Capacity Limits in Mechanical Reasoning

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Abstract

This paper examines capacity limits in mental animation of static diagrams of mechanical systems and interprets these limits within current theories of working memory. I review empirical studies of mental animation that examined (1) the relation of spatial ability to mental animation (2) the effects of working memory loads on mental animation, (3) use of external memory in mental animation and (4) strategies for task decomposition that enable complex mental animation problems to be accomplished within the limited capacity of working memory. The effects of capacity limits on mental animation are explored by implementing a simple production system model of mental animation in the 3CAPS production system architecture, limiting the working memory resources available to the model, and implementing strategies for managing scarce working memory resources. It is proposed that mental animation involves the visual-spatial and executive components of working memory and that individual differences in mental animation reflect the operation of these working memory components.

Introduction

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Studies of visual-spatial cognition have focused primarily on relatively simple tasks, such as scanning visual-spatial images (Kosslyn, Ball & Reiser, 1978), mental rotation (Shepard & Cooper, 1982) and perspective taking (Hintzman, O'Dell & Arndt, 1981). Diagrammatic reasoning tasks are typically more complex in that they involve making inferences from visual-spatial representations to reason or solve a problem.

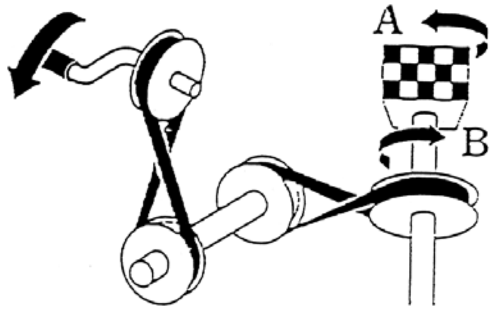
In this paper I will consider a diagrammatic reasoning task that involves inferring the behavior of a mechanical system from a visual-spatial representation (a static diagram). I refer to this process as mental animation (Hegarty 1992). Mental animation is an example of reasoning in that it involves inferring new information from the information given in the diagram. It is an example of spatial cognition in that the input to the inference process is an external spatial representation, i.e. a static diagram.

Consider the sample mental animation problems in Figure 1. These problems are more complex than the mental imagery tasks most studied by cognitive psychologists, such as mental scanning (Kosslyn, Ball & Reiser, 1978) and mental rotation (Shepard & Cooper, 1982) of images. First, they are more complex than scanning tasks in that they involve inferring motion rather than inspecting a static spatial representation. They are more complex than mental rotation in that they involve imagining the motion of several interacting objects that move simultaneously in different ways, rather than the motion of a single object.

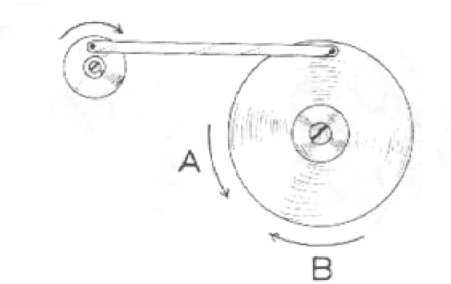
Mental animation tasks are therefore examples of complex visual-spatial inference. In this paper I argue that capacity limits in visual-spatial working memory are a major limiting factor in mental animation. However these limits can be compensated for by strategic processes for decomposing the task and managing limited resources, allowing for quite complex spatial inferences within the limited capacity of spatial working memory. Taking mental animation of mechanical systems as an example, this paper will therefore examine capacity limits in reasoning from diagrammatic representations, and interpret these limits within current theories of working memory.

Capacity Limits in Visual-Spatial Cognition.

The notion of capacity limits has been central to theories of imagery. In the dominant model of mental imagery (Kosslyn, 1980), these limits are conceptualized as limitations of the extent and resolution of a spatial buffer. This model can account for the processing of static pictorial images, in which the amount of detail in the image is proportional to the size of the image in the limited resolution buffer, and for simple transformations of static images, such as scanning and zooming. In contrast, mechanical reasoning involves tasks in which the spatial aspects of objects (especially their connectivity) are more important than their visual details, and in which the motions of several interacting objects must be represented.



When the handle is turned in the direction shown, in which direction (A or B) will the box turn? .



When the little wheel turns around, the big wheel will turn? Direction A, direction B or both directions?

Figure 1. Examples of mental animation problems

Another way of conceptualizing limitations of mental imagery is based on theories of working memory (Baddeley, 1986; Miyake & Shah, 1999). A dominant theory of working memory (Baddeley, 1986) distinguishes three components of the working memory system, a central control structure called the central executive and two more peripheral, domain-specific systems, the visual-spatial sketchpad and the phonological loop, specialized for maintaining visual-spatial and verbal information respectively. The visual-spatial sketchpad might be seen as the site of mental imagery processes (Logie, 1995). It is proposed that the visual-spatial and verbal systems have limited resources, and that maintenance of information in memory and processing of that information compete for these resources. Although there has been a lot of research elucidating the verbal component of working memory (e.g., Just & Carpenter, 1992) there has been much less work on the spatial component.

Early models of the visual-spatial component of working memory conceptualized it as a buffer that is merely responsible for maintaining information in memory. However, more recent evidence suggests that the dissociation between verbal and spatial working memory is at the level of mental processes, and not just maintenance of information (Shah & Miyake, 1986). In this view, maintenance and processing compete for common resources, often conceptualized as a limited amount of activation (Just, Carpenter & Hemphill, 1996). Therefore, one might be able to imagine a complex image, but lose part of the image when one tries to transform it, or one might be able to imagine a simple transformation but not a complex transformation of an image at a particular level of complexity.

Individual differences in spatial ability have been related to the operation of the spatial working memory system. Just and Carpenter (1985; Carpenter et al. 1999) have modeled individual differences in mental rotation tasks in terms of differences in working memory capacity. Shah & Miyake (1986) developed spatial working memory span tasks analogous to the word span and reading span tests used in studies of verbal working memory. These tasks were highly correlated with paper-and-pencil tests of spatial ability and dissociated from verbal span tests and tests of verbal ability. More recent research has confirmed that spatial ability tests are dependent on the spatial component of working memory, and has also shown that more complex spatial tests are also somewhat dependent on the executive component of working memory (Miyake et al., 1999; Hegarty, Shah & Miyake, in press).

A Brief Review of Research on Mental Animation.

Mental Animation Depends on Visual-Spatial Working Memory

Previous research has provided two types of evidence that mental animation depends on visual-spatial working memory resources (Hegarty & Sims, 1994; Sims & Hegarty, 1997). In these studies, the task was to infer how different components of a pulley system move when the free end of the rope was pulled (see Figure 2). First, Hegarty & Sims (1994) found that ability to mentally animate mechanical systems is highly related to spatial visualization ability, as measured by psychometric tests such as the Paper Folding Test (Ekstrom, French & Harman, 1976), but was not related to verbal ability. Specifically, low spatial people made more errors on mental animation but did not differ in their reaction time to solve problems. If we conceptualize individual differences in spatial ability as differences in operation of the visual-spatial working memory system, then mental animation seems to depend primarily on this system.

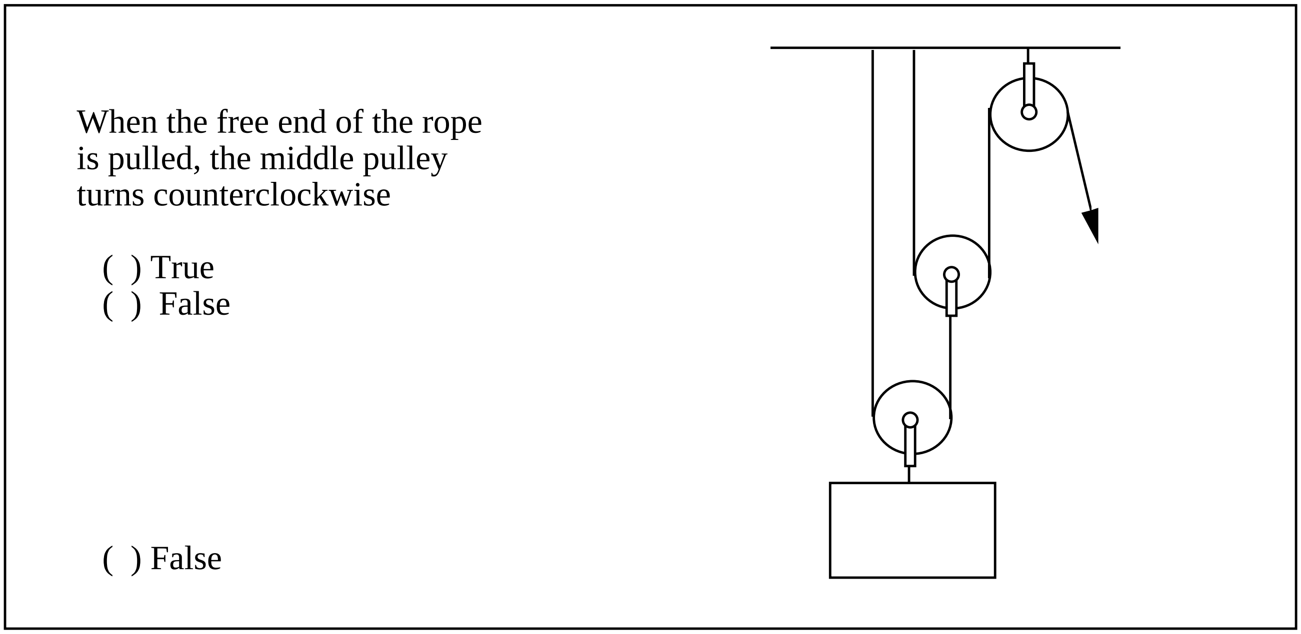


Figure 2. Sample mental animation problem (Hegarty 1992).

Another type of evidence, often used in studies of working memory, is based on the dual task methodology (cf. Baddeley, 1986). In dual task studies we measure the extent to which a primary task of interest (in this case mental animation) interferes with different secondary tasks, assumed to depend on different components of the working memory system. Sims & Hegarty (1997) measured the interference between mental animation tasks and verbal reasoning tasks (primary tasks) and secondary tasks involving maintenance of a visual-spatial working memory load (assumed to tap the visual-spatial component of working memory) and a verbal working memory load (assumed to tap the verbal component of working memory). They found that found that a visual-spatial working memory load interferes more with mental animation than a verbal working memory load and that mental animation interferes more with a visual-spatial working memory load than does a verbal reasoning task that takes approximately the same amount of time.

Note that not all mental animation tasks are necessarily dependent on spatial processing. In relatively simple tasks, such as inferring the motion of interlocking gears, with repeated trials, people infer a simple verbal rule, e.g., that every other gear in the chain turns the same direction (Schwartz & Black, 1996a). Performance on these tasks is less related to spatial ability and somewhat related to verbal ability (Hegarty & Kozhevnikov, 1999). This paper will be primarily concerned with mental animation of pulley systems, which has been shown to be highly dependent on spatial processing resources.

Mental Animation is Piecemeal

Other research has suggested that people do not mentally animate the motion of all components of a mechanical system in parallel, but decompose the system into components and infer the motion of components one by one, following the causal chain of events (Hegarty 1992). Consistent with this strategy, people take more time to infer the motion of components later in the causal chain when inferring the motion of components of a pulley system. Second, eye fixations reveal that they look at the component in question and components earlier in the causal chain, but not components later in the causal chain. Third, the errors made by low-spatial individuals are primarily in inferring the motion of components later in the causal chain.

The piecemeal strategy requires reasoners to store intermediate results of their inferences. That is, reasoners who make an inference about a sub-component of a device and do not immediately propagate the result to the next sub-component, must store the results for later inference. Given the trade-off between storage and processing in working memory, this might also interfere with the inference process. In this situation, a useful strategy is to offload information onto the external display, for example by drawing an arrow on each mechanical component in a diagram as its direction of motion is inferred. This relieves people of the necessity of maintaining this information in working memory. Hegarty & Steinhoff (1997) allowed some people to make written notes on diagrams of mechanical systems in a mental animation experiment. Although only about half of those who were allowed to make notes actually did so, making notes improved performance as predicted – low-spatial subjects who made notes had fewer errors than those who did not make notes.

A Model of Mental Animation.

Hegarty (1992) proposed a production system model of mental animation of pulley systems. In this model it was assumed that a pulley system is represented as a set of connected components (pulleys, a weight, rope strands etc.). The simulation begins with knowledge of how the system components are connected (a structural description) and the knowledge that the free end of the pull rope is being pulled, so that this rope strand is moving down. The model then infers how each of the components of the pulley system moves by applying rules of mechanical reasoning, such that each rule infers the motion of a single component of the pulley system and this inference is made from knowledge of the motion of a component that is adjacent to it (i.e. touches it).

In this model, the application of production rules is not meant as a literal model of how the motion of components of a mechanical system is inferred. There is evidence that when inferring the motion of two interacting mechanical components, people actually use an analog imagery process, such that the time it takes them to infer the motion of two interlocking gears is proportional to the angle of rotation (Schwartz & Black, 1996). Furthermore, in another mental animation task, Schwartz & T. Black (1999; Schwartz 1999) found that people can make the correct inference only through dynamic analog imagery and not through rule-based reasoning. Although production rules do not model the analog nature of mental animation, they are intended to model the following two aspects of mental animation:

1. The motion of a component can only be simulated from that of an adjacent component.
2. The number of components whose motions can be simultaneously animated is limited.

Although Hegarty's (1992) model provided a good fit to the data, it was limited in that it was a pencil-and-paper model and did not address the precise working memory demands of the task, in particular the tradeoff between storing intermediate results and inferring the motion of new components. To model these demands, the model was implemented in 3CAPS (Just, Carpenter & Hemphill, 1996). 3CAPS is a production-system architecture that has been developed largely in the context of theories of working memory. It has the following distinct characteristics.

* In the 3CAPS architecture elements are not considered to be merely in or not in working memory, but rather they are assigned different levels of activation. The activation of a given element can range from 0 to 1.
* 3CAPS allows one to create different pools of working memory resources to model, for example, the spatial and verbal working memory systems.
* 3CAPS allows one to limit or "cap" the total amount of activation available to any given pool of resources.

Hegarty's (1992) production system model of mental animation was implemented in 3CAPS. The mental animation process was modeled as taking place in a spatial working memory store. The production system contained three productions that successively inspected and read in information from an unlimited "external" store to spatial working memory, and 6 productions that inferred the motion of components. Mental animation of a simple two pulley system was modeled (see Figure 3). When no limits were placed on spatial working memory, the production system took 12 cycles (listed in Table 1) to mentally animate all components of the pulley system. The components were animated one by one and in the order of the causal chain of events.

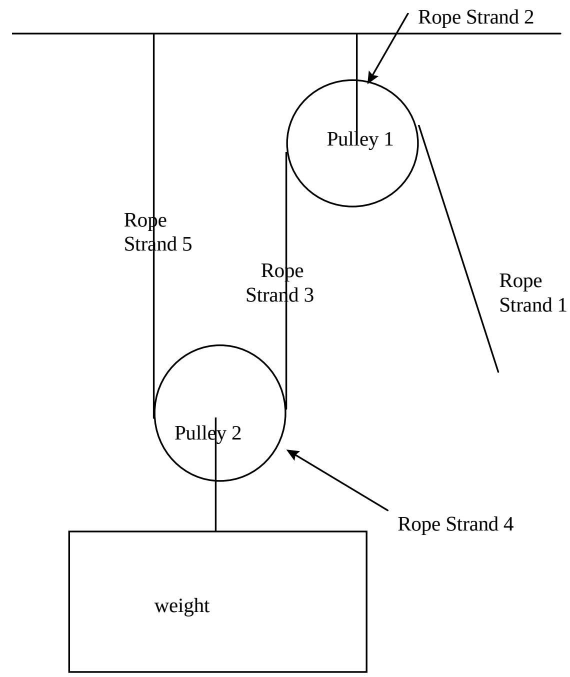


Figure 3. Diagram of the simple pulley system mentally animated by the 3CAPS simulation. The rope is divided into separate strands that move differently when the pulley system is animated. Rope Strand 2 is the section of rope that lies above Pulley 1 and Rope Strand 4 is the section of rope that lies under Pulley 2.

Table 1. Description of the action taken on each cycle of the 3CAPS production system trace. "Inspection" of a component means that information about the configuration of that component (what it is attached to etc.) is read into spatial working memory. Note that in the 3CAPS architecture, productions can fire in parallel if more than one production is matched on a given cycle.

Cycle	Action Taken
1	Rope Strand 1 is inspected (simulation is given knowledge that this rope strand is being pulled)
2	Rope Strand 1 is animated (i.e. its direction of motion is inferred)
3	Rope Strand 2 is inspected
4	Rope Strand 2 is animated
5	Rope Strand 3 is inspected
	Pulley 1 is inspected
6	Rope Strand 3 is animated
	Pulley 1 is animated
7	Rope Strand 4 is inspected
8	Rope Strand 4 is animated
9	Rope Strand 5 is inspected
	Pulley 2 is inspected
10	Rotation of Pulley 2 is inferred
	Translation of Pulley 2 is inferred
11	Weight is inspected
12	Weight is animated

To examine the effects of limiting working memory, the spatial store was capped at 3 items and a threshold parameter was set so that an item in working memory had to have an activation of at least .5 to be matched by a production. In this case, the motion of earlier items in the causal chain is inferred accurately. However as more components of the system are "read into" spatial working memory, the activation of all items is degraded, so that when later components are read in, there is not enough activation of the later components to infer their motion, so the production system halts at cycle 8. Increasing the resources of working memory to 4 allows the motion of all components in the causal chain to be inferred (see Table 2). With a cap of 3 items, the simulation behaves like a low-spatial reasoner, who makes errors in inferring the motion of components later in the causal chain. With a cap of 4 items, it behaves like a high-spatial reasoner.

One way of conceptualizing individual differences in performance on mental animation is therefore to assume that high- and low-spatial individuals have different spatial working memory capacities. However another possible difference is that high- and low-spatial individuals differ in how they manage scarce working memory resources. In a further version of the production system model, I added three productions that "cleaned up" the contents of working memory when they were no longer needed to make a further inference. These productions deleted information about a component from spatial working memory if it had already been mentally animated and it was not connected to a component that was yet to be animated. When these productions were added, the motion of all components in the simple pulley system could be inferred with a cap of 3 items in spatial working memory.

Discussion

In summary, mental animation is conceptualized as occurring in a limited-capacity spatial working memory system. Implementing a production system of a simple mental animation task in the 3CAPS architecture allows us to precisely specify the working memory demands of a mental animation task. The model produces behavior that is similar to human mental animation performance in that time (number of cycles taken) to mentally animate a component is related to its position in the causal chain. When a limit is placed on the spatial working memory resources available to the simulation, it models the behavior of low-spatial participants in that the simulation is able to mentally animate earlier components in the causal chain, but not later components. Differences between capacity limited and unlimited versions of the simulation are in accuracy and not in reaction time, similar to the differences between high- and low-spatial individuals observed by Hegarty & Sims (1994).

The model suggests two possible differences between people who are successful and unsuccessful at mental animation. One possible difference is that high-spatial reasoners have more spatial working memory resources than low-spatial reasoners. Another possibility is that high-spatial reasoners have the same working memory resources, but differ in their strategies for managing these resources. Such a strategy difference was implemented in the simulation by deleting elements from spatial working memory once they have been animated. A more robust strategy would be to alter the external display of the problem to reflect earlier inferences, as studied by Hegarty & Steinhoff (1997). Research to date suggests that both resource differences and strategy differences are responsible for individual differences in mental animation. Hegarty & Steinhoff (1997) found that when given the opportunity to make notes on diagrams, only some students did so. These students were able to use a strategy to compensate for limited spatial working memory resources. Other students were not able to use this strategy and were constrained by their limited resources, such that they were unable to mentally animate components later in the causal chain of a mechanical system. Furthermore, strategies for managing limited resources are not equally applicable to all mental animation problems because not all mechanical systems can be decomposed and mentally animated piecemeal

Table 2. Activation of elements in working memory for each cycle of the simulation with spatial working memory capped at 4 items. Items must have an activation of at least .5 to be matched by a production rule. Although the activation of some elements falls below this level in cycles 11 and 12, knowledge of the motion of these items is not needed to infer the motion of the weight, so all components are mentally animated.

Cycle	RS1	RS2	P1	RS3	RS4	P2	RS5	W	Total
1	1								1
2	1								1
3	1	1							2
4	1	1							2
5	1	1	1	1					4
6	1	1	1	1					4
7	.8	.8	.8	.8	.8				4
8	.8	.8	.8	.8	.8				4
9	.53	.53	.53	.53	.53	.66	.66		4
10	.53	.53	.53	.53	.53	.66	.66		4
11	.43	.43	.43	.43	.43	.53	.53	.8	4
12	.43	.43	.43	.43	.43	.53	.53	.8	4

(Hegarty & Kozhevnikov, 1999). Mental animation of problems that cannot be decomposed is particularly highly related to spatial ability, because these problems are more dependent on spatial working memory resources.

The two possible differences between high- and low-spatial people reflect differences in different components of the proposed working memory system. Differences in spatial working memory resources clearly involve the proposed visual-spatial component of working memory. Differences in task decomposition, scheduling and coordinating of task specific goals and suppression of irrelevant information are ascribed to the operation of the central executive (Miyake & Shah, 1999). The analysis presented in this paper therefore suggests that for complex visual-spatial tasks, both the spatial and executive components of working memory play an important role in performance. In an analysis of spatial abilities tasks, Miyake et al (1999) found that this was indeed the case – more complex tests that load on the spatial visualization factor (e.g. paper-folding and form-board tests) were more related to executive tasks than simpler spatial tasks (e.g. speeded mental rotation). Hegarty & Kozhevnikov (1999), in turn, showed that more complex mental animation tasks are more highly correlated with spatial visualization ability than with simpler spatial abilities.

In conclusion, this work combines insights from research on spatial abilities and working memory to provide an account of performance on a diagrammatic reasoning task. It suggests that capacity limits in visual-spatial working memory are a major limiting factor in mental animation. However these limits can sometimes be compensated for by strategic processes that decompose the task and manage limited resources, allowing for quite complex spatial inferences within the limited capacity of spatial working memory.

Acknowledgments

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