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The Role of Working Memory in Problem Solving

David Z. Hambrick and Randall W. Engle

> The combination of moment-to-moment awareness and instant retrieval of archived information constitutes what is called the working memory, perhaps the most significant achievement of human mental evolution. (Goldman-Rakic, 1992, p. 111)

> Working memory plays an essential role in complex cognition. Everyday cognitive tasks – such as reading a newspaper article, calculating the appropriate amount to tip in a restaurant, mentally rearranging furniture in one's living room to create space for a new sofa, and comparing and contrasting various attributes of different apartments to decide which to rent – often involve multiple steps with intermediate results that need to be kept in mind temporarily to accomplish the task at hand successfully. (Shah & Miyake, 1999, p. 1)

More than 25 years ago, Baddeley and Hitch (1974) lamented, "Despite more than a decade of intensive research on the topic of short-term memory (STM), we still know virtually nothing about its role in normal information processing" (p. 47). The primary concern for Baddeley and Hitch was the presumed centrality of limited-capacity short-term memory in contemporary models of memory, including Atkinson and Shiffrin's (1968) "modal model." For example, Baddeley and Hitch described a patient with brain-damage (K.F.) who exhibited grossly deficient performance on tests of short-term memory but normal performance on long-term learning tasks. Logically, this could not occur if information passes from short-term memory to long-term memory. Baddeley and Hitch also reported a series of experiments in which participants performed various reasoning tasks while concurrently performing a task designed to place a load on short-term memory. For example, in one experiment, the task was to verify sentences purporting to describe the order of two letters (e.g., *A is not preceded by B–AB*) while repeating the word "the," a predictable sequence of digits,

or a random sequence of digits. Surprisingly, short-term memory load had very little effect on reasoning.

How could these findings be reconciled with the view that short-term memory is the central bottleneck in information processing? Baddeley and Hitch (1974) proposed that short-term memory is not a single, capacity-limited store, but rather a more complex system consisting of three components: two "slave" systems – the *phonological loop* and *visuospatial sketchpad*, devoted to temporary storage and maintenance of information – and a *central executive* responsible for control processes such as reasoning, planning, and decision making. This model could easily handle empirical results that Atkinson and Shiffrin's (1968) modal model could not. For example, K.F. exhibited deficient performance on short-term memory tasks but normal long-term learning, because only the phonological loop component of his working memory system was impaired. K.F.'s central executive was intact. Similarly, in the experiments described by Baddeley and Hitch, decrements in reasoning performance emerged only when the storage load imposed by the secondary task exceeded the capacity of the phonological loop. Otherwise, the limited resources of the central executive could be devoted exclusively to reasoning. Thus, Baddeley and Hitch demonstrated that short-term memory is merely one component of an information processing system involving not only storage limitations but processing limitations as well.

THE GOAL AND ORGANIZATION OF THIS CHAPTER

As the quotations at the beginning of this chapter suggest, working memory has emerged as one of the most important and intensively researched constructs in cognitive psychology. However, we believe that there is still much to be learned about the role of working memory in real-world cognitive functioning. Indeed, one might conclude that despite nearly three decades of intensive research, we still know relatively little about the role of working memory in "normal information processing." For example, a literature search revealed only 12 publications devoted to working memory and problem solving during the 25-year period from 1975 through 1999. Furthermore, in a recent review, Kintsch, Healy, Hegarty, Pennington, and Salthouse (1999) noted that tasks studied by researchers interested in working memory are often simple and artificial, and cannot be considered what Hutchins (1995) termed "cognition in the wild" – complex cognitive tasks encountered in everyday settings.

Thus, the goal of this chapter is to speculate about the role of working memory in problem solving. The chapter is organized into three major sections. In the first section, we establish the scope of the chapter by considering the question, "What is a problem?" Research on problem solving is sometimes viewed as a narrow area of scientific inquiry restricted to "toy"

tasks such as Tower of Hanoi, but we suggest that many cognitive tasks and activities can be considered examples of problem solving in the sense that they involve purposeful, goal-directed behavior. Or as Anderson (1985) observed: "It seems that all cognitive activities are fundamentally problem solving in nature. The basic argument . . . is that human cognition is always purposeful, directed to achieving goals and to removing obstacles to those goals" (pp. 199–200).

In the second section of the chapter, we examine the role of working memory in various cognitive tasks. Evidence from two traditions of working memory research is considered. The first tradition is associated with work in Europe, primarily by Baddeley and his colleagues, and concerns the role of the phonological loop and visuospatial sketchpad "slave" systems in cognitive performance. The second tradition has been pursued by researchers, primarily in North America, interested in individual differences in working memory capacity and their relation to cognitive performance. In the third section, we consider the question of *when* working memory capacity should be expected to play an important role in problem solving.

WHAT IS A PROBLEM?

A *problem* is often defined as a goal that is not immediately attainable. For example, Duncker (1945) proposed that "a problem exists when a living organism has a goal but does not know how this goal is to be reached" (p. 2). Consistent with this definition, problem-solving research has traditionally focused on so-called insight problems. The Tower of Hanoi task is a prototypical example. In the version of this task illustrated in Figure 6.1, there are three pegs (1, 2, and 3) and three disks (A, B, and C). The initial state is that the disks are set on Peg 1, with the smallest disk (Disk A) on the top and the largest disk (Disk C) on the bottom. The goal is to move the disks from Peg 1 to Peg 3, but the rules state that only one disk can be moved at a time, that only the top disk can be moved, and that a disk can never be placed on a smaller disk. Once the target configuration of pegs is achieved, the problem is solved.

Perhaps the most salient aspect of tasks such as Tower of Hanoi is that the solution must be *discovered*. That is, although the initial state and the goal state are clear, how to transform the initial state into the goal state is unclear. By contrast, proficiency in more routine problem-solving tasks involves execution of well-learned skills and procedures. For example, success in a reading comprehension task depends not so much on figuring out the most effective way to read the material, but rather on the efficiency and effectiveness of processes already in place. As another example, how one should proceed in order to mentally calculate the answer to an arithmetic problem such as $1{,}356–234 = ?$ is probably clear for any educated adult. The

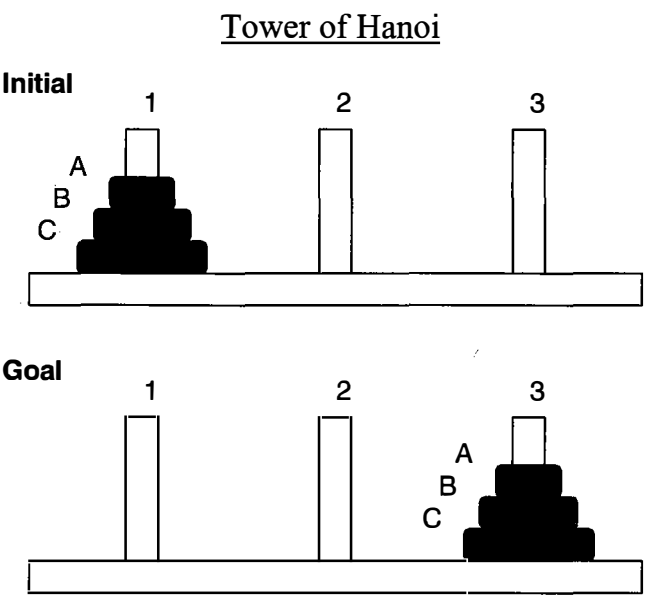


FIGURE 6.1. The Tower of Hanoi problem.

solution *1,122* is not discovered; rather, it is derived. In short, as Anderson (1993) noted, "Some activities, like solving a Tower of Hanoi problem or solving a new kind of physics problem, feel like problem solving, whereas other more routine activities, such as using a familiar computer application or adding up a restaurant bill, do not" (p. 39).

Working Memory as a Unifying Construct

How, though, are tasks such as Tower of Hanoi and other cognitive tasks similar, and how can they be compared at a theoretical level? Our view is that success in many tasks is predicated on the *ability to maintain goals, action plans, and other task-relevant information in a highly activated and accessible state, and when necessary, to inhibit activation of irrelevant or distracting information.* For example, during performance of the Tower of Hanoi task, what one must keep active are the rules of the task and subgoals created en route to the solution. In addition, discovery of a solution may depend on the ability to activate information from multiple, unsuccessful solution attempts, and to maintain that activation until the information is integrated. Similarly, a fundamental requirement of understanding the meaning of a difficult passage about an unfamiliar topic is the ability to maintain some representation, either verbatim or gist, from clause to clause, sentence to sentence, and paragraph to paragraph (Kintsch & van Dijk, 1978). Finally, in a mental arithmetic task, intermediate sums must be kept active in order

to compute the correct answer. To sum up, the argument is that working memory is a fundamental determinant of proficiency in a wide range of tasks.

Working Memory and Problem Solving

Research on working memory has proceeded along two theoretical paths during the past 25 years. Working memory research in Europe has concentrated primarily on the slave systems of the Baddeley-Hitch model. More specifically, what is the role of the phonological loop and the visuospatial sketchpad in working memory, and how are they involved in performance of tasks such as reasoning and comprehension? In contrast, working memory research in North America has focused primarily (although not exclusively) on the central executive component of working memory. More specifically, what is the nature of individual differences in central executive functioning, and how are they related to individual differences in performance of various cognitive tasks? Scholars from the European and North American traditions of working memory research have also tended to rely on different methodological approaches. Generally, working memory research in Europe is experimental, whereas working memory research in North America is more often correlational.

Theoretical and methodological differences aside, results from both traditions of research are informative about the role of working memory in higher level cognition. We review a subset of these findings in the context of the Baddeley-Hitch model of working memory. To review, Baddeley and Hitch (1974) conceptualized the phonological loop as a store for holding speech-based information and a subvocal rehearsal process responsible for reinstantiating or refreshing the information. Similarly, the visuospatial sketchpad refers to a memory store for holding visual or spatial information and a mechanism responsible for reinstantiating the information (Logie, 1995). The third component of the model, the central executive, is a general-purpose, attention-based entity responsible for control processes such as planning, reasoning, decision making, and coordination of the slave systems.

This organizational scheme provides a context for the discussion, given that much of the research that is reviewed below concerns the Baddeley-Hitch model. However, an important difference between the view of working memory set forth in this model and our view is that we conceptualize working memory as a system in which phonological and spatial formats are but two of many ways of representing information (see, e.g., Engle, Kane, & Tuholski, 1999). More specifically, we assume that working memory consists of two primary components. The first component – *short-term memory* – refers to long-term memory representations activated above threshold as a means of temporary maintenance. Long-term memory representations can

become activated through an external event or because an internal event (i.e., a thought) spreads activation to the representation. Furthermore, representations can be maintained in many different formats, including not only phonological and visual or spatial, but also orthographic, lexical, semantic, tactile, and so forth. Therefore, the phonological loop and the visuospatial sketchpad are different representational formats and not distinct storage modules (see Cowan, 1995, for a similar view). Finally, periodic attention to the representations is necessary to keep them active above a threshold, below which the information would have to be retrieved from long-term memory. In many circumstances, this is not a problem if retrieval can be carried out quickly and with little chance of error. By contrast, maintenance of information in the active state above threshold is particularly important under conditions in which retrieval from long-term memory is slow or error prone because of interference.

The second component of our model – *working memory capacity* – is a concept that has emerged from a synthesis of a number of ideas. For example, working memory capacity corresponds to individual differences in the capability of the central executive of Baddeley and Hitch's (1974) model. Therefore, it is assumed to play an important role in a wide range of tasks. In addition, it is similar to Kahneman's (1973) notion of effortful processing. That is, working memory capacity refers to a limited-supply cognitive resource that can be allocated flexibly depending on the demands of the task at hand. Finally, working memory capacity is reminiscent of what Cattell (1943) termed *fluid intelligence*, because it is thought to reflect a general and relatively stable cognitive ability. *However, the specific function of working memory capacity is to bring memory representations into the focus of attention, and to maintain these representations in a highly activated and accessible state.* Thereby, working memory capacity underlies what Horn and Masunaga (2000) recently described as the ability to maintain focused concentration. Working memory capacity may also be called on when it is necessary to suppress, inhibit, or otherwise remove memory representations from the focus of attention (see Hasher & Zacks, 1988, for a somewhat similar view).

The Slave Systems

One way that the so-called slave systems have been studied is through use of concurrently performed secondary tasks thought to interfere with the slave system believed to be important to the primary task. That is, participants perform a primary task (e.g., reasoning) while concurrently performing a secondary task designed to prevent storage of information in either the phonological loop or the visuospatial sketchpad. For example, a phonological secondary task might involve repeating a predictable sequence of digits (e.g., 1 to 6) or the word "the," whereas a visuospatial secondary task might require tracking a visual target. If performance of

the primary task is impaired in the secondary task condition relative to a no-interference control condition, then involvement of the targeted slave system is suggested.

Of course, a fundamental problem with this technique is the problem inherent in all methodological approaches that rely on subtractive logic (Donders, 1868/1969) to isolate the role of a component process (e.g., the action of a slave system) in performance of a complete task. To be exact, when a secondary task produces a decrement in primary task performance, one cannot be sure that this decrement reflects involvement of only the targeted slave system. For example, even a very simple task such as repeating the word "the" may require some level of central executive resources, in addition to the slave system in question. Despite this limitation, research using a secondary task approach has contributed to the theoretical understanding of working memory. A brief review of this research follows.

Comprehension

Comprehension – the ability to understand the larger meaning of a set of events or words – is a fundamental aspect of cognitive functioning. For example, a person would have little hope of success in a task such as Tower of Hanoi unless he or she first comprehended the instructions. Indeed, Kintsch (1998) proposed that comprehension is fundamental for understanding many different types of cognition. What, then, is the role of the slave systems in comprehension? Not surprisingly, much of the research germane to this question has focused on storage of speech-based information in the phonological loop. For example, Baddeley, Elridge, and Lewis (1981) found that a phonological secondary task interfered with participants' ability to detect errors of word order in sentences such as: *We were to that learn he was a very honest person, even though he loved money.* Waters, Caplan, and Hildebrandt (1987) replicated this result and also found that the detrimental effect of articulatory suppression was greater for sentences with multiple propositions than for sentences with a single proposition. Finally, Baddeley, Vallar, and Wilson (1987) found that patients with brain damage who had deficits in phonological processing had difficulty comprehending long sentences but not shorter ones.

Much less is known about the role of the visuospatial sketchpad in comprehension, but there is some evidence to suggest that this slave system contributes to comprehension of high-imagery prose. For example, in a study by Glass, Eddy, and Schwanenflugel (1980), participants read and verified sentences that were either concrete and highly imageable (e.g., *The star of David has six points*) or abstract (e.g., *Biology is the study of living matter*). In addition, for half of the trials, participants concurrently maintained a visual pattern and indicated whether it matched a pattern presented after the sentence. Glass et al. found that, although maintaining the visual pattern

did not selectively disrupt verification of the high-imagery sentences, verification of the high-imagery sentences impaired pattern matching. Thus, Glass et al. concluded that comprehension of the high-imagery sentences involved the visuospatial sketchpad.

Reasoning

The contribution of the phonological loop and the visuospatial sketchpad to reasoning has been investigated in a number of studies. For example, using a phonological secondary task similar to the one described above, Evans and Brooks (1981), Halford, Bain, and Maybery (1984), and Toms, Morris, and Ward (1993) found no evidence for involvement of the phonological loop in a conditional reasoning task in which participants evaluated conclusions for rules stated in the form "if p then q" – for example, *If I eat haddock, then I do not drink gin. I drink gin. I do not eat haddock.* Toms et al. also reported that reasoning was unimpaired by concurrent performance of a spatial secondary task. Similarly, Gilhooly, Logie, Wetherick, and Wynn (1993) found no effect of either phonological or spatial secondary tasks on syllogistic reasoning. Thus, in contrast to comprehension, there is little evidence to suggest that the slave systems play an important role in reasoning.

Insight Tasks

The preceding review indicates that the slave systems may play a limited role in comprehension, but perhaps play no role at all in reasoning. What is the role of the slave systems in tasks, such as Tower of Hanoi, traditionally studied in research on problem solving? One possibility already mentioned is that the phonological loop influences performance of such tasks through comprehension of instructions. Furthermore, for tasks such as choosing a move in a chess game, it seems reasonable to suggest that the visuospatial sketchpad may contribute to performance, at least when a spatial visualization strategy is used. Consistent with this speculation, in a study of chess, Robbins et al. (1996) found that a spatial secondary task (pressing keys in a repetitive counterclockwise fashion) had a detrimental effect on performance in a "choose-a-move" task in which chess players were shown an unfamiliar chess position and attempted to generate an optimal move.

But how important are the slave systems for tasks such as Tower of Hanoi or choosing a move in a chess game? This question can be considered in light of evidence concerning reasoning already considered. More specifically, reasoning about the potential effectiveness of different ways to approach a task can probably be considered a critical aspect of performance in many complex tasks, at least when immediate retrieval of a solution from

long-term memory is not possible. If this is true, then the slave systems might be expected to play a minor role in tasks such as Tower of Hanoi relative to the third component of the Baddeley-Hitch model – the central executive. That is, a consistent finding is that secondary tasks designed to tap the central executive impair reasoning. For example, Gilhooly et al. (1993) and Klauer, Stegmaier, and Meiser (1997) found that reasoning suffered when participants performed a putative central executive secondary task in which they were asked to generate random numbers (e.g., from the set 1–9) at a constant rate. Similarly, Robbins et al. (1996) found that chess players were virtually unable to perform the aforementioned chose-a-move task while concurrently performing a random-letter-generation task. Summarized, our speculation is that the processes subsumed by the central executive represent one important determinant of success in a wide range of problem-solving tasks. The next section discusses research that has investigated this claim from an individual-differences perspective.

The Central Executive

In North America, interest in working memory gained momentum in the early 1980s with the development of a reliable measure of *working memory capacity*, the Daneman and Carpenter (1980) reading span task. Consistent with Baddeley and Hitch's (1974) conception of the central executive, this task was designed to emphasize simultaneous storage and processing of information. Briefly, the goal of the reading span task is to read a series of sentences while remembering the final word from each sentence. Working memory capacity (or "span") is then operationalized as the number of sentence-final words recalled. Hence, the reading span task is actually a dual task because the subject must read sentences while trying to remember the word following each sentence. The goal of a similar task, called operation span (Turner & Engle, 1989), is to solve a series of arithmetic questions and to remember a word following each for recall.

Measures of working memory capacity, such as operation span and reading span, predict performance in a wide range of tasks, including language comprehension (Daneman & Merikle, 1996), learning to spell (Ormrod & Cochran, 1988), math (Adams & Hitch, 1997), following directions (Engle, Carullo, & Collins, 1991), vocabulary acquisition (Daneman & Green, 1986), and writing (Benton, Kraft, Glover, & Plake, 1984). Clearly, then, working memory tasks "work" in the sense that they exhibit predictive validity. But why do they work? In other words, as illustrated in Figure 6.2, what accounts for the correlation between individual differences in working memory capacity and individual differences in various cognitive tasks?

The premise of what we have labeled the *task-specific hypothesis* is that measures of working memory capacity capture acquired skills involved in performance of the criterion task. For example, according to

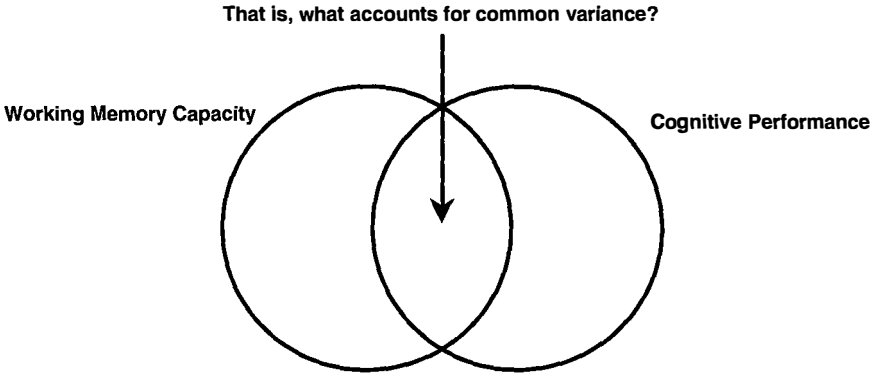


FIGURE 6.2. Why do measures of working memory capacity work?

this hypothesis, the reading span task predicts reading comprehension because both tasks involve reading. Consequently, a key prediction of the task-specific hypothesis is that a working memory task will exhibit predictive validity only when it captures the specific skills involved in the criterion task. By contrast, the basic idea of the *general capacity hypothesis* is that measures of working memory capacity capture domain-general information-processing capabilities that can be brought to bear on many tasks. Therefore, a key prediction of the general capacity hypothesis is that operations unique to a particular working memory task (e.g., reading sentences) are largely unimportant in accounting for the relationship between working memory capacity and cognitive performance. Instead, working memory tasks are thought to be imperfect indicators of a construct involved in the execution of a wide range of tasks.

Comprehension

Daneman and Carpenter (1980) were the first to demonstrate a relationship between central executive functioning and individual differences in comprehension. Their participants read a series of narrative passages and then answered different types of questions. For example, the final sentence of each passage contained an ambiguous pronoun, and the participants' task was to supply the referent, which occurred at some earlier point in the passage. Daneman and Carpenter found a strong positive correlation between reading span and this index of comprehension, particularly when several sentences separated the pronoun and referent. There were positive correlations between reading span and other indexes of comprehension as well, including memory for facts and verbal SAT score. Daneman and Carpenter argued that the relationship between reading span and reading comprehension occurs simply because both measures capture reading skill. That is, by virtue of more efficient and automatic reading strategies,

participants with high levels of reading skill were able to devote more working memory resources to remembering the sentence-final words.

Thus, Daneman and Carpenter (1980) argued that reading span is a consequence of reading skill. The results of a large number of subsequent studies from our laboratory run counter to this argument. We describe the results of two such studies. Turner and Engle (1989) reasoned that if the correlation between working memory span and reading comprehension reflects the fact that both measures index reading skill, then the strength of the relationship between the two measures should vary depending on the nature of the processing component of the span task. Following this logic, participants completed four working memory tasks in which the processing task was either reading sentences or solving arithmetic equations. The measures of reading comprehension were scores on the Nelson-Denny reading test and verbal SAT. Turner and Engle found that the processing component manipulation (sentences vs. equations) had little effect on the relationship between working memory span and reading comprehension.

Engle, Cantor, and Carullo (1992) conducted a more systematic investigation of the relationship between working memory capacity and reading comprehension. In a series of experiments, participants performed either the operation span task or the reading span task using a moving window technique in which each equation-word (operation span) or sentence-word (reading span) stimulus was presented one element at a time. The time required to advance through the equation or sentence was used as an index of skill in executing the processing component of the task; verbal SAT served as a measure of comprehension. Engle et al. reasoned that if skill in the processing component of the span tasks accounted for the correlation between working memory capacity and verbal SAT, then controlling for processing skill would eliminate the correlation. This was not the case: Controlling for processing skill had *no effect* on the correlation between working memory capacity and comprehension.

One possible interpretation of the evidence reviewed thus far is that working memory capacity reflects a domain-general capability instead of skills and procedures applicable to a particular task or class of tasks. Recently, however, Ericsson and Kintsch (1995) and Kintsch (1998) suggested a viewpoint more in line with the task-specific hypothesis. In particular, they suggested that what the reading span task measures is the efficiency of comprehension. For example, Kintsch stated, "What the reading span measures is the efficiency with which readers can comprehend sentences and hence store them in long-term memory" (p. 239). To support their claim, Ericsson and Kintsch reviewed evidence suggesting that long-term memory contributes to performance in the reading span task. For example, using a version of the reading span task, Masson and Miller (1983) found a positive correlation between recall of the sentence-final words and cued recall of words from earlier in the sentences. There were also positive

correlations of each measure with reading comprehension. Assuming that participants could not maintain all of the sentences in temporary storage, it seems clear that the sentences were stored in long-term memory.

Nevertheless, a critical point about the original Daneman and Carpenter (1980) reading span task, and the version of this task used by Masson and Miller (1983), is that the sentence-final "span" words were not *separate* from the sentences themselves. The problem with this task is that it is not possible to disentangle working memory capacity and reading skill. Indeed, recall of the sentence-final words may in part reflect the efficiency with which readers can comprehend sentences and store them in long-term memory (Kintsch, 1998). By contrast, in the version of the reading span task used by Engle et al. (1992), the span words were separate from the sentences. Hence, it was possible to examine effects of reading span on comprehension controlling for skill in the processing component of the task. To reiterate, reading skill did *not* account for the relationship between working memory capacity and comprehension. Based on this evidence, we believe that the findings cited by Ericsson and Kintsch (1995) are important, but they are not sufficient to falsify the claim that measures of working memory capacity reflect a general capacity that transcends task-specific skills.

Multiple Working Memory Capacities?

A study by Shah and Miyake (1996) is also relevant to the present discussion. The major question of this study was whether working memory capacity represents a single cognitive resource or whether domain-specific pools of working memory resources can be distinguished. To investigate this issue, Shah and Miyake had participants perform two working memory tasks, one verbal and one spatial. The Daneman and Carpenter (1980) reading span task served as the verbal working memory task. The spatial working memory task involved simultaneous maintenance and processing of spatial information. For each trial, participants indicated whether the orientation of a letter was normal or mirror-imaged. Then, after a number of trials, the objective was to recall the orientation of each letter. Verbal SAT score was used as a measure of verbal ability, and spatial visualization tests were used to measure spatial ability. Shah and Miyake (1996) found that the spatial working memory measure correlated moderately with spatial ability, but near zero with verbal SAT. Conversely, the verbal working memory measure correlated moderately with verbal SAT, but near zero with spatial ability. In addition, the correlation between the two working memory measures was weak ($r = .23$). The same basic pattern of results was replicated in a second study. Shah and Miyake therefore concluded, "The predictive powers of the two complex memory span tasks seem to be domain specific . . ." (p. 11).

Nevertheless, the results of these studies should be evaluated in light of two potential methodological limitations. First, the sample sizes were

very small for individual differences research (i.e., $N = 54$ for Study 1 and $Ns = 30$ for Study 2). This is problematic not only from the standpoint of low statistical power, but also from the standpoint of the replicability of the results. Second, given that the participants were college students from two selective universities, it seems likely that the score ranges on the working memory tasks (and other ability tests) were quite restricted. Therefore, it is possible that Shah and Miyake (1996) found evidence for separable working memory resources simply because variability due to a domain-general working memory capacity was effectively controlled, or at least reduced relative to what might be expected within more heterogeneous samples. To sum up, our view is that Shah and Miyake's suggestion of separable verbal and spatial working memory resource pools is intriguing, but should be investigated using larger and more diverse samples.

Reasoning and Fluid Intelligence

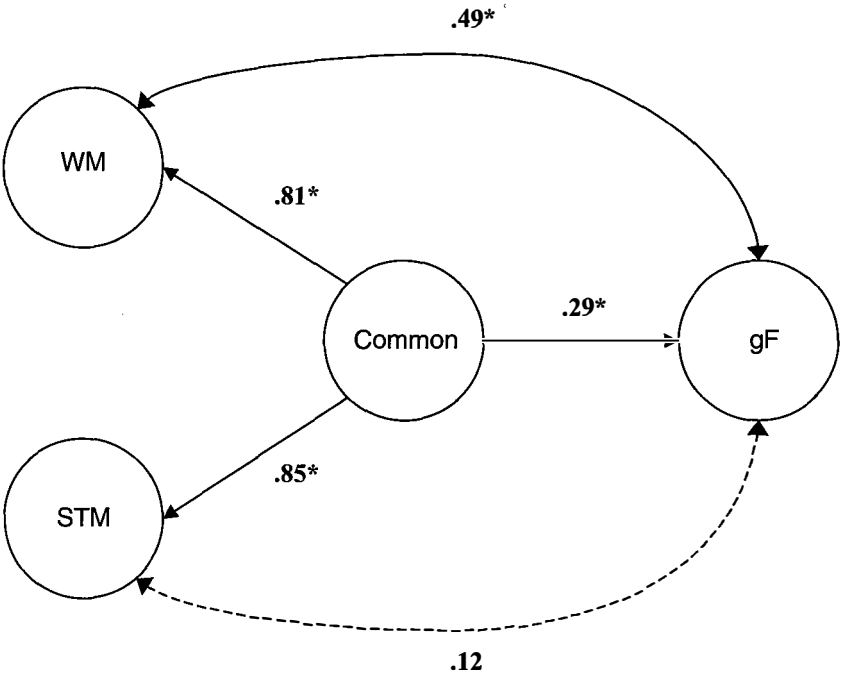
Research examining the relationship between working memory capacity and the broad aspect of cognitive functioning referred to as *fluid intelligence* provides additional evidence for claims about the domain-generality of working memory capacity. Fluid intelligence refers to aspects of cognition that are at least somewhat independent of prior knowledge and experience (Cattell, 1943), and it is typically measured with tests of abstract reasoning and spatial visualization that emphasize solution of novel problems. For example, in one commonly used test of fluid intelligence, Raven's Progressive Matrices, each item contains a series of abstract figures arranged in a 3×3 matrix. One figure is always missing, and the task is to identify which of eight alternatives completes the matrix.

Using a latent variable approach, Kyllonen and Christal (1990) found a strong positive correlation ($r = .90$) between working memory capacity and fluid intelligence. Furthermore, Kyllonen (1996) also reported high positive correlations between fluid intelligence and latent variables representing working memory capacity in three content areas: verbal ($r = .94$), spatial ($r = .96$), and numerical ($r = .95$). Kyllonen summarized his research as follows:

> We have observed in study after study, under a variety of operationalizations, using a diverse set of criteria, that working memory capacity is more highly related to performance on other cognitive tests, and is more highly related to learning, both short-term and long-term, than is any other cognitive factor. *This finding of the centrality of the working memory capacity factor leads to the conclusion that working memory capacity may indeed be essentially Spearman's g* [italics added, p. 73].

Engle, Tuholski, Laughlin, and Conway (1999) sought to better understand the nature of the relationship between working memory capacity and

fluid intelligence. Working memory capacity was measured with tasks similar to the span tasks described earlier; short-term memory capacity was measured with simple memory span tasks (e.g., word recall); and fluid intelligence was measured with two nonverbal tests of abstract reasoning ability. Engle et al. predicted that latent variables representing working memory capacity and short-term memory capacity would correlate, given that some of the same domain-specific skills and procedures are captured by both. For example, skill in encoding information into long-term memory could contribute to performance in both the reading span task and a word recall task. However, Engle et al. also predicted that once this correlation was taken into account, the residual variance in working memory capacity would reflect the controlled attention component of the working memory system. Therefore, the working memory capacity residual would predict fluid intelligence, whereas the short-term memory capacity residual would not. As illustrated in Figure 6.3, the data were consistent with



*p < .01

FIGURE 6.3. Structural equation model with the variance in common to the short-term memory (STM) and working memory (WM) capacity variables removed as common. The curved lines represent correlations between fluid intelligence (gF) and the residual for short-term memory and working memory capacity. Dashed line indicates nonsignificant relation.

this prediction. Working memory capacity and short-term memory capacity were correlated, as evidenced by the fact that they loaded onto a single common factor. However, only the working memory capacity residual variance was a significant predictor of fluid intelligence.

Insight Tasks

Relatively little is known about the role of this capability in insight tasks such as Tower of Hanoi. In fact, we could find only one relevant study. However, this study serves as a good example of how working memory capacity might affect performance in this type of task. Welsh, Satterlee-Cartmell, and Stine (1999) reported positive correlations between two measures of working memory capacity and performance on the Tower of London task, a variant of the Tower of Hanoi task in which the goal is to move a set of colored balls across different-sized pegs to match a target configuration. In fact, the two measures of working memory capacity accounted for a substantial proportion of the variance in solving the Tower of London problem (25% and 36%). Another interesting finding was that processing speed showed no correlation with solution success.

Welsh et al.'s (1999) finding adds to the body of evidence suggesting that working memory capacity plays an important role in many different types of problem solving. Furthermore, the finding that working memory capacity predicted Tower of London performance, whereas information processing speed did not, suggests to us that working memory capacity may even be the *primary* determinant of proficiency in cognitive domains, at least when the influence of prior knowledge and experience is minimal. But what specific functions might working memory capacity support in the context of problem solving? One possibility, alluded to before, is based on Hebb's (1949) proposal that a connection between two ideas is formed only when representations of those ideas are held together in an activated state. More specifically, the ability to maintain information in a highly activated state via controlled attention may be important for integrating information from successive problem-solving attempts in insight tasks such as Tower of Hanoi. A similar view of the importance of the coincident representation of events for subsequent connection between them is proposed by computational models of cognition such as Anderson's ACT-R (Anderson, 1983).

Problem Solving Difficulties

Working memory capacity may also be involved in a number of well-documented problem solving "difficulties," including *functional fixedness* and *negative set*. Functional fixedness refers to the inability to use a familiar concept or object in a novel manner. To illustrate, in the Duncker (1945) candle problem, the subject is given three items – a box of thumbtacks, a

matchbook, and a candle – and the task is to mount the candle on the wall. The solution is to empty the box of thumbtacks, tack the box to the wall, and mount the candle in the box. Hence, the box must be thought of as a platform instead of as a container. Similarly, negative set – or *Einstellung* – occurs when a person rigidly continues to use one effective solution approach when a simpler (and also effective) approach is possible. For example, in a study by Luchins (1942), participants were given the task of measuring out a particular quantity of water using three jugs, each with a different capacity. In addition, the trials were sequenced so that the first five problems required a lengthier solution than problems encountered later (i.e., the 6th and the 10th problems). Luchins found that the majority of participants (80%) failed to notice the simpler solution for the latter problems when they had already used the lengthier solution.

How might working memory capacity be involved in problem-solving difficulties such as functional fixedness and negative set? One possibility stems from the view that working memory capacity represents the capability for controlled attention, which in our view is responsible for not only maintenance of information in a highly activated state, but also for suppression or inhibition of irrelevant or misleading information (see also Hasher & Zacks, 1988). For example, according to this view, functional fixedness might occur because of an inability to suppress retrieval of some salient feature of an object or concept, and *Einstellung* occurs because of an inability to suppress previously retrieved solutions. Indirectly, evidence also suggests that working memory capacity may be particularly critical when it is necessary to suppress a solution that has been retrieved many times in previous solution attempts. For example, Rosen and Engle (1997, 1998) found that participants high in working memory capacity were able to prevent retrieval of previously recalled items in a word fluency task, whereas participants with lower levels of working memory capacity were less able to do so and thus suffered from many more intrusions.

More generally, inhibitory functions of working memory capacity may be critical for what Frensch and Sternberg (1989a) termed *flexibility in thinking* – "the ability to change one's mode or direction of thinking as a function of changing task or situational constraints ..." (p. 163) – and may underlie differences in the extent to which people experience difficulties in problem solving. Of course, a prediction that follows naturally from this speculation is that people with high levels of working memory capacity should be less susceptible to problem-solving difficulties than those with lower levels of working memory capacity. This possibility has not yet been investigated, but Miller (1957) found a negative correlation between general intelligence and problem solving rigidity in the water jar problem, such that low ability participants exhibited greater *Einstellung* than high ability participants. Given the strong relationship between working memory capacity and fluid intelligence, an interesting question for future

research would be whether, and to what extent, working memory capacity predicts the incidence of *Einstellung*.

Adult Age and Problem-Solving Difficulties

Studies of adult aging provide additional evidence for the potential importance of working memory capacity in problem solving. Research on aging and cognition has established that working memory capacity decreases across the adult portion of the life span (see Salthouse, 1992a, 1996, for reviews). In addition, such decreases appear to be partly responsible for concomitant decreases in more complex aspects of cognition, such as text comprehension (e.g., Hultsch, Hertzog, & Dixon, 1990; Stine & Wingfield, 1990) and reasoning (e.g., Babcock, 1994; Bors & Forrin, 1995; Salthouse, 1992b). Finally, there is some evidence to suggest that older adults are more susceptible to problem-solving difficulties than are young adults. For example, using a task modeled after the Luchins (1942) water-jar paradigm, Heglin (1956) found that older adults were more prone to *Einstellung* than were young adults. Similarly, using a concept identification task, Rogers, Keyes, and Fuller (1976) found that older adults had difficulty shifting from one solution rule to another. The hypothesis that problem-solving difficulties in older adults are attributable to age-related decreases in working memory capacity, in general, and to the inability to inhibit previous solutions, in particular, has apparently not been tested. However, it seems plausible in light of the finding that older adults may be less effective than younger adults in inhibiting extraneous and no-longer-relevant information from the focus of attention (e.g., Hasher, Quig, & May, 1997; Hasher, Zacks & May, 1999; Zacks, Hasher, & Li, 2000).

Summary and Conclusion

Why do working memory tasks work? That is, what accounts for the predictive power of working memory tasks? Our answer to this question is that they capture a domain-general aspect of cognition corresponding to the capability for controlling attention. Nevertheless, the evidence for this claim presented thus far is indirect. For example, although the finding of a strong positive relationship between working memory capacity and fluid intelligence seems difficult to reconcile with the view that working memory tasks tap task-specific skills, the idea that controlled attention underlies this relationship is speculative. The research discussed in the next section provides more direct evidence for this idea.

WHEN IS WORKING MEMORY CAPACITY IMPORTANT?

Common observation suggests that although everyday tasks can often be performed with little effort and concentration, there are times when

maximal attention is demanded. For example, consider how difficult it is to read a scientific journal article while trying to ignore a distracting conversation, or while trying to avoid worrisome thoughts about an upcoming medical exam. Consistent with this type of everyday experience, an important tenet of our model of working memory is that working memory capacity should correlate with cognitive performance *only* when controlled processing is demanded because task-relevant information must be maintained in a highly activated state under conditions of distraction or interference, or because distracting information must be inhibited. An implication of this idea is that performance can proceed with little or no involvement of working memory capacity in the absence of these conditions. Consequently, working memory capacity is *not always* important, and hence should *not always* correlate positively with performance. Unlike the research described in the preceding section, this hypothesis has been investigated using elementary cognitive tasks in which factors thought to moderate involvement of working memory capacity can be controlled. Three such tasks are described next.

Dichotic Listening Task

People are often very effective in attending to one aspect of the environment while ignoring other aspects. For example, in a series of experiments by Cherry (1953), participants were instructed to repeat a message presented in one ear and to ignore a message presented in the other ear. Cherry found that participants had little difficulty performing this task. To illustrate, they did not notice when the language of the unattended message was changed from English to German. Nevertheless, Moray (1959) demonstrated that content from an unattended message is not rejected completely. In particular, Moray found that a substantial number of participants (33%) heard their name when it was presented in the unattended message. By contrast, very few participants could recall a word that was repeated 35 times in the unattended ear. Moray concluded that only information important to the subject (e.g., his or her name) can break the "attentional barrier" evident in the dichotic listening task.

But why did only 33% of Moray's (1959) participants hear their own names? Why not 100%? Conway, Cowan, and Bunting (2001) made the somewhat counterintuitive prediction that if one function of working memory capacity is to inhibit distracting information, then people with high levels of working memory capacity (high-span participants) would be *less* likely to notice their names in an unattended message than people with lower levels of working memory capacity (low-span participants). To test this prediction, Conway et al. replicated Moray's (1959) experiment with participants classified as either low or high in operation span. The results were exactly as predicted: 65% of low-span participants heard their names

in the unattended message, whereas only 20% of high-span participants did so. Furthermore, inconsistent with the argument that low-span participants adventitiously heard their names after letting attention drift to the unattended message, there were no span-related differences in shadowing errors immediately preceding or concurrent with name presentation. Conway et al. concluded that high-span participants were better able to inhibit information from the unattended message.

Antisaccade Task

Kane, Bleckley, Conway, and Engle (2001) investigated the effect of working memory capacity on control of attention using a visual-orienting paradigm that might be considered simpler than even the dichotic listening task. The goal of the "antisaccade task" is to detect onset of a visual cue and to use that cue to direct the eyes to a location that will contain a target stimulus. Once the target stimulus appears, a response is executed. In the Kane et al. experiment, both low-span and high-span participants performed the following version of this task. For each trial, a cue flashed on the screen, and then a target (the letter B, P, or R) appeared. The task was to press a key corresponding to the given target. There were two types of trial: In the antisaccade trials, the cue and the target always appeared in opposite locations on a monitor, whereas in the prosaccade trials, the cue and the target always appeared in the same location.

Kane et al. (2001) found that high-span participants were faster in target identification than low-span participants *only* in the antisaccade trials. Eye movement data revealed the source of this difference. Relative to high-span participants, low-span participants were more likely to make reflexive eye movements toward the cue (and hence away from the target). One possible interpretation of this finding is that high-span participants were better able to maintain activation of a task-relevant goal (e.g., *look away from cue*). Another possibility is that high-span participants were better able to inhibit the tendency to look toward the attention-attracting cue. Whatever the case, the results of the Kane et al. study suggest that individual differences in working memory capacity are related to the ability to control attention. This finding also reinforces the notion that the predictive power of working memory capacity seems to be limited to situations that place a high demand on control of attention.

WHEN IS WORKING MEMORY CAPACITY IMPORTANT? A BROADER PERSPECTIVE

We believe that the preceding results are consistent with a controlled attention view of working memory capacity. But how important is working memory capacity in the performance of everyday problem-solving tasks,

and does it contribute above and beyond other individual-difference characteristics? Consider, for example, the question of whether working memory capacity contributes to the prediction of cognitive performance above and beyond knowledge within a specific domain.

The Knowledge-Is-Power Hypothesis

Research on expertise leaves little doubt that domain knowledge is a potent predictor of success in cognitive domains. For example, Chase and Simon (1973) found that an expert chess player recalled more information from game positions than less skilled players. By contrast, there was no effect of chess skill on recall of random configurations of chess positions. Chase and Simon concluded that expertise in chess is predicated largely on a vast store of information about chessboard positions. The finding that domain knowledge facilitates memory for task-relevant information has since been replicated in numerous domains, including bridge (Charness, 1981), computer programming (Barfield, 1997), music (Meinz & Salthouse, 1998), dance (Allard & Starkes, 1991), and map reading (Gilhooly, Wood, Kinnear, & Green, 1988).

Of course, the facilitative effect of domain knowledge on cognitive performance is not limited to tasks involving episodic memory. For example, in a study by Voss, Greene, Post, and Penner (1983), three groups of participants (political scientists with expertise in Soviet affairs, chemists, and undergraduate students) were given a problem in which the goal was to increase crop productivity in the Soviet Union. The political scientists began by creating a representation of the problem using their knowledge about the history of low crop productivity in the Soviet Union. By contrast, the chemists and the undergraduate students proposed solutions without clear specification of the possible causes, and their solutions were both judged ineffective. Thus, what was important in problem-solving success was not general scientific training, but rather specialized knowledge.

But what about the *joint effects* of domain knowledge and working memory capacity on problem-solving performance? One possibility is suggested by a viewpoint often referred to as the *knowledge-is-power hypothesis.* The major idea of this viewpoint is that domain knowledge is the primary determinant of proficiency in cognitive domains, whereas capacity-limited aspects of the system play a less important role. Minsky and Papert (1974) alluded to this idea in the following passage:

> It is by no means obvious that very smart people are that way directly because of the superior power of their general methods – as compared with average people. Indirectly, perhaps, but that is another matter: a very intelligent person might be that way because of the specific

> local features of his knowledge-organizing knowledge rather than because of global qualities of his "thinking" which . . . might be little different from a child's. (p. 59)

In a similar vein, Feigenbaum (1989) articulated the basic argument of the knowledge-is-power hypothesis in a principle:

> The Knowledge Principle states that a system exhibits intelligent understanding and action at a high level of competence primarily because of the specific knowledge that it can bring to bear. . . . A corollary of the KP is that reasoning processes of intelligent systems are generally weak and not the primary source of power. (p. 179)

Most people would agree that domain knowledge is "power." Clearly, within the domain of expertise, people with high levels of domain knowledge tend to outperform people with lower levels of knowledge. However, it is less clear what the knowledge-is-power hypothesis implies about the *interplay* between cognitive ability characteristics such as working memory capacity and domain knowledge. Three hypotheses are illustrated in Panels A to C of Figure 6.4.

Compensation Hypothesis

The first hypothesis is illustrated in Figure 6.4 (Panel A) and is based on the idea that domain knowledge is not only power, but also reduces, and may even eliminate, the effect of working memory capacity. Stated somewhat differently, high levels of domain knowledge can "compensate" for low levels of working memory capacity. Consistent with this idea, Ackerman and Kyllonen (1991) stated, "There is a relationship between knowledge and working memory capacity such that having specific knowledge can replace having to exercise working memory" (p. 216). In a similar vein, Frensch and Sternberg (1989b) observed that

> beginners in any game seem to be relying on domain-general abilities, whereas experienced players utilize an extensive body of domain-relevant knowledge. One might expect, therefore, that measures of general intelligence would be related to novices' but not to experts' game playing ability. (p. 375)

Basic Mechanism Hypothesis

The second hypothesis is illustrated in Figure 6.4 (Panel B) and stems from the view that although domain knowledge is power, it is not *all-powerful.* Rather, working memory capacity is a basic mechanism underlying proficiency in cognitive domains and contributes to performance even at high levels of domain knowledge. For example, although it may be possible to overcome the limitations associated with working memory capacity in very specific situations, the limitations may reemerge in the domain

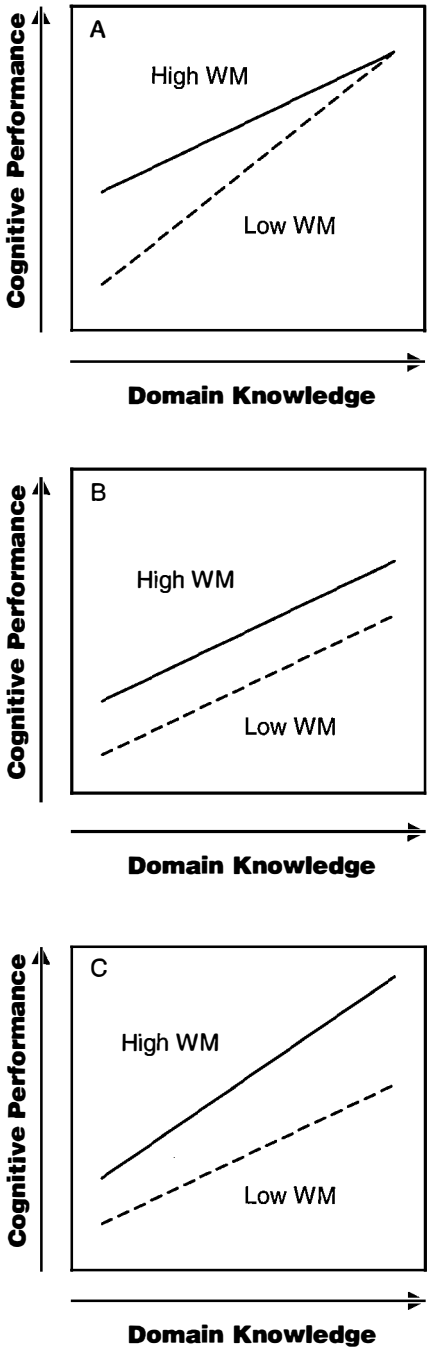


FIGURE 6.4. Possible effects of domain knowledge and working memory capacity on cognitive performance.

of expertise when the situation demands the maintenance of information in the highly active and accessible state under conditions of interference and/or distraction, or the suppression of interfering, competing, or irrelevant information.

Rich-Get-Richer Hypothesis

The third hypothesis concerning the interplay between domain knowledge and working memory capacity is illustrated in Figure 6.4 (Panel C). The basic argument of this model is that the "rich get richer" in the sense that the beneficial effect of domain knowledge on cognitive performance should be greater at high levels of working memory capacity than at lower levels. For example, to the extent that working memory capacity is related to the amount of information that can be maintained in a highly activated state during task performance, then people with high levels of working memory capacity may be able to draw on more domain knowledge than can those with lower levels. Furthermore, working memory capacity might be called on when a controlled search of long-term memory is necessary to determine which piece of preexisting domain knowledge is relevant to the current task or situation.

Relevant Evidence

Evidence concerning the predictions illustrated in Figure 6.4 is limited. For example, in studies of text comprehension, Haenggi and Perfetti (1992, 1994) found main effects of both domain knowledge and working memory capacity on measures of expository text comprehension. High levels of domain knowledge and high levels of working memory were associated with superior performance. Unfortunately, however, Haenggi and Perfetti did not evaluate the interaction between working memory capacity and domain knowledge. More recently, using structural equation modeling, Britton, Stimson, Stennett, and Gülgöz (1998) found that domain knowledge had a direct effect on expository text comprehension, whereas working memory did not. Britton et al. also did not evaluate the possibility of interactive effects of domain knowledge and working memory capacity.

Memory for Baseball Games

Recently, we conducted a study to better understand the joint effects of domain knowledge and working memory capacity on a task involving text comprehension and memory (Hambrick & Engle, 2002). The knowledge domain for this study was the game of baseball, and the criterion task involved listening to and then answering questions about simulated radio broadcasts of baseball games. The participants were 181 adults with wide ranges of working memory capacity and knowledge about baseball. The radio broadcasts were recorded by a baseball announcer for a local radio

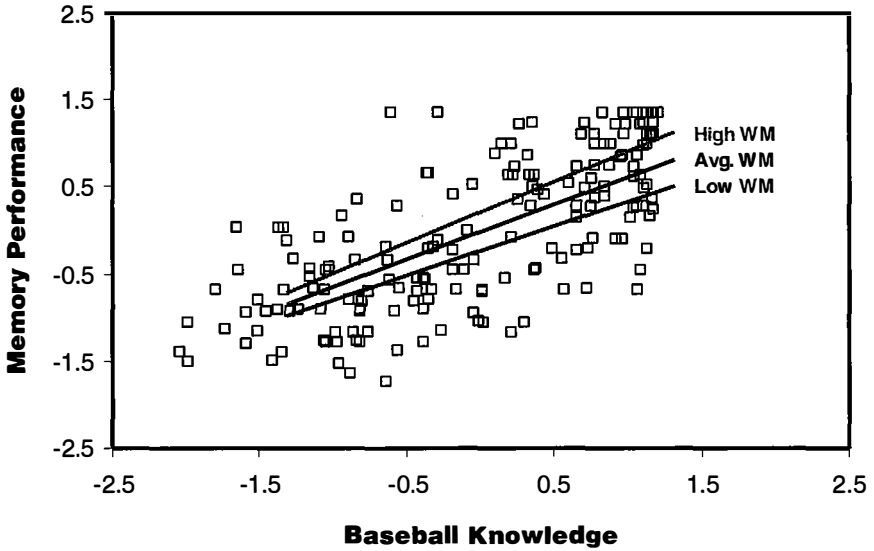


FIGURE 6.5. Effects of baseball knowledge and working memory capacity on memory for changes in game status. Values along the *x*-axis and the *y*-axis are *z* scores.

station and were realistic in presentation and content. (In fact, a number of participants mistook them for actual radio broadcasts of baseball games.) Baseball knowledge was assessed with paper-and-pencil tests, and working memory capacity was measured with tasks similar to those described earlier. Finally, memory for changes in the status of each game was evaluated after each broadcast. That is, participants answered questions about (a) which bases were occupied at the conclusion of each player's turn at bat and (b) the number of outs and number of runs scored during the inning.

For the analyses described next, composite variables were created for baseball knowledge, working memory capacity, and memory performance by averaging the *z* scores corresponding to each construct. Figure 6.5 depicts the effects of baseball knowledge and working memory capacity on memory for changes in game status. Perhaps the most striking feature of this figure is the magnitude of the knowledge effect. In fact, baseball knowledge accounted for over half of the reliable variance in memory performance (i.e., $R^2 = .56$). However, there was also a significant effect of working memory capacity above and beyond baseball knowledge (i.e., $R^2 = .06$). Furthermore, there was no evidence to suggest that baseball knowledge reduced, much less eliminated, the effect of working memory capacity on performance in this task. Therefore, although domain knowledge was clearly the most important predictor of performance, working memory capacity contributed as well.

Additional evidence concerning the interplay between domain knowledge and working memory capacity was reported by Wittmann and Süβ (1999). In an innovative series of studies, these researchers investigated the effects of domain knowledge and working memory capacity on performance in tasks designed to simulate complex work-related tasks. For example, in one task, the goal was to control the energy output of a coal-fired power plant by manipulating a number of variables (e.g., coal input). Another task involved managing the production of a garment manufacturing company. A consistent finding from this research was that task-specific knowledge (i.e., knowledge acquired during the simulations) was a strong predictor of final performance. However, Wittmann and Süβ also reported that working memory capacity was a significant predictor of performance above and beyond task-specific knowledge. Thus, both knowledge and working memory capacity contributed to performance differences in the simulated work tasks.

SUMMARY AND CONCLUSIONS

Baddeley and Hitch (1974) began their chapter by commenting on the dearth of evidence concerning the role of short-term memory in normal information processing. We end this chapter by asking whether the same can the same be said of working memory: After nearly three decades of research on working memory, have we made progress toward understanding the role of working memory in higher level cognition? The answer appears to be yes and no. First consider the "yes" part of the answer. There is a considerable amount of evidence concerning the role of working memory in comprehension and reasoning. For example, research suggests that the phonological loop and visuospatial sketchpad components of the Baddeley-Hitch model – or what we think of as maintenance of speech-based and imaginal information – play a limited, but not completely unimportant, role in tasks involving comprehension and reasoning. Moreover, the phonological loop may be especially important during reading or listening when sentences are long and complex, and the visuospatial sketchpad may be called on when comprehension depends on visualization. Furthermore, the central executive – or what we think of as working memory capacity – appears to be very important for certain tasks. That is, secondary tasks designed to tax the central executive usually result in a dramatic impairment in primary task performance, and working memory capacity predicts performance in various comprehension and reasoning tasks. The question of what accounts for this predictive relationship remains open, but our view is that the available evidence is consistent with the hypothesis that working memory capacity is a general information processing capability corresponding to controlled attention.

Now consider the "no" part of the answer. Very little is known about the role of working memory in tasks traditionally studied in research on problem solving. Nevertheless, we have both speculated about how working memory might contribute to performance in such tasks and pointed out directions for future research. For example, one way that the phonological loop (or maintenance of speech-based information) may play an important role in tasks such as the Tower of Hanoi is through comprehension of the instructions for the task. Furthermore, our theoretical view of working memory suggests that central executive functioning (or working memory capacity) should play a particularly important role in problem solving. To illustrate, one of the primary functions of working memory capacity is to maintain memory representations in a highly activated and accessible state. This function may be important when impasses in problem solving can be overcome by drawing together information from multiple problem-solving attempts. In addition, the ability to inhibit information from the focus of attention may be critical when one must shift from one way of solving a problem to another. Finally, research by Wittmann and Süß (1999) suggests that working memory capacity contributes to performance in complex problem-solving tasks even when the effect of domain knowledge is taken into account. We believe that additional research concerning the interplay between domain knowledge and working memory capacity will prove particularly informative about the importance of working memory capacity in problem solving.

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