

An Invitation to Cognitive Science

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Chapter 7

Working Memory and Thinking

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In all its various forms, thinking recruits a complex set of mental processes. These processes differ, of course, depending on what sort of thinking is involved. Trying to decide whether two objects belong to the same category involves mental operations different from those which are critical to working out the solution to a problem in chess. The former may depend on judging the similarity of the objects to each other and the similarity of each to some mental representation of the category in question (see chapter 1). By contrast, solving a chess problem may rely on assessing the difference between your current board position and your desired board position, in the light of what you know about the rules of chess and the likely outcomes of various moves (see chapter 8 for more on problem-solving strategies). As different as these examples seem on the face of it, they nonetheless illustrate that there is an important role for memory in thinking, whether it involves categorization, problem solving, deduction, or whatever. You wouldn't be able to decide whether an object belonged in some category unless you had stored some representation of that category in memory. Likewise, you wouldn't be able to make a decision about a move in chess unless you had stored at least the rules of chess. In fact, memory comes into play in thinking in even subtler ways than these. To see this extensive influence, let us examine three quite different cases of human reasoning to illustrate not only the critical role of memory in many complex cognitive tasks, but also the varied forms of memory that are required.

7.1 Thinking and Memory

7.1.1 Raven Progressive Matrices

Anyone reading this chapter has taken one or more tests of basic cognitive skills, such as an IQ test. One of the most demanding of these is the Raven

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the box and to determine what figure should fall in the missing box at the bottom right of the matrix in order to fit properly within the matrix. The instructions tell test takers to examine the figures in the matrix to determine what rules govern the orderliness of figures along the rows and columns, and then to use the rules they have determined to pick the missing entry. Before reading on, try to solve the problem in figure 7.1.

Here is one line of reasoning that will yield a solution to this problem. Notice that each of the top two rows contains three geometric forms. In the top row, they are a diamond, a square, and a triangle, reading from left to right. In the second row they are a square, a triangle, and a diamond. The third row has two of these figures, a triangle, and a diamond. And so, if this row is to follow the same rule as the top two, the final item must contain a square. Notice also that the top row has a bar through each of the figures in the same orientation in each. In the left figure it is solid, in the middle one it is striped, and in the right one it is clear. Likewise, the second row shows three parallel bars, in the order clear, solid, and striped. To follow the same rule, the last row must also have three bars in the same orientation, with the first striped, the second clear, and the third solid. Thus the figure required to complete the matrix must be a square with a solid diagonal bar through it; this is alternative 5 among the choices.

You can see from this example that the Raven test is not trivial in its cognitive demands (the actual test has yet more difficult problems). Carpenter, Just, and Shell (1990) proposed an analysis of the test that includes component processes required to complete it successfully. For example, one component process involves identifying the elements in each cell of the matrix that correspond to each other. In figure 7.1, this identification amounts to noticing that the three bars, for example, are the critical figures to compare with respect to one another in each row, and likewise that the three geometric forms are the relevant figures to compare. Carpenter et al. (1990) found that a component critical to successful performance was ability to keep track of the characteristics of figures in each problem and of the rules that had been tentatively determined. Introspection about the problem in figure 7.1 reveals this relation also. Solving the problem requires storing the rule about variation in the shape of figures at the same time as one is working through the variation in the shading of the bars.

What is meant by "keeping track" in this analysis? Clearly, we need a memory that will store partial information about figures and rules for a brief period while still allowing computation of the remaining information needed to solve the problem. We shall call this "working memory," in keeping with current cognitive literature. Carpenter et al. (1990) used this concept of working memory in developing computational models to account for performance in the Raven test. Their computer models included a working memory component in which information from figures is stored

Progressive Matrices Test, an instrument that is used to measure problem-solving and reasoning skills in the face of novel information (Raven 1962). The Raven test is especially interesting because it is impressively correlated with measures of achievement, and it correlates well with a host of other basic tests of intelligence.

The test itself is best understood by considering an example problem, such as that shown in figure 7.1 (from Carpenter, Just, and Shell 1990). Test takers are given a problem like the one in the box at the top of the figure together with eight alternative answers shown at the bottom of the figure. Their task is to examine the 3×3 matrix of geometric forms in

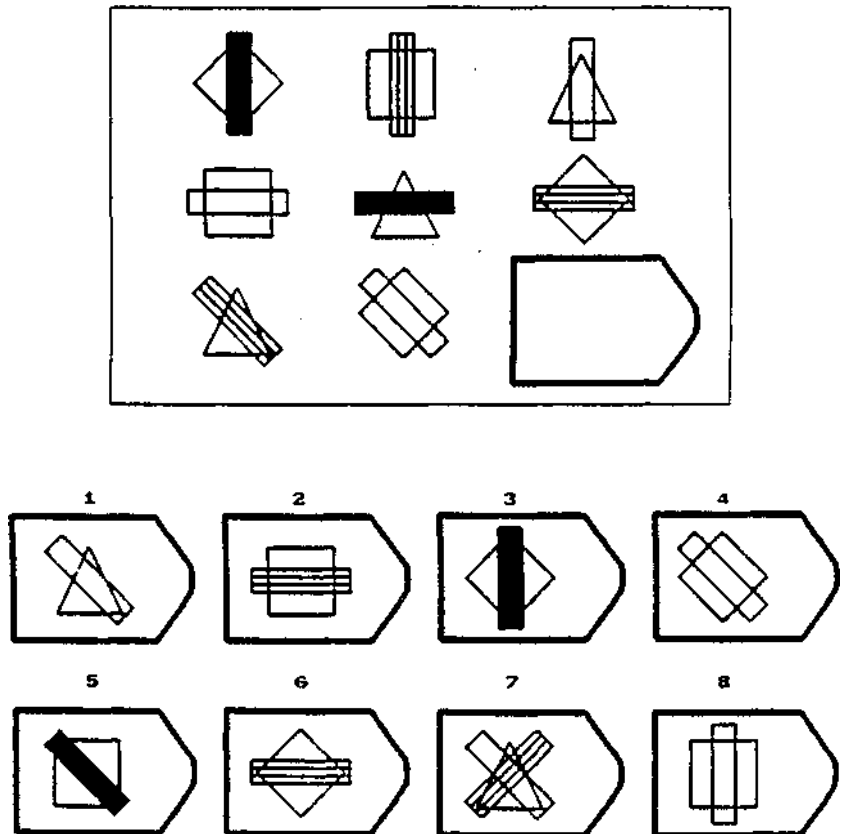


Figure 7.1

An example of a problem that is similar to ones on the Raven Progressive Matrices Test. This problem is not on the actual test, to preserve the test's security. As described in the text, the goal is to choose one of the eight alternatives that best fits in the missing cell to complete the matrix (from Carpenter et al. 1990, fig. 2, 107).

and used as the basis of further computations about a problem. In fact, Carpenter et al. (1990) argued that much of the variation in problem difficulty, and in differences among people in solving a particular Raven problem, is due to differences in working memory ability.

Success in solving Raven problems involves a very different type of memory as well, which is called long-term memory. This is the memory that allows the problem solver to comprehend the instruction that attention to row and column regularities is what is needed to be successful. To comprehend this instruction, the test taker must rely on his or her knowledge of what a row and a column is, and what it means to compare one figure to another. You may take this memory for granted because it seems so natural and automatic, but long-term knowledge on the part of the problem solver is clearly a necessary condition for any skillful problem-solving performance. The present discussion of memory will not concentrate on the long-term system largely because it is not the major source of variation in skilled performance in problems like those due to Raven. That is, differences between one person and another in Raven performance are not due largely to differences in ability to comprehend the instructions and to understand the concept of comparison. Likewise, differences in performance within an individual between one problem and another are not due to the long-term memory demands of the task. Rather, these differences are mainly a function of our ability to juggle the information at hand in each individual problem. This is not to say that long-term memory is unimportant in thinking. Indeed, there would be no thinking without it. For the present, though, what is of most interest is identifying the nature of working memory that seems to be at the heart both of differences among individuals in thinking and of differences among thinking activities that are difficult versus those that are relatively easy.

7.1.2 Thinking About Spatial Relations

Let us now examine a second case in which working memory plays a role in human reasoning. There are many times in normal life when we need to reason about spatial relations. For example, giving directions from one place to another or working out a travel route are tasks in which there is direct need to manipulate spatial information in the service of solving a problem. The study of spatial reasoning has taken many forms in the psychological literature, but one form especially highlights the role of memory. The task in question is one in which a respondent has to solve a problem that requires working out the spatial relations among various elements. Consider this problem, for example (after Byrne and Johnson-Laird 1989):

A is on the right of B
 C is on the left of B
 D is in front of C
 E is in front of B

Where is D with respect to E?

There are a number of ways to solve problems like this one, and, indeed, people may adopt different strategies depending on one factor or another. One strategy seems to appear quite often, however, and it makes use of an internal representation of both the elements and the spatial relations in a kind of image that is presumably stored in working memory. For the problem above, you might have created an image that looked something like this:

C	B	A
D	E	

This representation could then be used to answer the question in the problem by reading off the inference that D must be to the left of E.

The evidence that people at least sometimes solve spatial problems in this way is compelling. For example, the farther two terms are from each other in the image, the easier it is to judge their relative spatial locations, just as it would be easier to judge the spatial relations between two objects if they were clearly separated in the visual field (for example, it would be easier to make a judgment about the relation between A and C than between B and C; see Potts 1974 and Scholz and Potts 1974 for discussion). Another effect is illustrated by this problem:

B is on the right of A
 C is on the left of B
 D is in front of C
 E is in front of B

Where is D with respect to E?

Using the same sort of layout as in the first problem, we might represent this problem in working memory as follows:

C	A	B
D		E

This representation allows us to answer that D is to the left of E. But notice that this is not the only representation that is possible. The following also properly follows from the stated premises:

A	C	B
	D	E

Notice that in either case, we can conclude that D is to the left of E. But also notice that we have to consult two internal representations in order to conclude this. The complication here is that more work needs to be done internally to represent both versions of the second problem than to represent the single version of the first problem. The additional work is due to both the processes required to create the representations and the memory required to store and retrieve them. Indeed, the evidence is that problems of the second sort are solved less accurately than problems of the first sort, presumably due to the extra work required and to the possibility of error that may come about with that extra work (Byrne and Johnson-Laird 1989).

If you compare your introspections in solving spatial problems of this sort to those in solving Raven problems, you may come to the conclusion that something quite similar is involved. In both cases, there seems to be a working-memory system that is being taxed both to store information for a brief time and to operate on this information in a way that will yield a problem solution. Before turning to the details of this system, let us consider yet one more example to see how broadly working memory is involved in cognition.

7.1.3 Mental Arithmetic

Try this mental addition problem and think about the strategy you use to solve it. Read the problem and then look away as you solve it:

$$\begin{array}{r} 434 \\ +87 \\ \hline \end{array}$$

Most people report a strategy that involves stages of calculation (Hitch 1978). One common strategy is to divide the problem into parts, adding the units digits, followed by the tens digits, followed by the hundreds digits. Notice that for a strategy like this to be effective, a memory system that can hold various pieces of information must be involved. For example, in this problem you have to store the entire problem, pick out the units digits (4 and 7), store the sum of these, retrieve the tens digits (3 and 8), retrieve the fact that a 1 has to be carried from the units digits, and so on. Obviously, a memory is required for the numerical material and partial results, and a computational mechanism is required to carry out the arithmetic in an orderly way. The memory component, furthermore, is a fragile one. If you had used the units-tens-hundreds strategy that is fairly common for this problem but had been constrained to write your answer from left to right rather than from right to left, you would have made more errors in writing the units part of your answer (Hitch 1978).

task (Hitch 1978). It is presented in figure 7.2. According to this flow model, the presentation of a mental addition problem causes representations to be created in both long-term memory and working memory. Long-term memory supplies the knowledge, strategies, and skills that are needed to execute a solution. The actual computation is done by an executive processor, making use of partial information stored in a working-memory buffer. The partial results are also stored in the buffer awaiting a response when the entire problem is complete (or one digit at a time, if you are permitted to give your response in that way).

Let's step back from the details of this model and consider its general implications. The important features of this model for the present are three: First, it includes two very different types of memory systems. Second, it shows that interactions among these systems are the driving force of thinking processes. And third, the working-memory system itself is more than just a memory; it includes processing capability as well. Before exploring the characteristics of the working-memory component in this model in more detail, let us briefly consider the two types of memory that are implied by this model.

7.2 Working Memory and Long-Term Memory

What is clear from the study of mental arithmetic, spatial reasoning, and performance on the Raven test is this: Thinking requires memory. It is also compelling that the type of memory required is not unitary in character. There is need for both a long-term memory system that holds knowledge and skills and a working-memory system that can hold information briefly for present purposes. Introspection tells us this. But there is more than introspection that we can use to justify thinking of memory as having a dual character. Various sorts of other evidence also indicate that there is a dissociation between long-term memory and working memory.

7.2.1 Neurobiological Evidence About Long-Term and Working Memory

Perhaps the most convincing evidence pointing to the existence of more than one memory system comes from studies of patients who have suffered brain injury that has a detrimental effect on their memory—patients who suffer from amnesia. Amnesia is itself not a unitary phenomenon, and, in fact, two quite different forms are relevant to the dissociation of long-term and working memory.

Consider first a phenomenon called anterograde amnesia. This type can be caused by a variety of brain insults. Perhaps the most famous case of anterograde amnesia is a patient whose initials are H. M., studied in detail

by Milner and her colleagues (for example, Milner, Corkin, and Teuber 1968). This patient underwent surgery in 1953 to remove the hippocampus bilaterally; this was an extreme measure to alleviate intractable epileptic seizures. The surgery was successful in relieving H. M. of his seizures, but the unexpected side effect was quite devastating cognitively: H. M. was rendered largely unable to learn any new information after his surgery. This is the hallmark of anterograde amnesia, the inability to learn new information. By contrast, H. M. was perfectly able to recall information that he had learned prior to his surgery: He knew facts of his life prior to surgery (such as events from his school days), he had preserved language skills, he recognized people whom he had known before the operation, and so on. He could not, however, identify people whom he met after the surgery, even after repeated meetings with the same people. And even very salient events that occurred after his trauma, such as the hospitalization of his mother for surgery, were ones that H. M. could not remember, even on the same day they occurred. He was only dimly aware of the sudden death of his father, or of the job that he was doing at a new place of employment, even after working at it for six months. (Interestingly, H. M. and other anterograde amnesics have relatively spared memory for motor skills, classical conditioning, and other tasks that do not require explicit retrieval of information for successful performance.) By contrast to these startling memory deficits in long-term acquisition, H. M. has a normally functioning working memory. For example, his performance on the digit span test (memory for a series of random digits that is read to the subject) is close to that of normal subjects. This performance is true of other anterograde amnesics who have been studied as well, ones whose amnesia was the result of disease such as Korsakoff's syndrome or Alzheimer's disease. The dissociation between the inability to learn new information that is remembered for long periods and the normal ability to remember new information for brief periods supports the distinction between long-term and working memory.

This distinction is also supported by examining cases of amnesia for working, but not long-term memory. One such case, a patient with the initials K. F., who suffered a closed head injury, has been studied in great detail by Elizabeth Warrington and her colleagues (for example, Warrington and Shallice 1969). K. F.'s deficit was first recorded by Warrington while administering him the Wechsler Adult Intelligence Scale, which has a number of subtests that tap various cognitive skills. K. F. performed quite normally on most of the subtests except for a test of digit span. On this test, K. F.'s digit span was only 1 item, far inferior to the normal digit span of 7 or so items. Succeeding tests of K. F. revealed that his deficit on working-memory tasks extended well beyond memory for digits; he was consistently below average on all tests of working memory, as are a

middle. These are called "primacy" and "recency" effects respectively, indicating that the first and last parts of a list enjoy better retrieval than the middle. Why? One influential theory about this result is that recall at the two ends of the list is drawn from two memory systems. Items at the end, being most recent in their presentation, are still stored temporarily in a working store. Items at the beginning, however, have had time to be coded into a more lasting representation in a long-term store. This theory is supported by several lines of evidence. For example, if you simply observe subjects as they are engaged in a free-recall task, immediately after presentation of a list they typically begin their recall with the last items, as if they need to get these out before they are forgotten. This sequence is just what one would expect if these items are stored in a fragile working memory.

More evidence comes from experiments that systematically manipulated variables having different effects on the long-term and working memories. Postman and Phillips (1965) conducted one such set of experiments. They either allowed subjects to begin their recall directly after a list had been presented, or they enforced a delay before recall by requiring subjects to count backward for a 30-second interval. When there was no delay between list presentation and recall, there was a substantial recency effect. That is, items at the end of the list were recalled with higher probability than items in the middle; but this was not the result when a delay was enforced between presentation and recall. This is as it should be if the end of the list is stored in working memory; when items reside there too long, as in the delay condition, they are forgotten. Delay has essentially no effect on recall of the early part of a list, though.

By contrast, Glanzer and Cunitz (1966) have demonstrated that it is possible to influence the primacy effect without touching the recency effect. In their experiment, they presented 20-word lists to subjects at either a fast or a slow rate. They found that the slow rate improved the primacy and middle portions of the serial position curve but had little or no effect on the recency portion. This result is consistent with the claim that items in the primacy and middle portions have been coded into a long-term representation, but those at the end of the list have not had this opportunity. A slower rate of presentation provides subjects greater opportunity to engage in long-term coding and results in a higher accuracy rate.

Notice that the pattern of behavioral evidence just reviewed constitutes another double dissociation, similar to the one that was suggested by examining patients with amnesias. The double dissociation comes about because different behavioral variables have different effects on the serial position curve. One affects the recency portion of the curve but leaves the primacy portion intact. The other affects the primacy portion but leaves

number of other patients who have been studied. Yet even in the face of their severe deficits in working-memory tasks, these patients have a quite normal level of performance on tasks that involve long-term memory. For example, they can recall a short story, learn word lists when the lists are presented repeatedly, and perform quite well on long-term recognition tests for lengthy lists of items.

Let us summarize, then, what we know from patients who have amnesic symptoms. On the one hand, there are patients such as H. M. who suffer from inability to place new information into long-term memory in a way that will allow later retrieval, yet have reasonably normal working-memory performance. On the other hand, we have patients such as K. F. who have severely impaired working-memory performance, but can engage in long-term memory tasks with little difficulty. This pattern of results presents us with what is known as a "double dissociation."

To understand the implication of a double dissociation for a theory of memory, consider the following line of reasoning. Suppose there are two memory systems, one responsible for the long-term retention of information and one responsible for the retention of information for a short period. If these two systems are separate in their function and in their representation in the brain, then it may be possible to find a person with a brain injury that insulted the long-term system, but not working memory, and likewise a patient who suffered injury to the working-memory system, but not the long-term one. This pattern of results is what constitutes a double dissociation when it comes to the study of brain injury and its effect on cognition. Thus, the two patients cited above, H. M. and K. F., constitute a double dissociation for working and long-term memory. The fact that patients exist who show the symptoms that they do lends credence to the theoretical notion that memory consists of at least two components. Notice in passing that more components may be involved than just two. For example, the working-memory system may itself be composed of separable subsystems. Establishing this composition, however, would require yet more double dissociations, in this case between, say, two types of working-memory disturbance. This issue is elaborated below.

7.2.2 Behavioral Evidence About Long-Term and Working Memory

Neuropsychological evidence is not the only means to dissociate working from long-term memory. It is supplemented by evidence of a purely behavioral nature. Suppose, for example, that people are given a list of 30 nouns to memorize and recall in any order. The probability of recall will not be uniform as a function of the position of an item in the list (for example, Deese and Kaufman 1957). Rather, items at the beginning and end of the list have a higher probability

the recency portion intact. This pattern suggests that two different mechanisms are at work in determining the shape of the serial position curve. One interpretation is that these two mechanisms are two memory systems, one responsible for working-memory retention and the other for long-term retention.

The weight of evidence such as we have just reviewed indicates a distinction between working and long-term memory. (Even more recent evidence suggests that long-term memory may itself be composed of more than one system: for example, Squire 1992, Schacter, Chiu, and Ochsner 1993.) Let us concentrate now on the features of the working-memory system that is suggested by this analysis and on its role in thinking.

Reflect on the Raven, mental-arithmetic, and spatial-reasoning tasks with which this chapter begins. In all three of these tasks, it seemed introspectively compelling that working memory was required for successful performance. In the Raven problems, this memory is needed to remember hypotheses about critical features that might describe any row or column. In mental arithmetic, working memory is necessary to store the problem at hand and intermediate solutions. In spatial reasoning, working memory is needed to store the spatial relationships that are specified, so that new ones can be deduced. These introspections are real and valuable in leading to the conclusion that working memory is an integral part of thinking. But there is more than this as well. Evidence comes from two behavioral sources about the involvement of working memory in thinking, the study of individual differences and the study of interference effects. Examining these two sources of evidence implicates working memory in various thinking tasks and possibly in language comprehension as well.

7.3 Working Memory in Thinking

People differ in their thinking skills, sometimes dramatically. The causes of these individual differences are undoubtedly many. One factor that has been implicated repeatedly is differences in working memory.

Consider first one of the model tasks described above, the Raven test. The test is designed, as are all tests of basic cognitive skills, to reveal differences among individuals. What is required in this test is an extensive program of managing information in working memory about attributes and about rules that relate these attributes to the figures, which Carpenter et al. (1990) call goal and subgoal management. This is what taxes working memory in these problems. If success on Raven's problems comes about because of success in goal and subgoal management, then the same subjects who do well on Raven's problems should do well on other problems of the same sort.

Carpenter et al. (1990) compared the performance of subjects on Raven's problems and on another problem that involves extensive subgoal management, called the Tower of Hanoi (see chapter 9 for more about this problem). In this problem, subjects are presented three pegs, with three disks of different sizes stacked on one of the pegs, the smallest on the top and the largest on the bottom. The task is to move the pyramid of disks from the source peg to a goal peg, one disk at a time, never stacking a larger disk on a smaller one. The third peg can be used to solve the problem. Extensive research with this task shows that a frequent strategy is to set up goals of disk movement in working memory that are nested within one another. For example, you might set the goal of moving the largest disk from the source peg to the goal peg. This sequence requires first moving the two disks above it, which in turn can be analyzed as a problem in moving the larger of these to a goal peg, and so on. It is easy to see that creating and managing subgoals is the hallmark of this strategy. Thus, it is of interest that performance on the Tower of Hanoi problem correlates highly with performance on the Raven test ($r = .77$: Carpenter et al. 1990), suggesting that the two tests recruit the same sorts of processes in working memory.

The claim that working memory is involved in performance of Raven's problems is confirmed by the study of adult age-related differences in Raven's test scores and age-related differences in working memory. Salthouse (1992) reviewed a number of studies of age differences in performance on Raven's test, finding that the correlation of Raven's score and age averaged $r = -.61$ among adults. That is, as age increased among adults, Raven's score decreased. Why? One possibility suggested by analyzing the working-memory requirements of Raven's test is that older adults are impaired in their use of working memory compared to younger adults. Indeed, evidence from a wide range of tests supports this general assertion (see Salthouse 1990, for a review of relevant evidence). Furthermore, it is well established that there is a strong relationship between several measures of working memory and performance on Raven's test (Larson, Merritt, and Williams 1988, Larson and Saccuzzo 1989, Salthouse 1993). Perhaps most telling, however, is the evidence that Salthouse (1993) presents showing that when variation in working memory performance is statistically controlled (by multiple regression), the correlation between Raven's performance and age essentially disappears. This result confirms that working memory plays a leading role in producing variation among people in Raven's performance, hence it is reasonable to conclude that working memory is an important component in successfully solving Raven's problems.

The study of individual differences in reasoning allows us to extend our

lems orally (versus visually) depressed accuracy in solving the problems. Oral presentation requires one to store the premises and the computations on these premises as the problems are solved, but visual presentation allows the problem to be always at hand, making the working-memory requirement relatively lighter. The second result of interest is that a secondary task in which subjects were required to generate numbers from the set 1-5 in random order reliably decreased accuracy in the reasoning task, whereas simply repeating the numbers 1-5 over and over again did not. Randomly generating numbers is a task that places heavy demands on working memory. To generate a string that appears random, one must store the previously generated numbers and compare the present candidate against that string to see if it conforms to a seemingly random pattern. By contrast, repeating a fixed string over and over again does not impose much of a memory burden on the subject. Random generation is a task that engages executive processes that are part of working memory, leaving them relatively less available to work on the syllogistic-reasoning problems.

To summarize, the weight of evidence from studies of individual differences, from effects of competing tasks, from computational studies of reasoning performance, and from our own introspections leads to the conclusion that working memory plays an important role in a variety of reasoning tasks. Were this the only role of working memory in thought it would be significant. However, there is evidence that working memory is involved in language comprehension as well.

7.4 Working Memory in Language Comprehension

In his insightful 1908 book, *The Psychology and Pedagogy of Reading*, Huey recognized that working memory must be recruited in the service of language comprehension. His hypothesis, as indicated in the following quotation, was that working memory (which he and others at that time called "primary memory") was required to store words early in a sentence so that later words could be integrated with them to form a coherent meaning:

The initial subvocalization seems to help hold the word in consciousness until enough others are given to combine with it in touching off the unitary utterance of the sentence which they form___It is of the greatest service to the reader or listener that at each moment a considerable amount of what is being read should hang suspended in the primary memory of the inner speech. It is doubtless true that without something of this there could be no comprehension of speech at all.

confines of Raven's task. It seems clear that performance on a number of reasoning tasks relies to a significant extent on working-memory skill (see, for example, Carpenter et al. 1990). Kyllonen and Christal (1990) present an argument that this relationship may be mediated by speed of processing. That is, success in tasks that rely on working memory may depend on how quickly subjects can process the information involved in the task. Perhaps this is because the faster the processing, the less likely it is that the material in working memory will be forgotten. Indeed, Salthouse (1992) has shown that the differences among adults of different ages in working-memory ability may be due in large part to differences in processing speed.

One natural implication of these studies of individual differences in reasoning is that interfering with working memory in an individual should interfere with that individual's ability to reason and solve problems. This is a sound inference, but difficult to test. The problem is this: Many tasks will interfere not only with working memory, but with other psychological processes required in reasoning as well. Suppose, for example, that we had a subject write her answers to some problem with her nondominant hand. This would surely lengthen problem-solving time, but probably not because we had interfered with working-memory capacity.

Gilhooly, Logie, Wetherick, and Wynn (1993) provide one example of careful application of the logic of interference. In their study, the task of interest was syllogistic reasoning. Syllogisms are deductive-reasoning problems that involve presenting two premises that are presumed true, from which a valid conclusion may follow (see chapter 9 for more on these problems). A simple example is:

All A's are B's
All B's are C's
Therefore ...?

It is not hard to see that one can properly conclude that all A's are C's. Syllogisms vary a good deal in how easily a conclusion can be drawn from the premises. Consider this example:

Some B's are not A's
All B's are C's
Therefore ...?

A proper conclusion is that "Some C's are not A's"; however, reaching this conclusion takes some work. Indeed, Johnson-Laird and Bara (1984) found that a sample of subjects nearly all successfully solved the first of these two examples, whereas none solved the second.

Two pieces of evidence from the study by Gilhooly et al. (1993) implicate working memory in syllogistic reasoning. One is that presenting prob-

If working memory is involved in language comprehension, as Huey suspected, there could be two functions it would serve. First, it might store partial information about an utterance or a piece of printed text while the remainder of that utterance or text was encoded. Second, comprehension processes might work with the information being temporarily stored to produce a coherent meaning for an entire utterance or a piece of text. Huey's assertions about the role of working memory come alive when one tries to comprehend this sentence from a study by Daneman and Carpenter (1983):

There is a sewer near our home who makes terrific suits.

The beginning of the sentence appears to be about the network of pipes and the like that collect water from a street. However, a reinterpretation is necessitated by the balance of the sentence. Huey's argument is that comprehending this sentence requires interpreting the words as they are read and storing them as well, so that a proper *reinterpretation* of them can occur as necessary. There is evidence from several sources which confirms Huey's view of language comprehension but which also shows the boundary conditions within which working memory may play a role.

One implication of Huey's view is that people with better working memories should be better at language comprehension. This implication was evaluated in a line of research by Daneman and Carpenter (1980, 1983). They developed a measure of working memory that includes its capacity to store information for brief periods and to perform computations on that information. The measure is quite simple: They presented subjects with a sequence of sentences, after which the subjects had to recall the last word in each sentence. This task requires both storage of the words and comprehension of the meanings of the sentences because subjects were queried about the meanings. "Working memory span" was defined as the number of sentence-final words that subjects could recall correctly as the number of sentences was increased from two to six. In different tests with this measure, Daneman and Carpenter (1980) found that it correlated with a separate test of reading comprehension from $r = .72$ to $r = .90$. Lest you worry that the high correlations come about because the working-memory span and the reading-comprehension tests both involve a comprehension component, Turner and Engle (1989) confirmed the finding with a working-memory measure that included solving arithmetic problems (rather than reading sentences) coupled with storage of a set of words for later recall. The correlations between working-memory span and comprehension are bolstered by the demonstration that subjects with relatively small working-memory spans are worse at interpreting sentences such as the one above about the "sewer" than subjects with relatively large spans. (Daneman and Carpenter, 1983, p. 101)

Individual differences in comprehension are not the only reason to think that working memory may play a role in language comprehension. A very different line of evidence from Hardyck and Petrinovich (1970) shows that suppressing working memory causes a reduction in the comprehension of text that is relatively difficult to comprehend under ordinary circumstances, but not text that is easy to understand. Thus, it may be that working memory is engaged when significant effort is required for language comprehension to be successful. One might think of such instances as problem-solving episodes, times when the seemingly automatic processes of language comprehension are not sufficient to analyze a linguistic construction; rather, other processes, such as those of working memory, must be engaged as well.

What of subjects who have pathologically deficient working memories? A direct implication of the work with normal individuals is that such patients should be substantially worse at language comprehension due to their inability to use working memory as effectively. The evidence on this issue is mixed. On the one hand, there are patients such as P. V., described by Vallar and Baddeley (1984, 1987). P. V. is a right-handed woman who at age twenty-three had a stroke that caused extensive damage to the left hemisphere of her brain. One of P. V.'s presenting symptoms was a severely reduced memory span, much like the patient K. F., discussed in section 7.2.1 above. P. V. also showed difficulty in interpreting sentences with complex syntactic constructions, even though she had little difficulty comprehending either short or long simple sentences. This and similar evidence has led to the hypothesis that working memory is involved in sentence comprehension, but only when sentence structure is sufficiently complex that many words have to be held in memory while the remainder of the sentence is perceived.

This hypothesis has been called into question, however, by contrary evidence from other patients who also show working-memory deficits, but who do not show significant sentence-comprehension difficulties. One such patient is E. A., a woman who has a recorded memory span of just two items. Even with this limited working-memory ability, E. A. appears to be quite close to normal in her comprehension of sentences that have complex relative-clause structures (Martin 1993). Moreover, E. A. is not the only such patient with reduced working memory but nearly normal language comprehension; others have been documented (see, for example, Waters, Caplan, and Hildebrandt 1991).

The resolution of whether pathology in working memory produces deficits in comprehension is not yet at hand. It may be that the discrepant results from different patients will be resolved by finer-grained analyses of the deficits that each patient has and of the locus of each patient's lesions. Perhaps, for example, patients who show both deficient working memory

of simple sentences, a working-memory requirement did not seem to intrude much on this language-comprehension task.

These data tell us that comprehension of relatively simple linguistic constructions is not mediated by a significant involvement of working memory. As discussed above, however, when sentence constructions become more complex, working memory may play a more significant role in comprehension.

There has been a common theme in all the studies implicating working memory in thinking, whether in explicit problem solving or in comprehension of language. In all the cases we have considered, information must be stored for a brief period while processes operate on this information for purposes of the task at hand. This implies that a comprehensive theory of working memory must distinguish storage from processing components. A major theory of this sort is due to Alan Baddeley and his colleagues. We consider it next.

7.5 A Working-Memory Theory

Recognizing that a proper theory of working memory must include both storage and processing components, Alan Baddeley and colleagues (1986, 1992, Baddeley and Hitch 1974) developed a view of the working-memory system that is schematized in figure 7.3. The major feature of this view is that working memory consists of a central executive that is responsible for computational operations on information and for scheduling the allocation of attention to various tasks at hand. Acting in the service of this central executive are two storage devices, called the phonological loop and the visuospatial buffer. The first of these is responsible for storing information that is speechlike in form, and the second is responsible for storing visual information. Of course, Baddeley's list of storage devices is incomplete. It does not include a facility, for example, for nonlinguistic auditory information (for example, the sound of a passing truck). Also, the two buffers, tied as they are to speech and visuospatial codes, are not assumed to store information about the meaningful or propositional content of the speech or visual information in question. Thus, for example, the phonological loop

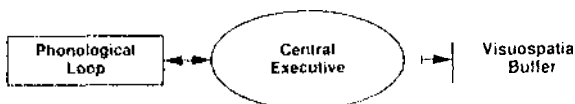


Figure 7.3

The working-memory theory of Baddeley (1986, 1992). The theory has two major components: a central executive and two buffer systems that serve the executive.

and deficient comprehension are ones whose brain injury has damaged not only the storage component of working memory but also the processing component. Patients who show deficient working memory with little deficiency in language comprehension may be ones with deficits in only a storage component. Because the jury is still out on the data from patients with working-memory pathologies, one must be cautious in interpreting these results. Nevertheless, the evidence certainly suggests some sort of link between working memory and verbal comprehension.

Even if there *is* such a link, however, it has boundaries. Perhaps the most obvious is that it does not apply to the comprehension of relatively simple language constructions. This has been demonstrated in a variety of contexts. As one illustration, Baddeley and his colleagues have shown that comprehension of relatively simple sentences is not interfered with by a secondary task that taxes working memory significantly. For example, in one experiment subjects had to judge the truth or falsehood of sentences such as: "Canaries have wings" or "Cats have gills" (Baddeley 1986). Subjects had to make judgments of this sort while they stored from zero to eight random digits in memory. The experiment was designed to maximize interference between the two tasks because subjects were first given the digits to store, then they were presented a sentence about which they had to make a judgment, and finally they had to recall the digits that had been presented. What is remarkable about performance in this experiment is that judging whether the sentences were true or false was affected only modestly by the number of digits that subjects stored.

Another example comes from a bit more demanding language-comprehension task. This is a study by Hitch and Baddeley (1976). They had subjects solve reasoning problems in which short sentences were presented with letter pairs, and subjects had to verify whether the sentences accurately described the letter pairs. Examples are:

A is preceded by B	AB
A follows B	BA
B does not follow A	BA
A is not preceded by B	AB

A subject who successfully solved these problems would answer, "false, true, true, true." Half the subjects in Hitch and Baddeley's experiment had to solve these problems, after which they had to memorize and recall a string of six letters. The other half of the subjects had to listen to a string of six letters, then solve a problem, then recall the letters. This second group was therefore responsible for holding the letters in memory while they were problem solving. The result was straightforward: There was little interference from storing six letters in memory while making judgments about the sentences. As with the experiment involving verification

may store a speechlike code for the sentence, "Mary bashed Jack on the neck with her umbrella," but nothing is assumed in the theory about storing the various aspects of the meaning of this sentence (for example, who did the bashing, what the instrument was, what the likely effect was on Jack).

However incomplete, Baddeley's theory helps us understand such tasks as mental arithmetic. Indeed, Hitch's (1978) analysis of mental arithmetic, reviewed in figure 7.2, explicitly distinguishes storage from processing. Reexamining that figure will show that Hitch has made explicit use of the concepts of storage and processing that are central to Baddeley's theory. In Hitch's version, the central executive is the seat of mental-arithmetic operations, drawing on information stored temporarily in a buffer that holds the numerical facts of the problem at hand (as well as drawing on a long-term memory system, of course). This and other models of thinking and reasoning (for example, Carpenter et al. 1990) have made good use of the sort of view that Baddeley has developed.

In light of the growing use of this view of working memory in theories of thinking, it is appropriate to examine the evidence that supports it as a basis for a working-memory system. Let's start with the case for multiple storage buffers as part of a working-memory system. Available evidence confirms the proposal of two storage systems, and it provides some specification of the characteristics of each. It also suggests that the number of memory systems may even be more than two.

7.5.1 The Phonological Loop

Imagine picking up a telephone book and looking up a randomly selected number. If you had the opportunity to dial the number immediately, you'd have the number available in memory while you were dialing. If you had to store the number in memory for a few seconds while you went to the phone, you'd still have the number available in memory for dialing, but, to keep it fresh, you would have to engage a rehearsal process that involves internally repeating the number until you dialed it. This example highlights the assertion that there are two components to the phonological loop. One is a memory, called the phonological buffer or store, that is responsible for storing the information. The other component is a rehearsal process that is responsible for recirculating the contents of the phonological store.

As its name implies, the phonological loop is responsible for coding linguistic information in phonological form. This procedure is as opposed, for example, to coding in a form that represents meaning, visual qualities, or some other aspect of the memory trace. As we shall see shortly, the evidence for phonological coding is quite strong. If ??? of a

phonological code, there must be the capability to create such a code for information that is not directly presented in auditory form. By assumption, the rehearsal process is charged with this responsibility. Thus, for example, if a list of words is presented auditorily, the phonological code for this material is, by hypothesis, created directly by the perceptual system responsible for auditory input, and this code can be directly deposited in the phonological buffer. If a list is presented visually, the visual code that is created during perception of the list is then translated into a phonological code (by the rehearsal process) for storage in the phonological buffer.

The foregoing picture embodies some noteworthy assumptions. For example, we have assumed that the code for verbal information is phonological in form, that the memory in question has limited capacity for storing information, that there is a rehearsal process that keeps information in verbal working memory fresh, that this presumed rehearsal process is distinct from the phonological store itself, and that auditory presentation of verbal information is handled somewhat differently than visual presentation. In fact, there is evidence in favor of each of these assumptions, as we'll now see.

7.5.1.1 *Phonological Coding*

The nature of the code stored in the phonological loop was first described by Conrad (1964). The task he gave his subjects was ordered recall of strings of six letters. What was critical in his experiment was the set of letters from which the six were drawn on each trial. This set included the letters BCPTVFMNSX. Notice that the first five letters in this set are acoustically confusable because they end in the sound "ee," and the last five are confusable because they all begin with the sound "eh." Notice also that letters in one subset of five are acoustically different from those in the other subset of five. Conrad chose this set of ten letters so that he could assess whether subjects were likely to make acoustic confusion errors in their recall. He did this by examining cases in which subjects correctly recalled all but one of the six letters in a sequence. In those cases, he asked whether the letter that was misrecalled was more likely to come from the confusable subset than from the other subset. For example, if the letter B was included in one series and was not correctly recalled, was it more likely that subjects would substitute a letter from the similar-sounding subset (that is, CPTV) than from the dissimilar-sounding subset (that is, FMNSX)? Indeed it was. In the case of the letter B, for example, it was four times more likely that subjects would substitute a confusable than a nonconfusable letter. And the same held true for the other letters as well. These confusions indicate that the code in which information is held in working memory must have some property of the sound of the letters. If

added, suggesting again that suppression prevented creation of an articulatory code for the letters in the list.

7.5.1.2 *Storage Capacity*

How much can be stored in the phonological loop? This issue has been under debate since a classic paper by George Miller (1956) proposed a limitation on the capacity of what we now call working memory. Miller's argument was that the limitation of working memory was best characterized as a limitation in the number of chunks of information that could be stored. The definition of a chunk is not altogether clear, but intuitively it amounts to any coherent unit of information. A single word would typically qualify as a chunk in a list of words, or a syllable might if the list were composed of isolated syllables. Perhaps even a short phrase might be a chunk if a list of these was presented. Miller's point was that, however measured, the fundamental capacity of working memory was limited, and this limitation was approximately constant when measured in chunks.

More recent experiments suggest that this view needs modification. Among the more interesting experiments motivating reanalysis are those of Baddeley, Thomson, and Buchanan (1975). They had subjects memorize lists all of which were composed of two-syllable words, but some of the words were relatively quickly articulated (such as "bishop" or "pectin") while others took longer to articulate (such as "harpoon" or "voodoo"). Baddeley et al. (1975) found that more of the words like "bishop" could be remembered than the words like "harpoon." Furthermore, Baddeley et al. (1975) made this effect of word length disappear by using articulatory suppression, suggesting that articulatory suppression has its effect by interfering with the operation of rehearsal. An important implication of the effect of pronunciation length on recall is that the capacity of the phonological loop cannot simply be measured in chunks (for example, words if the stimuli are words), otherwise it would have been constant regardless of the length of pronunciation of a word. This experiment raises the hypothesis that the length of a stimulus may be a determinant of the capacity of the loop.

How could both the number of chunks and the length of the stimulus have an effect on capacity? One plausible hypothesis is that there are two limits on the capacity of working memory, not just one (see, for example, Longoni, Richardson, and Aiello 1993). One is the limit imposed by the size of the phonological store, which may be best measured in constant items, such as chunks. The other is the limit imposed by the rehearsal process, which may be best measured by time rather than by items. Suppose, by analogy, that the rehearsal component of the phonological loop, like a tape-recorder loop, can store a fixed time-slice of information. Anything that can be represented in that time-slice can be stored, but the

so, then partial forgetting of a letter leaves some trace of part of its sound, leading to possible confusion with a similar-sounding alternative letter.

We can be even more specific about the nature of phonological coding. In a follow-up experiment, Conrad (1970; see also 1972) tested profoundly deaf schoolboys, some of whom were better than others at producing speech. The test was recall of words. The words were drawn from either a set of phonologically similar or phonologically dissimilar words. The results of this experiment are interesting because they are counterintuitive: The subjects who were better at producing speech were worse in their recall of the phonologically similar words than the subjects who were poorer in producing speech. This was the result that Conrad predicted because he reasoned that the subjects who could articulate more proficiently ought to be more confused by the articulatory similarity between words like "way" and "weigh" (two of the words in the confusable set); the subjects who were relatively poor at articulation would not be as confused by articulatory similarity (perhaps because they would store the words using a visual representation). Thus, Conrad's evidence suggests that the coding used by the phonological loop is partly articulatory in character. This hypothesis makes sense of our introspection about remembering a telephone number that must be dialed after a delay; we feel as if we are internally articulating the number to keep it in memory.

There follows from this conclusion a quite simple implication: Hindering someone from creating an articulatory code should cause a decline in working-memory performance if the person tried to use an articulatory representation even in the face of interference. Testing this implication requires the kind of dual-task methodology introduced earlier. Applied to the present case, the logic is to have a secondary task interfere with subjects' creation of an articulatory code for material that is presented visually (visual presentation is necessary so that the phonological code is not inherent in the stimulus, but must be created). An experiment by Murray (1968) illustrates this technique. He had subjects memorize visually presented letters while they had to articulate some irrelevant material. Subjects were presented with lists of letters to memorize that varied in the extent to which the letters were confusable with one another in sound. In one condition, subjects studied the lists, rehearsing the letters silently. In another, they had to say the word "the" with the presentation of each letter in a sequence. In general, having to articulate the irrelevant word "the" (called "articulatory suppression") hurt performance, as predicted if the internal code that needs to be created in the phonological loop is articulatory. An additional result from Murray's (1968) experiment supports this conclusion: Without articulatory suppression, similar-sounding letters were remembered more poorly than letters that differed in sound. But this effect all but disappeared when articulatory suppression was

time-slice is approximately fixed, so that representations that exceed it (such as longer words) will not be accommodated.

The effect of word length (for example, length of pronunciation) on memory capacity—as distinct from the effect of sheer number of items—points to a time-based account of the capacity of rehearsal. According to this account, the phonological loop stores whatever can be articulated within a fixed span of time, by some estimates about two seconds. This relation explains why people who naturally speak quickly have a larger working-memory capacity for verbal material than people who speak slowly (Baddeley et al. 1975). It also explains why languages that have relatively longer words result in relatively poorer working-memory spans measured word by word (Ellis and Hennis 1980; Naveh-Benjamin and Ayres 1986). Thus, there is considerable consistency among results in leading to the conclusion that time is the limiting commodity in determining the capacity of rehearsal. This evidence can be added to the evidence summarized by Miller (1956), among others, that there is also a fundamental limit on the capacity of verbal working memory as measured in number of items or chunks. The best presumption is that the latter limit is a limit in the capacity of the phonological buffer, added to the time limitation of about two seconds that apparently constrains rehearsal.

7.5.1.3 *Rehearsal*

We have been constructing a model of the phonological loop, including the assumption that it is composed of two parts: a phonological storage buffer and a rehearsal component. Rehearsing verbal material from the buffer is assumed to refresh the strength of the memory trace. If material is not rehearsed, as might be the case if something distracted the memorizer from her task, the material would be subject to forgetting. All this leads directly to the implication that the phonological loop should make heavy use of language processes to store information and recirculate it; hence there should be evidence that the language centers in the brain are engaged and active during working-memory tasks. Recently, it has become possible to investigate this implication using neuroimaging techniques. Positron emission tomography (PET) and functional magnetic resonance imaging (fMRI) are techniques that allow one to see brain activation that accompanies neural activity, and they have been used to examine the circuitry involved in storage and rehearsal. These techniques make possible measurement of regional blood flow in the brain with little or no invasion of the tissue in question. Since the classic work of Roy and Sherrington (1890), it has been known that when neural activity increases in a portion of the brain, there is an accompanying increase in the flow of blood in that portion. This phenomenon makes possible the use of neuroimaging techniques to make inferences about neural activity. (Wherry et al. 2005)

blood flow increases regionally there is assumed to be an underlying increase in neural activity.

An example of research that has been used to identify rehearsal processes in working memory comes from a study by Paulesu, Frith, and Frackowiak (1993). In one of their experiments they had English-speaking subjects remember a series of six items after which a probe item was presented; subjects had to judge whether the probe was identical to one of the six previous items. In one condition, the items were letters of the English alphabet. In the other, they were letters of the Korean alphabet, with which the subjects were not familiar. In the first condition, subjects were instructed to use rehearsal to store the items and in the second condition they were told to store them visually. The logic of the experiment was that many of the processes in the two conditions would be similar (for example, a decision to say Yes or No, preparation of a motor response, perception of the visually presented items), and so if the images of the control condition (with Korean letters) were subtracted from those of the English-letter condition, the resulting subtraction image should contain evidence of brain activation that accompanies working memory for verbal material in one's own language. Subtracting one image from another (that is, subtracting the brain activation at each point in one image from the activation at a corresponding point in the other) is a standard technique in neuroimaging studies of this sort. In the Paulesu et al. (1993) experiment, subtraction resulted in several sites of activation, among them an area in the front of the brain, with the largest activation in the left hemisphere. This area, called Broca's area after the neurophysiologist who first documented it, is known to participate in the production of spoken speech (see chapter 13 by E. Zurif in Volume 1 of this series). It is reasonable to surmise, then, that Broca's area plays a role in working memory for letters by being the seat of processes that are involved in rehearsing the letters while they are held in memory. This and similar evidence (for example, Kocpe, Minoshima, Jonides, Smith, Awh, and Mintun 1993) supports the proposal that one of the components of working memory is a rehearsal process that makes use of internal processes much like the processes used in overt language production. Thus, rehearsal can be characterized as inner speech in the service of memory maintenance.

7.5.1.4 *Distinguishing the Buffer and Rehearsal*

The preceding section provides evidence that rehearsal is important to working memory. Let us now ask whether rehearsal is distinct from (the phonological buffer. Perhaps, by counterargument, there is no need to assume two components; rehearsal by itself may be sufficient to account for working-memory phenomena for verbal material.

long words. But these two effects were quite independent of each other, suggesting that they had their influences on different processes. If, as discussed above, word length has its effect on rehearsal processes, then it is reasonable to conclude that the effect of irrelevant speech was on another process, the phonological buffer.

This behavioral evidence for two components of the phonological loop is supported by studies of brain-injured patients as well. One of these is P. V., the patient whom we considered in section 7.4. One of P. V.'s presenting symptoms was a significant deficit in tests of verbal working memory, but her deficit was largely limited to auditory presentation (Basso, Spinnler, Vallar, and Zanobio 1982). For example, when presented sets of three letters to recall, she was able to get only 20 percent of the sets correct when they were presented auditorily, but she was completely successful in recalling all the sets when they were presented visually (Vallar and Baddeley 1984). Now consider some aspects of P. V.'s performance. First, she shows a phonemic similarity effect in her recall; that is, phonemically similar material is recalled more poorly. Second, this similarity effect appears *only* when material is presented auditorily, not when it is presented visually. Third, when given articulatory suppression during a memory test, she showed no interference when material was presented visually, in contrast to what happens to normal subjects. Finally, P. V. shows no effect of word length in her memory performance, yet another difference from normal subjects. The absence of a word-length effect confirms damage to her rehearsal process; as shown above, the word-length effect is one sign of intact rehearsal.

What can we conclude about P. V.'s working memory from these results? She certainly shows evidence of a phonological buffer when material is presented by ear, as if auditory presentation gains obligatory access to this store. To be sure, her performance with auditory presentation is not nearly normal in quantity, but the presence of a similarity effect does indicate that there is some semblance of a phonological buffer mediating performance. With visual presentation, however, there is no similarity effect, indicating that she does not create a phonological representation from the visually presented material. This result indicates that one of the functions of rehearsal is deficient, the ability to create a phonological code from visual material. Further evidence of damage to rehearsal comes from the result that she is not affected by articulatory suppression. This result would be expected if rehearsal was not a functional process for her; she should not be adversely affected by inhibiting rehearsal with articulatory suppression. The absence of a word-length effect confirms damage to rehearsal; *as reviewed above*, the word-length effect is one of the hallmarks of a normally working rehearsal process.

The issue is whether two components are involved or just one. This issue can be addressed by testing the effects of different experimental variables on working memory. The logic is this: If there are two working-memory components (a buffer and a rehearsal process), one might be able to identify two experimental variables, one of which influences storage of information in the buffer but not rehearsal, and the other of which influences rehearsal but not storage in the buffer. Each variable would have an effect on working-memory performance, but the two effects would be independent of each other—that is, the influence of one variable would not modulate the influence of the other. In the case of the phonological buffer and rehearsal, this kind of experimental logic has been applied by several investigators, perhaps most impressively by Longoni, Richardson, and Aiello (1993). In a series of carefully designed experiments, these investigators teased apart the buffer from rehearsal by testing the joint effects of articulatory suppression, phonemic similarity, and word length in a working-memory task. The task involved memory for word lists that were presented by ear to eliminate any possible influence the rehearsal process might have in creating a phonological code to begin with. The words in a list could be phonemically similar or not; they could be long or short in length; and subjects had to memorize them under silent study conditions, or under articulatory suppression, that is, while saying "one, two, three" to themselves over and over (they did this in Italian, being Italian university students). In a pair of experiments, the results were quite clear: First, as others had found, longer words were remembered more poorly than shorter words. Second, phonemically similar words were remembered more poorly than phonemically distinct words. What was striking in the experiments was that articulatory suppression abolished the effect of word length, but had no such influence on the effect of phonemic similarity. This result suggests that articulatory suppression and word length both affect the same psychological process, different from the one affected by phonemic similarity. It is reasonable to presume that the common site for word-length and suppression effects is rehearsal, and the site for the phonemic similarity effect is the phonological buffer.

In another experiment, these authors took advantage of another variable known to affect verbal working memory: the presentation of irrelevant speech during presentation of the stimulus materials. It has been documented that irrelevant speech damages performance in verbal working-memory tasks (for example, Salame and Baddeley 1982). Longoni et al. (1993) composed an experiment in which they simultaneously varied whether irrelevant speech was presented for word stimuli that were either short or long. In that experiment, they found that both variables had an effect on memory: Memory performance was worse when presentation of the words was accompanied by irrelevant speech, and it was worse with

Overall, P. V.'s results confirm the conclusions based on studies of normals. P. V. shows a dissociation between a phonological buffer and a rehearsal process. She has a functioning phonological buffer (although it is not functioning completely normally), but evidence of significant rehearsal is absent. Likewise, normal subjects also show a dissociation between these components when they are tested on the effects of variables such as word length, phonological similarity, and irrelevant speech. Taken together, these results inspire confidence in the view that the phonological loop is a two-part mechanism, both parts of which are important to its function in working memory.

7.5.2 The Visuospatial Buffer

Think back to one of the problems with which this chapter begins:

A is on the right of B
 C is on the left of B
 D is in front of C
 E is in front of B

Where is D with respect to E?

Various lines of evidence suggest that problems of this sort require construction of an internal representation that preserves the spatial relations among elements. There are many circumstances in which creation and manipulation of a representation that preserves spatial features is critical to normal thinking. Examples are as varied as giving and comprehending directions from one location to another, remembering where you left car keys in your house, solving geometry problems, mentally rotating a statue to imagine how it looks from the other side, and imagining someone else's perspective in viewing a scene. These are all tasks that may depend on use of an internal representation that includes spatial information. Solving tasks of this sort requires ability to store spatial information as well as ability to manipulate it when needed. In this way, the requirements for spatial reasoning are much the same as the requirements for verbal reasoning: a working-memory system that can both store and operate on information. What differs, of course, is the nature of the code that is involved. No kind of phonological coding will allow you to deduce the correct solution to the spatial problem above, for example. A very different sort of representation is needed, and allowance for this has been made in Baddeley's (1986, 1992) model of working memory.

That model includes a structure, the visuospatial buffer, that is presumed to store information in a visuospatial code for use by central executive processes. Although Baddeley's model does not provide detail on the interplay between the visuospatial buffer and the central executive processes,

this detail is available in other theories. The most prominent among these is that of Kosslyn (1980, 1981), who describes a theory in which a working-memory component is specialized for using visuospatial information. This component can retrieve information from a propositional code in long-term memory and can create from it an internal representation that is perceptlike; or it can represent information coming in from the senses, creating from it an imaginal representation. According to the theory, to form a visuospatial representation in working memory is to construct a representation that shares similarities with a percept that would be formed if we were viewing a scene that contained the imagined objects. Indeed, evidence from PET studies of mental imagery suggest that much the same neural machinery is used for imagery as for visual perception (Kosslyn, Alpert, Thompson, Maljkovic, Weise, Chabris, Hamilton, and Buonanno 1993). Once formed, the representation is similar to a percept of a scene: it can be inspected, scanned, rotated, enlarged, shrunk, and so on. This is just the sort of representation one would need to solve spatial-relations problems, to give directions from information in long-term memory, to take another's perspective on a scene, or to accomplish any of the other skills that require visuospatial manipulation (see Kosslyn's chapter in volume 2 of this series).

Apart from intuitive appeal and computational sufficiency, what evidence is there that such a representation is part of the working-memory system? Is there evidence of a double dissociation between the visuospatial buffer and the phonological buffer, for which there is already well-established empirical support? Indeed, there is, and it comes from both behavioral and neuropsychological sources.

7.5.2.1 *Visuospatial vs. Phonological Buffers: Behavioral Evidence*

Consider first two tasks from a classic experiment by Brooks (1968). For the visual task, subjects were briefly shown a block capital letter such as

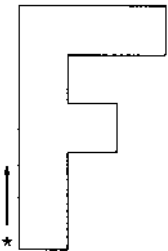


Figure 7.4

An example stimulus from the experiment of Brooks (1968). Subjects had to imagine the block letter, begin at the vertex marked by an asterisk, and mentally trace around it in the direction indicated by the arrow.

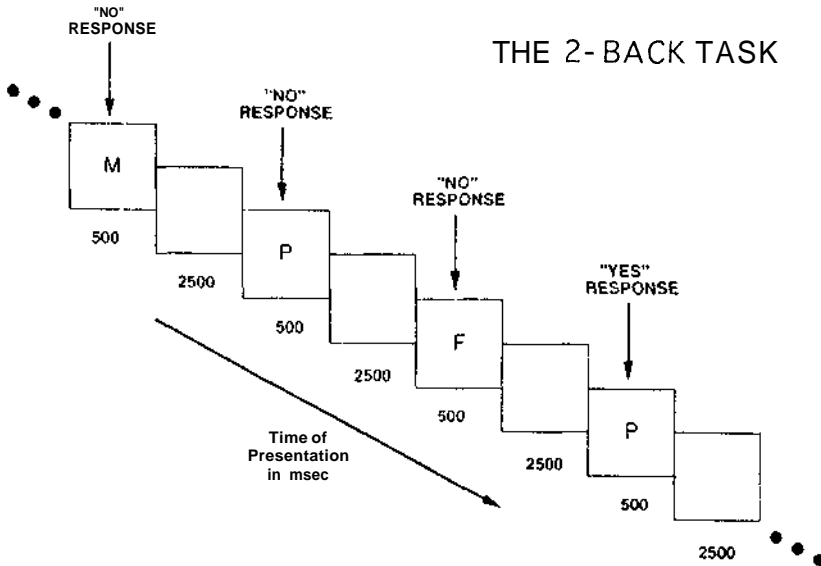


Figure 7.5

A schematic of the events in the "two-back" task. A sequence of single letters appears, and subjects must respond to each depending on whether each matches the letter that appeared two letters back. A correct response to each letter is shown above it.

figure illustrates the proper response for the example sequence shown. It is easy to see that this task is demanding of working memory. Subjects need to keep a constant stream of at least three letters in mind: the present one, plus the two that appeared previously. Then they must match the present one with its "two-back" counterpart, after which they have to update the contents of working memory in preparation for the next letter. The rate of presentation, one letter every three seconds, leaves time to do the updating and to rehearse the sequence that is relevant at any given time. In this way, this task ought to recruit both the phonological loop and the rehearsal process, in addition to adding a central executive component involved in the updating. In order to isolate the working-memory processes of interest from other processes involved in the task (encoding of the letters, response execution, and so on), we included another task in which subjects simply responded for each letter whether it matched a constant target letter for that sequence. This control task minimized the load on working memory because the target letter was constant for an entire sequence, while including perceptual and motor processes in common with the memory condition shown in figure 7.5.

The results of this experiment are consistent with the evidence reviewed in section 7.5.1.3 about the biological basis of rehearsal, and they

the one in figure 7.4. From memory, subjects had to begin at a corner marked by an asterisk and move around the letter mentally in a direction indicated by an arrow. As they encountered each vertex, if it was at the top or bottom of the figure, they responded, Yes; if it was in the middle, they responded No. These responses were given in one of two ways that are relevant here: In one condition, they said the words Yes and No aloud. In the second condition, they pointed to a Y or an N on an answer sheet in which the Y's and N's were haphazardly arranged, forcing subjects to scan the sheet for the spatial location of their desired response before pointing to it. The second task in Brooks's experiment was verbal. Subjects were presented a sentence on each trial that they held in memory. They then had to retrieve the sentence, going from left to right, indicating for each word whether it was a noun or not. Again, Yes and No responses were given in one of two ways, as in the visual task. The rationale behind the experiment hinged on the predicted selective interference of each response mode on each memory task. The visuospatial buffer used to store and work on the block letters should show selective interference from the pointing task, which is also visuospatial in form, because of the layout of the letters on the answer sheet. The verbal buffer should show selective interference from the vocal responding required, in that this response mode introduced irrelevant speech to interfere with the required memory for the sentence.

The results of the experiment establish a double dissociation of verbal from visuospatial working memory. For the visual task, having to give responses by pointing to the Y's and N's on the answer sheet produced worse performance than having to say Yes and No aloud. By contrast, for the verbal task, verbal responding produced worse performance than pointing. The experiment supports the distinction between two buffer systems of working memory, one for visuospatial information and one for verbal information.

7.5.2.2 *Visuospatial vs. Phonological Buffers: Biological Evidence*

Recent evidence from studies of the biological basis of working memory in human beings adds to the evidence from behavioral studies by offering glimpses of the circuitry that may underlie the verbal and spatial working-memory systems. What is revealed in these studies is a different pattern of brain activation that accompanies spatial versus verbal working-memory tasks. Two experiments from our laboratory illustrate this difference in activation.

One task is illustrated in figure 7.5. The illustration shows a series of stimulus presentations of single letters that each subject saw while being scanned with PET. The task is to report for each letter presented whether it matches the letter that appeared two items before in the sequence. The

add to those data a view of the rest of the circuitry involved in working memory. The data on rehearsal by Paulesu et al. (1993) and others implicates the language-production centers of the frontal lobes, principally Broca's area in the left hemisphere. Likewise, our verbal working-memory experiment also shows activation in this area, indicating that subjects are applying rehearsal processes to the task of keeping in mind and updating the letters they are required to store. In addition, the "two-back" task shows marked activation in another area of the frontal lobe, different from Broca's area, an area that we shall see shortly is similar to one found in studies of working memory in monkeys. The final major focus of activation in the "two-back" task is in the parietal lobe at the back part of the brain, principally in the left hemisphere. Many have suggested on the basis of evidence from brain-injured patients that this area is involved in working memory. For example, this is the site of damage of the patient K. F., whose deficits in working memory have been extensively documented.

Notice that the major foci of activation in the two-back study and in other studies of verbal working memory are in the left hemisphere. This placement contrasts with the results of a study by Jonides, Smith, Koeppel, Awh, Minoshima, and Mintun (1993) on a spatial working-memory task. The task and its control are illustrated in figure 7.6. The memory task shown in that figure involved presentation of three dots at seemingly random locations around the circumference of an imaginary circle centered on a fixation cross. These were presented briefly, following which a retention interval of three seconds intervened. Then a single outline circle was presented. Subjects were to decide whether the outline circle encircled a location previously occupied by a dot or not. If so, they made one response; if not, another. This task required faithful memory of the locations of the three dots because if the outline did not fall directly over a dot, it fell quite close to one. Thus, subjects had to encode and store the dot locations quite accurately to perform well. Subjects engaged in this task while PET measurements were taken. Notice that the major portion of this task was occupied by the retention interval, and so activation patterns revealed by PET should have resulted largely from processes during this interval. In order to subtract out perceptual and motor processes, a control condition, also illustrated in figure 7.6, was included. In the control, subjects were also shown three dots, but they did not have to commit them to memory because the probe display included a re-presentation of the dots together with the probe outline. Again, subjects indicated whether the outline probe encircled a dot location or not, and activation patterns were collected from this condition and subtracted from the memory condition.

There were four major foci of activation in this task, two in the frontal lobe, one in the parietal lobe, and one in the occipital lobe. One hypothesis

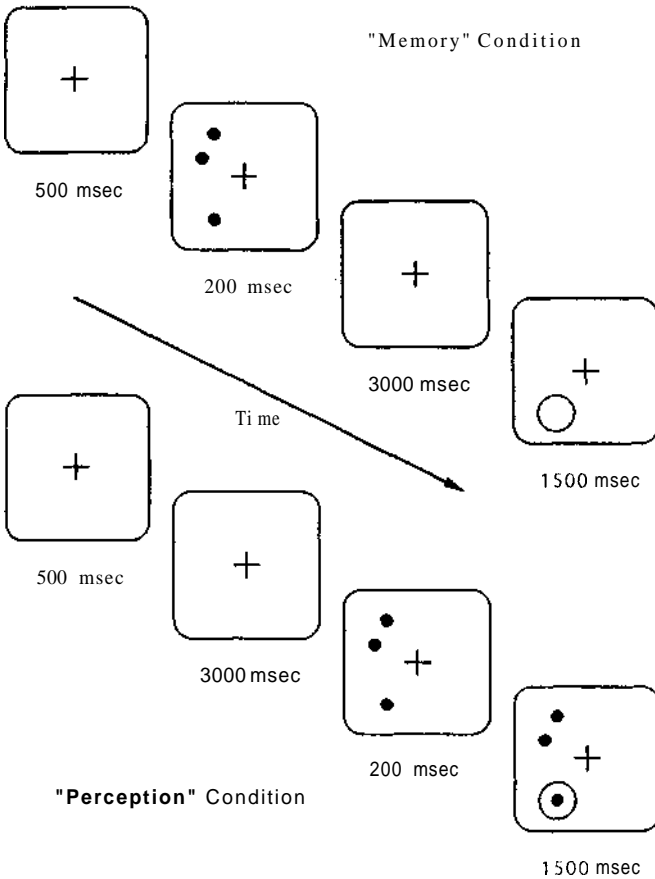


Figure 7.6

A schematic of the events in the Memory and Control tasks of the experiment by Jonides et al. (1993). In the Memory condition, subjects had to store the dot locations in memory for three seconds before the probe appeared. In the Control condition, the dots and probe appeared simultaneously and so no memory was needed to succeed in the task.

of the dot locations, using processes of the occipital lobe. They encode the locations of the dots from this image using processes of the parietal lobe, and they then store these encoded locations using frontal mechanisms. Whether this or another interpretation ultimately proves true, one feature of the data from the spatial task is critical: All the significant activations were discovered in the right hemisphere; none were found to be *reliable* in the left hemisphere. Take these data together with those of the two-back task, and you see a clear dissociation between working memory for phonological and spatial information respectively. The phonological task re-

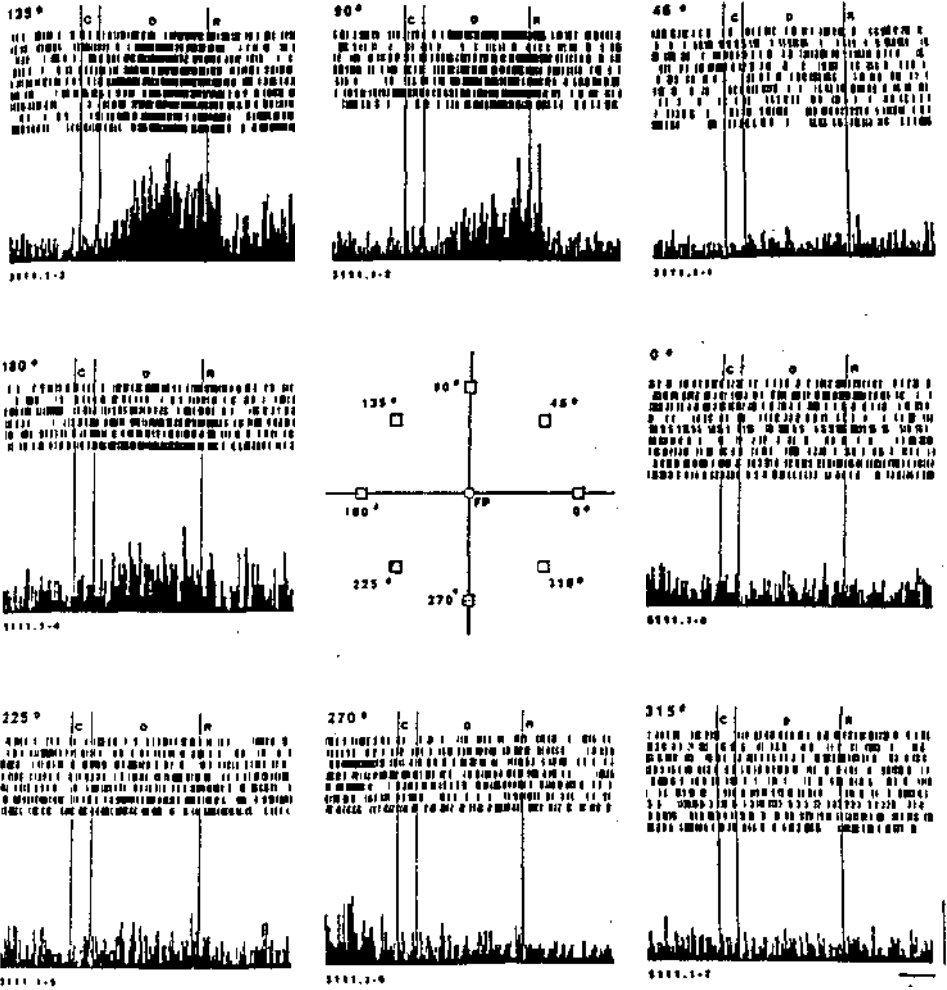


Figure 7.7
 A schematic of the stimuli from the experiment by Funahashi et al. (1989) together with data from a neuron and its responses to stimuli that appeared at each of the eight possible stimulus locations. Notice that this neuron was selectively responsive largely during the delay period of each trial, and it responded best to stimuli in the vicinity of 135 degrees from the fixation point (from Funahashi et al. 1989, fig. 4, 335).

those of the right hemisphere. These data, then, are consistent with the behavioral data of Brooks (1968) and others showing a distinction between working memory for verbal and spatial information.

7.5.2.3 *Neurophysiological Studies of the Visuospatial Buffer*

The imaging data on working memory in human beings have limited usefulness in revealing the details of processes. Partly, this limitation is because the techniques that have been used have limited spatial resolution, so that only fairly large areas of brain tissue can be resolved (on the order of multiple cubic millimeters). Partly, this is because the techniques do not allow one to cleanly isolate just the memory processes in tasks of interest; some other processes undoubtedly remain even after activations from control conditions are subtracted. Thus, there is great interest in examining more precise data from experiments on nonhuman animals. In such experiments the localization and details of working-memory processes can be studied with greater precision. There is a long tradition of such experiments, beginning with those of Jacobsen (1936), many of which have implicated mechanisms of the frontal lobes (among other loci) in mediating working-memory effects. The most recent developments in this tradition are especially exciting because they have uncovered mechanisms of working-memory processes at the level of single neurons in the cortex. This research has been led by Patricia Goldman-Rakic and her collaborators (Goldman-Rakic 1987).

A representative result from these experiments is illustrated in a report by Funahashi, Bruce, and Goldman-Rakic (1989). They had three monkeys engage in a working-memory task for spatial location that is illustrated schematically in figure 7.7. The monkeys were trained to fixate on a small spot at the center of a screen, illustrated by the FP in the figure, indicating the fixation point. After achieving fixation on a trial, a monkey would be briefly presented with a small square presented at an unpredictable one of eight locations surrounding the fixation point, as indicated in figure 7.7. The animals were trained to maintain their fixation during the presentation of this square and during a three-second delay period that ensued. At the end of the delay, the fixation point disappeared, and this was the cue to the animal to shift its gaze to the location of the previously presented square. The animals were quite accurate in moving their eyes to the position of the square even after a delay. Of interest is the pattern of response that was discovered in single neurons in the frontal cortex whose activity was recorded during the trial events.

Although different neurons exhibited different characteristics, a substantial number had the pattern shown in figure 7.7. The figure shows the responsiveness of a single neuron in the right hemisphere of a monkey to stimuli that appeared at each of the eight positions tested. Each of the

distinction that we have not made heretofore. The theory due originally to Baddeley (1986) about working memory assumed that there were but two buffer systems involved, a phonological one and a visuospatial one. However, quite recent evidence from both monkeys and human beings suggests that more than two stores are implicated. This new evidence allows us to distinguish between a buffer responsible for spatial information (shown in the studies by Funahashi et al. 1989, and by Jonides et al. 1993 reviewed here) and one responsible for visual information that is not spatial in character.

7.5.3 The Visual Buffer

In retrospect, notice that the evidence marshaled to support the claim of a visuospatial buffer has been based on tasks requiring storage of spatial information, yet it is quite clear that not all visual information need be spatial in character. Color and shape, for example, are dimensions of visual stimuli that are not spatial. In principle, then, one need not conflate spatial and visual processing when considering working memory. This observation raises the following question: Are spatial and visual information coded by the same buffers in working memory or are they treated separately? Evidence from recent studies of the biological basis of working memory invites the conclusion that there are separate buffers for these two dimensions.

The first documentation of a distinction between visual and spatial memory coding was by Wilson, O Scalaidhe, and Goldman-Rakic (1993). They paired a test of spatial memory much like the one described in the preceding section with a test of visual memory for shape, both administered to monkeys. The spatial task involved presenting stimuli for a short duration to the left or right of a fixation point while the monkeys fixated on that point. As in the experiment by Funahashi et al. (1989), the monkeys were trained to shift their gaze to the location of the stimulus after a delay interval. The visual-memory task involved brief presentation of a pattern at the center of a screen following which there was a delay. The monkeys were trained to shift their gaze to the left or right after the delay depending on which of two patterns had been presented. This pair of tasks presents the animals with quite different memory requirements, yet with the same response requirement. In the first task, they must maintain memory of the spatial location of the stimulus, but in the second, they must maintain a representation of the stimulus's shape. In both cases, though, they are required to make a left or right eye movement as the response, thus equating the motor task.

As in other experiments, individual neurons were found that were responsive largely during the delay interval of each task. The spatial-

might seem inefficient because if each of the buffers themselves stored a meaningful code, there would be no need to do a translation of this information every time it had to be used in the service of some reasoning task. However, the sensory systems are known to be involved in coding by these three formats, and so storage of information according to these formats *may* just be an inevitable consequence of how the information flows from the sensory systems to systems responsible for using the information (see, for example, Wilson et al. (1993), for an argument of this type related to the storage of information of a spatial or visual sort).

Another quite different possibility is that there is a separate storage buffer in working memory that is designed precisely to store information in a modality-free way, in terms of its conceptual properties. Potter (1993) argues that such a buffer might receive information from encoding processes that allow a direct semantic code to be stored in parallel with the storage of a phonological, spatial, or visual code for the same information. If so, then executive processes that need to make use of the semantic content of some incoming information could have direct access to it, rather than just having access to a modality-specific code for that information.

Compelling as it seems that there must be some conceptual code for information in working memory, there has been surprisingly little research to uncover how this information is stored and accessed by central executive processes. There are, however, a series of reports that make plausible the notion that some sort of semantic code is stored in working memory (see Shulman 1971 for a partial review). Hintzman (1965) found, for example, that in a working-memory task in which letters and digits were the stimuli, not only were errors in recall explainable by acoustic confusions, in addition there was some tendency for subjects to confuse items within the same class (letter or number), as if the class of the items had been coded in addition to the phonological characteristics of each. Also, blocking items in a working-memory task by their conceptual category (words versus digits) improves recall for the items versus intermingling them (Schwartz 1966).

The study of forgetting from working memory has also produced evidence supporting the view that a conceptual code may be stored as well as modality-specific codes. Dale and Gregory (1966) demonstrated that introducing retroactively interfering material during a retention interval caused forgetting, and that this interference was accentuated by conceptual similarity of the interfering material to the material that had to be remembered. Wickens, Born, and Allen (1963) also implicated a conceptual code in their studies of release from proactive inhibition. In these studies, subjects engaged in a series of trials of a working-memory task. The material to be remembered was of the same conceptual type (for example, consonant strings), with occasional switches to another conceptual type (for example, digit strings). Performance on successive trials with the same type of

previously documented by other studies (for example, Funahashi et al. 1989). This area is in the frontal cortex. The pattern memory task also led to activation of neurons during the delay interval but the neurons that showed this activation were in a different area, just below the ones found active during the spatial task. It was also largely the case that the neurons active during the spatial task were not active during the pattern task, and vice versa. Thus, this experiment documents a double dissociation between spatial and pattern memory by documenting different brain areas active during these two tasks.

This pattern of dissociation is not limited to monkeys, as research by Smith and Jonides (1994) shows. In their study of working memory in humans using PET, they also showed a dissociation between working memory for location and working memory for object shape. For humans, the major dimension of difference in brain activation patterns was left versus right hemisphere. The right hemisphere was engaged in a spatial working-memory task while the left hemisphere was active during an object-memory task. Thus, research on humans and other primates leads to the view that it is best to consider the working-memory system for visuo-spatial information as having two components, visual and spatial respectively, not just one.

7.5.4 The Conceptual Buffer

This brings the number of buffers involved in working memory to at least three: a phonological loop, a spatial buffer, and a visual buffer. But this view of working memory must be incomplete. We know from the sort of research reviewed at the beginning of this chapter that working memory is an integral component of many thinking tasks, tasks that require meaningful codes for the information that is being processed, not just sensory codes. How could this be so *if the only* information stored in working memory is a code defined by only phonological, spatial, or visual characteristics? We also know that there are some patients who can process complex language constructions quite well even though they show profound deficits in their phonological working-memory capacities (for example, Martin 1993). Because language processing must involve some working memory capability (as reviewed in section 7.4), these patients must be using a working-memory system that goes beyond simple phonological storage. Indeed, this and other examples raise the issue of how semantic information is extracted from codes stored in working memory. Two possibilities suggest themselves.

One possibility is that although the three modality-tied buffer systems (phonological, visual, and spatial) store information according to their three respective codes, central executive processes that use this information create a meaningful code for what is stored every time it is used. This

material gradually declined, but it then recovered when the type of material was changed. This recovery suggests that part of the code for the items included information about their conceptual category, and similarity of category gradually increased interference for the items themselves.

These and other results raise the possibility of a semantic or conceptual code as part of working memory. Exactly how this code is stored in relation to the modality-specific codes is not yet clear, however, and deserves further empirical research. All that is presently clear is that a conceptual code of some sort is needed in order to make working memory useful in the stream of information processing, for it is a conceptual code that is often used by executive processes, which we examine next.

7.5.5 Central Executive Processes

The central executive in working memory is often discussed as if it is a unitary processing mechanism, but it is perhaps better characterized as a *set* of operations that can process information in the buffers of working memory in the service of one task or another. To appreciate this structure, think again about the reasoning tasks with which this chapter began. Solving problems on the Raven test involved executive processes that can extract the critical dimensions of the stimuli, compare these dimensions among members of a row or column, and extrapolate the values of these dimensions to predict the missing member of the matrix. Solving mental arithmetic involves a quite different set of operations, which manipulate numerical information. Different again from these examples are the processes required by the spatial reasoning tasks of Byrne and Johnson-Laird (1989), in which arrays of symbols must be created with the spatial relations among them well specified. It is easy to see that the processes involved in these varied tasks are quite different from one another. In short, understanding the nature of central executive processes will involve studying myriad processes in myriad tasks. It is perhaps for this reason that it is widely recognized that progress in understanding central executive processes has lagged behind progress in understanding the buffer systems that report to these processes (see, for example, Baddeley 1990).

7.5.5.1 Goal Management

The fact that there seem to be many executive processes may make one wonder whether they have *anything* in common—that is, whether there is any value in arguing that they all belong to a single category of executive processes rather than each being different from the others. If the processes had no common characteristics, then the label "executive processes" would be more gratuitous than real. Analyzing the many processes that can be performed on information, however, that they share some features

One has to do with doing more than one thing at once. Often, various goals confront a person simultaneously. Think about driving a car when you have a passenger with whom you are having a conversation. In this case, you have two goals at the highest level of analysis: keeping the car heading where you intend, and keeping up your end of the conversation. Each of these, in turn, has subgoals. On the driving end, you not only want to get to your destination, but you want to do so by observing the law, keeping up a decent level of speed, allowing other drivers their turn at a stop sign, and so on. On the conversation end, you want not only to spew out a series of words when it's your turn to speak, but you want the words to form sentences, convey your thoughts, allow you to develop your arguments, and so on. This example and others illustrate that there are many times when we have goals and subgoals which have to be kept in mind, and which have to control our behavior in a changing fashion from one moment to the next. One function of central executive processes is to keep the goals of the current situation in memory and to allow each to control behavior in a manner that is coordinated with each of the other goals. Also, of course, there is the need to update the goal list as time passes so that new ones can be added and defunct ones can be deleted. All this activity requires significant coordination.

The empirical analysis of this sort of goal-tracking behavior has relied on fairly spare tasks, but ones in which two or more goals have to be monitored and respected. In such tasks, one finds that the more complicated or difficult each task associated with a goal, the more difficult it is to switch from honoring one goal to honoring another. This is true even for tasks that are quite familiar to us. Let's return to the mental arithmetic example. Consider this: Suppose you are given a series of simple addition problems to do mentally, or a series of subtraction problems. Now consider being given a series of problems that alternate between addition and subtraction. If goal setting were automatic and simply a function of the task at hand, it should take no longer to do the mixed series of problems than the average of each individual series. But Rubenstein and colleagues (1993; Rubenstein, Meyer, and Evans, submitted) showed that this is not remotely the case. In their experiment, the time to do a set of addition problems was 37.50 seconds, and the time to do subtraction was 44.33 seconds, but the time to do a mixed series of the same length as the addition and subtraction series was 46.50 seconds. On average, they calculated, it took about .51 second to switch from each addition to subtraction problem and back in the mixed series. Furthermore, if the comparison was between multiplication and division (more complex mathematical calculations), the switching time increased to 1.27 seconds. This is consistent with the view that one function of central executive processes is to monitor task goals, and that monitoring trades off in its processing resources with the

order in which they attack the different parts of the mouth, going from left to right and top to bottom, for example. This, of course, is not usually a matter for deep thought in the morning. Quite the contrary: one can think about the plan for the day quite effectively and still do a good job of getting around the mouth. More complex tasks such as driving a car might qualify as well. Sometimes drivers find that they have driven for some miles with little memory of how they negotiated the drive. To be sure, decisions had to be made along the way, including how much to press on the accelerator, whether to apply the brakes, whether to turn the steering wheel to remain in the center of one's lane, and so on. But once driving becomes a well-learned skill, these sorts of operations can be handled with little effort.

Substantial research has been conducted to determine the conditions under which automaticity develops for skills, and it is impressive to find that even complex skills such as reading and taking dictation can be done together after they have become automatic (see, for example, Spelke, Hirst, and Neisser 1976). Research has also shown that the critical variable in the development of automaticity is the regularity of the relationships that one is practicing. When there is a consistent relationship between stimuli and responses to those stimuli, automaticity in processing develops nicely. By contrast, when the relationship between stimuli and responses is variable, automaticity never develops. Apparently, consistency in learning conditions coupled with extensive practice can automate the scheduling of even complex tasks, making the work of executive processes relatively effortless (Schneider and Shiffrin 1977).

Of course, many of the mental tasks that occupy our time are not automatic. It is these that tax the scheduling function of executive processes. Norman and Shallice (1986) recognized this in devising a model of executive control over scheduling that includes a component responsible for scheduling in relatively automatic contexts and a component that dominates when scheduling is required for novel or unpracticed behaviors. They argue that when faced with tasks that can be accomplished by well-learned sequences of processes, we call up from memory processes that can be strung together to reach the task goal. For example, in driving to work, you might retrieve a representation for a standard route. This choice, in turn, would cause lower-level representations or subroutines to be engaged to sequence the various parts of the drive. These, in turn, would engage the processes necessary to start the car, press the accelerator, hit the brake, and so on. In many cases, Norman and Shallice (1986) argue, we function by virtue of having a large number of these processes in memory, and we can engage them in the proper sequence, having done so many times previously. Once triggered, a representation will then compete with similar representations for other actions, inhibiting ones that will

tasks at hand. The more complex the task, the more time it takes to disengage from it and switch to another.

Given this result, you won't find it surprising that if one of the tasks involved in a two-task situation is the Raven Matrix task, switching between it and another task will be quite taxing. Hunt (1980) discovered this difficulty in examining performance on a motor guidance task while subjects tackled Raven's problems of varying difficulty. As the difficulty of the Raven problems increased, performance on the guidance task suffered, indicating that the increased Raven difficulty made it more difficult to switch from it to the guidance task. This overall result may be due to the increased difficulty in switching, or to the decreased availability of processing resources as they are stretched ever more thinly with more demanding tasks. In either case, executive processes must balance one set of goals against another.

7.5.5.2 *Scheduling*

Another of the functions of executive processes is to schedule the subcomponent processes that are required to follow through on any task that is aimed at a single goal. As discussed, any complex cognitive task—mental arithmetic being just one—is best described in terms of a set of processes that must be engaged to arrive at a task goal. Sometimes these processes are engaged in turn, sometimes in parallel with one another, but there are multiple ones nonetheless. This assumption of multiple subcomponent processes makes clear that there must be executive control over scheduling as well as executive control over goal management, as we saw in the preceding section. Scheduling involves assigning priority to one or another mental operation so that it has control at any given time, as well as switching priorities among different mental operations as they are needed. Thus, for example, in solving a Raven's matrix problem, scheduling would coordinate among feature identification, feature comparison within a row or column, and extrapolation to the missing item, among other processes. In working on a mental-addition problem, scheduling is critical so that the units digits are added before the tens digits, that the carrying operation is done before the next column of digits is processed, and so on. Most tasks that face us in our daily lives involve some element of scheduling, in that most tasks have identifiable components, and these components need to be coordinated one with the other to reach a successful outcome (see chapter 8).

There are many occasions when we have learned some skill well and can apply it to a situation easily, with little depth of analysis of the variables in that situation. In such cases, scheduling processes for working on a task is considered to be automatic. Scheduling the order of strokes when brushing your teeth might be an example. Most people have a quite stereotyped

other stimuli present in the visual array. Another is being able to adopt new strategies as needed to solve problems with which one is faced (see chapter 8 for more on the role of the frontal lobes in cognition).

One symptom that has been cited frequently as a sign of frontal damage is high susceptibility to interruption. Many tasks require sustained attention to a task, something that patients with frontal damage often find difficult (see, for instance, McCarthy and Warrington 1990, for a description). Their symptoms are characterized by relative inability to ignore irrelevant stimulation in the environment. This condition seems most prevalent when the task at hand does not itself contain stimuli that capture attention. In such cases, of course, concentration on the task is made more difficult because it must be internally generated, rather than relying on the salience of stimuli that occur. There are many illustrations of this general difficulty to resist interruption. For example, it appears in tasks that require vigilance to infrequently appearing stimuli, a task that is difficult if attention is not concentrated on the stimuli for long periods (for example, Salamaso and Denes 1982). Difficulty with tasks such as this in the face of frontal damage indicates a disruption of the scheduling function of executive processes, a disruption that interrupts the normal flow of information processing when irrelevant stimuli intrude.

Another symptom of frontal damage is the tendency to perseverate. Perhaps the most frequently cited evidence of this difficulty comes from use of the Wisconsin card-sorting task (Milner 1964). In this task, subjects are given four target cards, each bearing a design in which shape is one dimension of variation (for example, cross or triangle), color is another, and number of figures is the third. The subjects are then given a stack of cards to sort, placing each card in front of one of the four target cards. The cards can be sorted according to one of the dimensions, but the subjects do not know which. All they are told with each card placement is whether their sorting is right or wrong. Subjects continue sorting until they are correct in placing cards according to the dimension the experimenter has in mind, and then the criterion dimension is changed without notice. Subjects then must reach criterion with this new dimension, and so on with another dimension. Normal subjects can learn to adopt one or another dimension as the critical one within a few trials, but patients with frontal damage may continue to use an incorrect dimension for as many as 100 trials without switching. This behavior indicates quite graphically how patients with frontal damage can perseverate in their behavior. They can do so even when they realize that what they are doing is incorrect moreover, suggesting a certain lack of control over strategic processes. It is as if they can set up a routine to pay attention to one dimension, but they cannot switch attention to another dimension even when they know that it is incorrect. This inability to switch from one dimension to another is

of these lines of research will be found in the reference sections of these works by Baddeley 1986, 1992.

Realize that aspects of the view of working memory presented here are not without controversy. Some, for example, question its role in language function (Martin 1993). Some question the arguments about the nature of the codes stored in working memory (Reisberg, Rappaport, and O'Shaughnessy 1984). Some question whether what we know about working memory relates to its role in thinking (Potter 1993). Yet others question the appropriateness of various tasks for measuring working memory (Klapp, Marshburn, and Lester 1983). In addition, the view presented here is different from the classical view of working memory (then called "short-term memory") that is exemplified in Atkinson and Shiffrin (1971). These arguments and others are worth considering to evaluate the promise of the present view of working memory and to decide the crucial issues for further study; a student who wishes to examine this topic further should consult these sources.

Problems

7.1 Carpenter et al. 1990 found a substantial correlation between performance on Raven's problems and the Tower of Hanoi problem. This they interpreted as indicating that both tasks tapped working memory insofar as goal and subgoal management are features of working memory. Goal management has been identified as one of the hallmarks of the central executive in working memory. In view of this finding, if you were to search for patients who had a deficit in working memory that would reveal itself in either Raven's problems or the Tower of Hanoi, what patients would you seek? That is, where would you expect to find damage in the brain that interfered with tasks such as Raven's? How would you doubly dissociate a deficit in goal management from a deficit in other tasks dependent on working memory, such as memory span? If you could establish such a double dissociation, what would this tell you about the relationship of central executive processes to the memory buffers of working memory?

7.2 Baddeley 1986 and others have found that having subjects store a number of items in working memory while they also engage in a task that requires sentence comprehension does not seem to have profoundly damaging effects on performance in the sentence-comprehension task. Does this result critically wound the hypothesis that working memory plays an important role in language comprehension?

7.3 The evidence reviewed in this chapter strongly supports the hypothesis that phonological coding is critical to the storage of verbal material. One might wonder, then, what code is used by people who are congenitally deaf. Given that they cannot code information phonologically, do they have working-memory spans for verbal material of zero? Design an experiment to examine the nature of the code used by congenitally deaf subjects.

7.4 Neurobiological studies of cognitive processes have been criticized on occasion for offering little evidence beyond what one can gain from strictly behavioral experiments. As the criticism goes, the only new information offered by neurobiological studies is an indication of where information processing takes place in the brain. Critics argue that knowing about the localization of processes tells us relatively little about the functioning of the cognitive system. Is this true of research on working memory? What else is offered by neurobiological studies in this domain?

References

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symptomatic of a difficulty in arranging goals properly in the face of changing task demands.

The results of studies of central executive processes paint a picture of a coordinating mechanism. Its repertoire of functions can vary from mental arithmetic, to logical analysis, to spatial problem solving, and beyond. But whatever the particular processing required, there remains a need to coordinate the various goals that must be attained moment by moment, as well as a need to organize the component processes that will be scheduled to meet these goals. Although much remains to be understood about how this coordination is accomplished, viewing processing requirements in terms of a central set of principles such as goal management and scheduling will help organize a variety of findings about executive processes.

7.6 Summary

As the discussion in this chapter lays out, it can be fairly argued that working memory is the engine of cognition. It is intimately involved in the complex cognitive processes that underlie reasoning, problem solving, and, perhaps, certain aspects of language processing. It participates in all these activities of our cognitive lives by allowing us to execute a large array of cognitive routines and by temporarily storing information on which these routines operate. Although limited in capacity to store and compute, working memory nonetheless enjoys considerable horsepower by virtue of fine coordination between the storage buffers and the computing operations. This architecture, though not an inevitable design for powerful computing devices, serves human beings quite handsomely.

Suggestions for Further Reading

Many textbooks about cognition and memory can provide introductory material about working memory and about the thinking processes that it serves. Among them are Baddeley 1990, Medin and Ross 1992, and Best 1992. These texts provide an overview of the topics in cognition that may be helpful not only to one interested in working memory, but also to one who would like to place the role of working memory in the context of a functioning cognitive system. Those with an interest in the breakdown of this system that accompanies brain injury might be advised to consult a text by McCarthy and Warrington 1990. Even more focused material on deficits accompanying damage to the particular systems that affect working memory can be found in Vallar and Shallice 1990.

Research about working memory populates the major journals in the field of cognitive psychology, and the journals that publish research about brain injury and its effects on cognitive processes. Many of these journals are represented in the reference list that accompanies this chapter. An overview of a theory of working memory that includes memory buffers and a central executive can be found in Baddeley 1986, 1992. This theory has been subject to test in a variety of ways: using behavioral tests of dual-task performance, studies of individual differences in working memory and the relation of these differences to other cognitive skills, and studies of patients with lesions. Discussion of each

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