear preferences among their rules so that their responses are inconsistent. High-scoring subjects, on the other hand, prefer rules based on attributes that are highly correlated with mechanical advantage. Also their rules are quantitative and take configural properties of the system into account.

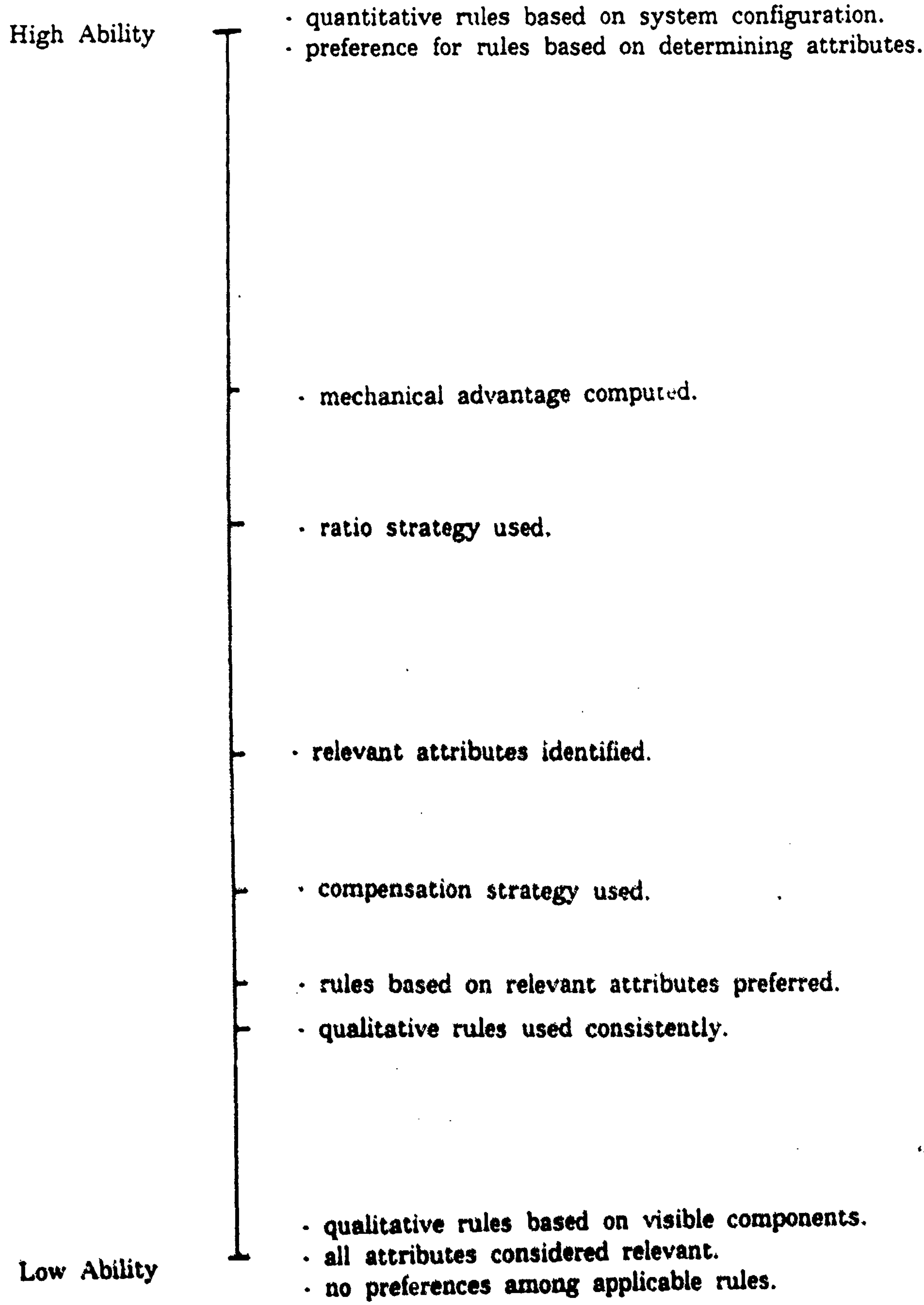
Figure 2 - Schematic representation of the progression

In order to specify mechanisms that can underlie performance on the problems and that can account for the individual differences identified in Experiment 1, we developed a simulation model. The model simulates the performance of one high-scoring and one low-scoring protocol subject. It simulates the response choices that the subjects gave to the problems in Experiment 1, as well as stating the rationale for each choice. The simulation model is written in the Soar production system language (Laird, Newell, & Rosenbloom, 1987). As in other production systems, Soar's procedural knowledge is contained in productions, some of which, in this case, are intended to correspond to the rules subjects use in solving the pulley problems. This research illustrates how a cognitive analysis provides an understanding of the knowledge that underlies mechanical ability. Consequently, it provides a better foundation for how one might acquire that knowledge, as well as how one could test for its effects.

Individual differences in spatial skill. In earlier work, we examined individual differences in spatial skills, such as those tapped by psychometric tests (Just & Carpenter, 1985) of spatial rotation and transformation. Two such tests are the Cube comparisons task and the Shepard and Metzler (1971) meatal rotation task. Strategic differences in such spatial tasks can be explained in terms of different cognitive coordinate systems that subjects adopt. The strategy of mental rotation that occurs in many recent experiments uses a coordinate system defined by the standard axes of our visual world (i. e., horizontal, vertical, and depth axes). Several other possible coordinate systems (and hence other strategies) for solving the problems that occur in psychometric tests of spatial ability are examined in this article. One alternative strategy uses a coordinate system defined by the demands of each test item, resulting in mental rotation around arbitrary, task-defined axes. Another strategy uses a coordinate system defined exclusively by the objects, producing representations that are invariant with the objects' orientation. A theory of the mental rotation of individuals of low and high spatial ability solving problems taken from psychometric tests is instantiated as two related computer simulation models whose performance corresponds to the response latencies, eye-fixation patterns, and retrospective strategy reports of the two ability groups.

In another series of studies, we examined two approaches to the analysis of spatial

Figure 8: Schematic representation of the progression from low to high ability.



skills: psychometrics and information processing (Carpenter & Just, 1986). The central question was what processes could be responsible for the general correlation observed among performance on spatial tests, the general spatial factor? This chapter suggests that both quantitative and qualitative differences constitute high spatial ability. In general, high spatial subjects are better at generating, maintaining, and coordinating information during spatial transformations. In the tasks we have studied, high spatial subjects were less likely to re-execute a spatial transformation or regenerate a spatial representation. They appeared to find it easier to encode spatial information and might do so more accurately or in more detail than low spatial subjects. While more research is needed on this topic, it may be that high spatial subjects have a better spatial "vocabulary", that is, that they have chunks that allow for more efficient encoding and construction and more accurate retrieval of spatial information. High spatial subjects also have more facility with spatial transformations. When there are alternative ways of solving rotation problems, the high spatial subjects are more likely to use the more complex trajectories. They may also be faster at performing basic spatial operations, but this facility could reflect the more efficient representation that they use. Finally, our definition of spatial ability in terms of information processing, unlike the traditional psychometric one, distinguishes between subjects who use spatial transformations and those who use non-spatial processes, even if the two groups have roughly similar speed and accuracy on a psychometric test.

In another series of studies, we have investigated individual differences in a more complex type of visual problem solving (Carpenter & Just, 1989). We analyzed the cognitive processes in a widely-used non-verbal test of analytic intelligence, the Raven Progressive Matrices Test (Raven, 1962). The analysis determines what processes are common to all subjects and all items on the test, and what processes differentiate between higher-scoring and lower-scoring subjects. The analysis is based on detailed performance characteristics such as verbal protocols and eye fixation patterns. The theoretical model is expressed as a pair of computer simulation models that perform like the median or best college students in the sample. The processes that distinguish among individuals are primarily the ability to induce abstract relations and the ability to dynamically manage a large set of problem-solving goals. The processing characteristic that is common to all subjects is an incremental, re-iterative strategy for encoding and inducing the regularities piece by piece. Additional experiments and discussions relate the theoretical account of the processing in the Raven test to performance in other tests of intellectual ability.

II. Learning mechanical information from texts and diagrams

Diagrams accompanied by text have been a common means of recording and conveying scientific and technical information since the 15th Century. Illustrated technical books originated in engineers' notebooks and manuals of technical processes. These books relied heavily on graphics and when they included text, it served to explain the pictures. The invention of the printing press in the 15th century made these illustrated books available to a large audience. Some historians have suggested that their availability may have been a major cause of the large technological advances between the 16th and 18th centuries (Ferguson, 1977). In recent years, there has been an analogous advance in the capabilities of graphic technologies, as well as their availability. Graphics innovations, such as animation software, computer aided drawing, and plotting programs, have made the techniques of graphic communication available to an ever growing community of users. These innovations have made clear the need for a theory of communication that would specify which media are suited to conveying different types of information, where and when graphics should be included, and the extent to which information in graphics and text should overlap (Bertin, 1983). But such prescriptions must be grounded in a theory of the processes in understanding texts and diagrams.

The chapter of Hegarty, Carpenter and Just (in press) describes the beginnings of such a theory, focusing on how readers understand technical texts and diagrams, particularly diagrams that have a close correspondence to their concrete referents. Of course, the processes in text comprehension have been the focus of considerable research in the last 15 years (Just & Carpenter, 1987; Pearson, Barr, Kamil, & Mosenthal, 1984; van Dijk & Kintsch, 1983). In this chapter, we build on what is known about text processing to describe how the process changes when diagrams accompany the text. Our discussion focuses on how text comprehension is influenced by the diagram, how the diagram itself is processed, and how information from the two sources is integrated. But a psychological analysis that considered only the properties of the text and diagram would miss a significant component of the story. The processes in understanding a text accompanied by diagrams also depends on the reader's profile of cognitive aptitudes, so that the theory must take into account the differences among individuals.

One of the important results to come from this research is that low mechanical ability individuals are "text driven." They are dependent on the text to draw their attention to particular aspects of the diagram and they use to text to help interpret the diagram, even when the diagram is highly representational, rather than abstract. In contrast, subjects of high mechanical ability can use either source for information about the structure and function of the device. As our earlier research revealed, an important aspect of high mechanical ability is knowledge about the relevance of various features of mechanical devices, which can guide the inspection and interpretation of diagrams.

One series of studies has examined the way high and low mechanical ability subjects examine texts and their accompanying diagrams (Hegarty & Just, 1989). The goal has been to develop a model of the types of processes engendered by the two media. By analyzing the patterns of eye fixations while readers are learning about a device, we have found characteristic distinctions that reflect the differences between high and low mechanical ability subjects (Hegarty & Just, 1989; Hegarty, 1988). In the experiments, subjects are presented with a page of text (approximately 80 words) and a diagram describing a mechanical devices, typically pulley systems of varying complexity. The initial research examined how long and how well subjects examined the diagram as a function of various characteristics of the text.

In general, high ability subjects construct a good representation of the pulley system after reading the first sentence and then inspecting the diagram. After the first sentence (when both highs and low ability subjects tend to scan the device), the highs gaze along lines of action, rather than just single components. The high ability subjects make fewer mid-text inspections than the lows, and in general, use the diagram to verify that the text is consistent.

By contrast, low ability subjects are "text driven." In one experiment, we found that if the text was disorganized (but still accurate) the high ability subjects could and would compensate (by rereading the text and inspecting the diagram); the low ability subjects could not compensate. The quality of the text was manipulated by rearranging some of the internal sentences, so that they still had internal coherence (that is, they were not ambiguous), but they were rearranged so that they sentences referring to the same components were not clustered together. The high ability subjects reread the text more often for the disorganized text and inspected the diagram slightly more often. By contrast, the low ability subjects could not compensate: in fact, they inspected the diagram even less often for the disorganized texts. Correspondingly, the low ability subjects had particularly poor scores on a subsequent comprehension test.

Low ability subjects construct their representation as they read the text. Indeed, other studies (Hegarty & Just, 1989) have shown that for coherent texts, the more often the text refers to information in the diagram, the more often the low ability subjects examine the diagram. The experiment varied the amount of structural detail given in the text (it was always also available in the diagram). Low ability subjects spend more time on the diagram when the text has more information about the diagram. This reflects their "text drivenness." By contrast, high ability subjects can utilize the diagram to encode or organize information about the device, even if the text is very concise or even disorganized.

In some, these studies illuminate basic differences in how individuals of varying mechanical ability learn new information from texts and diagram. The differences mirror the knowledge differences we examined in our analysis of individual differences, described in Section I.

III. Perception of diagrams

A final project under the current proposal examined how people examine animated displays to determine if the device was realistic. When a person inspects a machine that is operating, perhaps to check that it is working correctly, he collects information about the motions of the machine's components, and evaluates this information using his mechanical knowledge. Several studies examined how people collect such information, and the knowledge about machines that they use to evaluate this information, and its relation to mechanical ability (Fallside, 1988). The importance of this project from a scientific vantage point is that it is the first clear demonstration of stimulus sampling during decision making. Stimulus sampling, the idea that evidence is accumulated in a probabilistic manner, has been a major theory in several domains, including learning, decision making, and pattern recognition. The current research externalized the sampling process by recording how people inspect a machine to decide if it is malfunctioning.

In the experimental paradigm, subjects were presented with dynamic displays (computer animations) of a pulley system, and they were asked to judge whether or not a real pulley system could actually work like the animation. In the experiment, the ropes and weight were animated so that they move up and down: also, the pulleys could move clockwise or counterclockwise. Finally, a computer simulation, called PULLMAN, was developed: it uses a production system architecture and it is able to account for the pattern of eye fixations of high mechanical ability subjects inspecting the pulleys, as well as their errors and response times for different pulley systems.

Three experiments investigate how people scan dynamic displays of a pulley system, to determine whether it could be realistic. The purpose of the experiments is to discover what psychological processes are involved in making this decision. The first experiment examines the sequence in which pulley components are scanned and the decision processes that are used in comparing interacting components to determine whether their motions are mutually consistent. The experiment examines the eye-fixations of a group of subjects who performed the task. The eye-fixation and reaction time data are used to develop a simulation model that performs the task and exhibits similar characteristics to the human subjects. The second experiment uses the framework developed within the model to examine how the spatial layout of the pulley system components affects the nature of the scan and the decision processes. It also examines the role of individual differences in mechanical ability in performing the task. The third experiment examines performance on the task when the unrealistic pulley animations are quantitatively incorrect rather than qualitatively incorrect.

Peoples' mechanical abilities were investigated in a series of experiments that used pulley systems as the target machines. Pulley systems were chosen because they have interesting properties and they are easily adapted to visual-processing tasks. One of the interesting properties of pulley systems is that they are dynamic: weights are lifted, ropes move, and pulleys rotate. Any mental model of a pulley system probably includes a representation of some of the mutually constraining motions of interacting components. Another interesting property of pulley systems is that they appear to provide something for nothing, in the sense that they make it possible to lift heavy weights with ease, without any external sources of force. This property, mechanical advantage, is also associated with visually perceptible cues such as the different relative velocities of a system's components. In general, pulley systems are amenable to visual inspection tasks because the interesting structures and motions of their components are visually available.

A single experimental paradigm was used in each of the three studies described in this paper. Subjects were presented with dynamic displays (computer animations) of a pulley system, and they were asked to judge whether or not a real pulley system could actually work like the animation. Subjects were also asked to localize the difference between a real pulley system and the animation, if they judged that a real pulley system could not work like the animation. Some of the displays were realistic, but in others, one or two components of the system behaved inconsistently with respect to their neighbors. For example, consider the simple pulley system, which consists of a pulley attached to the ceiling, a weight on the ground, and a rope that is attached to the weight. The rope from the weight passes over the pulley from left to right, and its free end is between the pulley and the ground. In a realistic display of this system, when the free end is pulled, the segment of rope between the free end and the pulley travels downwards, the pulley rotates clockwise, and the left hand rope segment and the weight travel upwards. In an unrealistic display, the pulley might be shown rotating counter-clockwise, a direction inconsistent with the motions of the two rope segments and the weight.

The subjects' use of a stochastic sampling process to inspect the pulley system components implies that their inspection has some interesting and counter-intuitive properties. First, the sampling process does not select every component in a display, so some components may never be looked at before the subject responds. Second, some other components are selected more than once. The results of the first experiment reveal some of the major characteristics of the processes subjects used to determine whether a pulley system was behaving realistically. These characteristics were used as the main building blocks in the construction of a computer simulation model which performs the same task.

Pullman is a production system model that simulates how people judge dynamic pulley displays. Pullman examines the components of a pulley system and decides whether the system is behaving realistically or not by checking the consistency of its components' motions. It was developed from the performance data obtained from the subjects in Experiment 1. The first part of this section describes the model and how it works, and the second part compares its performance with the performance of the human subjects.

Pullman judges a pulley system by collecting evidence about the consistencies and inconsistencies of the motions of the system's components. It collects one piece of evidence at a time, adds it to the existing evidence, and then assesses the accumulated evidence. If the evidence for or against the existence of an inconsistency passes a threshold, then Pullman makes a response. Otherwise, another piece of evidence is collected and the cycle starts over. Three processes are responsible for collecting evidence, assessing it, and making a response: (1) a selection process, (2) an evaluation process, and (3) a response process. The flow of control between these processes and the operations underlying each one are summarized in Figure (m-process). The three processes and their operations are first described in general terms, and then in more detail.

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