HUMAN MEMORY
AND COGNITION

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To the three who matter most:

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Chapter 4

SHORT-TERM, WORKING MEMORY

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Elementary memory makes us aware of . . . the just past. The objects we feel in this directly intuited past differ from properly recollected objects. An object which is recollected, in the proper sense of that term, is one which has been absent from consciousness altogether, and . . . is brought back . . . from a reservoir in which, with countless other objects, it lay buried and lost from view. But an object of primary memory is not thus brought back; it never was lost; its date was never cut off in consciousness from that of the immediately present moment. In fact it comes to us as belonging to the rearward portion of the present space of time, and not to the genuine past. (James, 1890, pp. 643–47)

The dialogue that follows is an example of conversational “abuse” of working memory.

Five-year-old to father: “Dad, can I get a new toy? Because when I was playing with Joey today, he had a new car, and he let me play with it, but then we had to go in because it started raining. But then his Mom gave us some cookies and said we could watch TV for a while. And then it didn’t stop raining, so we stayed inside until I had to come home for dinner. So, can I?”

Father: “Can you what?”

Five-year-old, exasperated: “Get a new toy!”

Primary memory, elementary memory, immediate memory, short-term memory (STM), short-term store (STS), temporary memory, working memory—all of these terms refer to the same memory component, to the same aspect of the human information processing system. It is this component where the “immediately present moment,” in James’s explanation, is held in consciousness. It is this component where active mental effort is expended, whether to remember a phone number from directory assistance or to help in memorizing your own new phone number. It is this component where comprehension “takes place,” where ideas of new toys leave a father’s head as he tries to understand the meandering conversation of his five-year-old son. What is this component? It is the short-term, working memory system. What it is, what it does, and how it does it are the topics of this chapter.

Notice that James’s term primary memory suggests wrongly that it’s the first memory stage. It’s not the first, of course—the sensory memories are the first memories a stimulus encounters on its way into the information processing system. But it is the first memory system we are conscious of, sufficiently aware of that we can offer intuitions and introspections about its functioning. Many of those intuitions and introspections match what has been discovered empirically. After all, the metacognition theme suggests that adults have a fair understanding of how their own memories work. On the other hand, some mental processes that occur in short-term, working memory are not revealed to consciousness—they are automatic. Naturally, these processes yield no useful introspections;

indeed, people often naively feel that they don’t exist. (This is why I’ve said that short-term memory is only roughly the same as consciousness.

While at the same time we are aware of the contents of short-term memory, we are not necessarily aware of the processes that occur in short-term memory.)

Modern cognitive research on short-term memory came hard on the heels of the selective attention studies of the mid-50s. George Miller’s (1960) classic paper, which we’ll discuss shortly, is an excellent example of the upsurge in interest in short-term retention. A commonplace observation, that we can remember only a small number of isolated items presented rapidly, began to take on new significance as psychology groped toward an understanding of the entire human memory system. Miller’s insightful remarks were followed shortly by the surprising Brown (1968, and then Petersen and Peterson (1959) reports. An amazing simple three-letter stimulus, such as CHH, was forgotten almost completely within 15 seconds if the subject’s attention was diverted by a distractor task, counting backwards by threes. Such reports were convincing evidence that the limited capacity of the memory system was finally being pinned down and given an appropriate name—short-term memory.

We will take a chronological approach again in this chapter, beginning with Miller’s influential paper, then progressing up through current conceptions of this immediately experienced, conscious memory system. You’ll notice as we go that we’ll shift from calling it short-term memory to calling it working memory. Why do we need two terms here? After all, at a rather general level, “short-term memory” and “working memory” refer to the same memory system, the same system discussed as far back as James. Wouldn’t it make more sense to settle on one term?

I think there is good reason for keeping the two names separate. Stated simply, the terms have historically different connotations. Short-term memory is the older of the two terms, and carries a somewhat simpler, less elaborate sense to it. It is the label we usually use when the focus is on the input and storage of new information. When a rapidly presented string of digits, for example, is tested for immediate recall, we generally refer to short-term memory and imply a simple “recycling” kind of mental activity as an explanation of recall. Likewise, when we focus on the role of rehearsal we are examining how short-term memory assists in the memorization of new information, highlighting the “control processes” (Atkinson & Shiffrin, 1971) component of STS. Operationally, short-term memory is observed whenever relatively short retention is being tested—no more than 15 or 20 seconds—and when little, if any, transfer of new information to long-term memory is involved.

The term working memory, on the other hand, is the newer term for this “short” component of the memory system and has been the subject of substantial research over the past ten years or so. The term generally has the connotation of a workbench or a mental scratch pad, a place where conscious mental effort is applied (Baddeley & Hitch, 1974). The term usually refers to the mental workspace for retrieval and use of already
Thus, when word meanings are retrieved from long-
term memory and then put together to understand a sentence, working
memory is the place where this “connection” happens. It is the location of
conscious, attention-consuming mental effort. Traditional immediate
memory tasks may be a component of working memory research, but usu-
ally are only a secondary task to the reasoning, comprehension, or
retrieval task. Indeed, Baddeley has proposed that the short-term memory
responsible for digit span performance is but a single component of
the more elaborate working memory system.

Notice further that even the terms themselves imply a somewhat dif-
ferent set of characteristics, and consequently a somewhat different set of
empirical questions that researchers have tested. Short-term memory is
short—it doesn’t last very long. The very term embodies the notion of a
limited-capacity system. Where is the limitation in capacity? It’s in short-
term memory. Why is short-term memory limited? It’s too short!

Working memory, on the other hand, uses the active verb work. This
is an action-packed, busy place, a place where mental activity happens.
Where is the limitation in this system? It’s in how much work can be done
at one time.

We’ll preserve these differences in connotation throughout the chapter,
since the differences are predictive of the kind of research that has been
done. At the end of the chapter, we’ll present a combination of the two
terms, based on Baddeley’s notion that many of the traditionally inves-
tigated functions of so-called short-term memory occur in one section of
the broader system he calls working memory.

\[ \text{Short-Term Memory—A Limited-Capacity “Bottleneck”} \]

If you hear a string of about 10 single digits, read at a constant and fairly
rapid rate, and then are asked to reproduce the string, you generally can-
not recall more than about seven or so of the digits. Likewise, you can
 reproduce only about seven unrelated words, presented in a comparable
fashion (see Table 4-1 for sample lists for immediate memory tests, and
try a few on a willing volunteer). As Miller (1956) put it, “Everybody
knows that there is a finite span of immediate memory and that for a lot of
different kinds of test materials this span is about seven items in
length” (p. 91). Indeed, this limit has been recognized for so long, it was
included in the earliest intelligence tests (for example, Binet’s 1905 test;
see Sattler, 1982). Small children and individuals of subnormal intelli-
gence generally have a shorter “span of apprehension” or “span of imme-
diate memory,” so digit span is a reasonable diagnostic test in intelligence
testing. In fact, in the field of intelligence testing, it’s almost unthinkable
to devise a test without the digit span assessment.

\[ \text{Table 4-1 IMMEDIATE MEMORY SPAN LISTS} \]

Test a friend’s immediate memory span with these lists, being sure to read the items at
a fairly constant and rapid rate (no slower than one item per second). After you’re done,
ask the friend if there was anything different about any of the lists (other than the
obvious difference on the last two word lists).

1. 870314
2. 71505436
3. 2166872545
4. 681437952470
5. 284393482551

1. TSYLOP
2. CIMWODX
3. QWERTYUIOP
4. KWUCRALNYWGSJ
5. LABONNEAISON

1. LEAF GIFT CAR FISH ROCK
2. PAPER SEAT TIRE HORSE FILM BEACH TREE BRUSH
3. BAG KEY BOOK WIRE BCX WHEEL BANANA FLOOR BAR PAD BLOCK RADIO
4. LOVE EMOTION PLAN ATTEMPT RULE LAW ANALYSIS SYSTEM FINE PAYMENT
5. WHILE I WAS WALKING THROUGH THE WOODS A RABBIT RAN ACROSS MY
PATH

\[ \text{The Magical Number Seven, Plus or Minus Two} \]

For our purposes, the importance of this limitation is that it reveals
something absolutely fundamental about the human memory system. Our
immediate memory cannot encode or input vast quantities of new infor-
mation and hold that information accurately. Instead, there is a rather
severe limit on how much can be encoded, held, and reported imme-
 diately. Miller stated that limit aptly in the title of his article: “The Magical
Number Seven, Plus or Minus Two: Some Limits on Our Capacity for
Processing Information.” We can take in large amounts of stimulation
into the sensory memories. We can hold truly vast quantities of informa-
tion in a permanent long-term memory system. And yet, the transfer of
information between sensory and long-term memory is troublesome.
Immediate memory is the narrow end of the funnel, the four-lane bridge
between sensory and long-term memory with only one tollgate, the bot-
tleneck in our information processing system. It imposes “severe limita-
tions on the amount of information that we are able to receive, process,
and remember” (Miller, p. 95).\[1\]

\[ ^1\text{Miller was using the technical definition of information, related to uncertainty, measured in bits; see footnote 2 in chapter 2 for an explanation of “bits of information.”} \]
And so the limitation remains ... unless the seven items we are trying to remember are richer, more complex items than seven single digits, or unless the items are grouped in some fashion, as in the 3-4 grouping of a telephone number or the 3-2-4 grouping of a social security number. In Miller's terms, the richer, more complex item is properly referred to as a chunk of information, a unit that can hold something as impoverished as a single digit or letter, or as complex and elaborate as a word or phrase. By chunking together the individual items into groups, we can overcome this limitation and "break (or at least stretch) this informational bottleneck" (Miller, p. 95).

What follows is a simple example of the power of chunking, of forming larger units:

BYGROUPINGITEMSINTOUNITSWEREMEMBERBETTER

No one can remember these 40 letters correctly if they are treated as 40 separate, unrelated letters in a string. But the effect of the chunking process is that grouping together the isolated items into a richer chunk enables us to retain more information. You can easily remember the eight words in the phrase above because they are familiar words that combine grammatically to form a coherent thought. You can remember a social security number more easily by grouping the digits into the arbitrary 3-2-4 pattern. And you can remember a telephone number more easily if you further group the last four digits into two, two-digit numbers.

Recoding Miller's central point, then, was that our short-term memories are inherently limited in the total amount of information that can be held at any one time. Seven units or chunks, plus or minus two, seem to be the limit. Any quantity greater than this, if it is to be retained successfully, must be grouped or chunked, again with a limit of about seven of these enriched chunks. The technical term for this process of grouping items together, then remembering the newly formed groups is recoding. By recoding, a novice begins to hear not the isolated dot and dash sounds of Morse code, but whole letters, then words, and so forth.

The principle behind recoding schemes is very straightforward—recoding reduces the number of units to be held in short-term memory by increasing the richness of each individual unit. Short-term memory is therefore not as heavily loaded with units after recoding, although the individual units are of course packed with more information than before. Forming these enriched units requires some difficult mental effort, however. Try recoding the longest digit list in Table 4-1 into two-digit numbers (28, 43, etc.), trying to remember these enriched units. This will illustrate the mental effort required for this kind of recoding.

Given the active, attention-consuming nature of recoding, you might feel that the BYGROUPINGITEMS example you saw earlier isn't quite fair. After all, the meaning and grammar serve to make the sentence easily understood and eliminate the need for all of that hard mental work. Actually, the example clarifies the goal of any recoding scheme—to make the newly formed units as meaningful and as related to easily retrievable information as possible. A string of 40 digits, obviously longer than the capacity of short-term memory, can still be recalled accurately if your recoding scheme is powerful enough and if you can apply it flexibly and quickly. Miller, in fact, discussed the individual who could recall 40 binary digits (1s and 0s): "It is a little dramatic to watch a person get 40 binary digits in a row and then repeat them back without error. However, if you think of this merely as a mnemonic trick for extending the memory span, you will miss the more important point that is implicit in nearly all such mnemonic devices. The point is that recoding is an extremely powerful weapon for increasing the amount of information that we can deal with. In one form or another we use recoding constantly in our daily behavior." (p. 95).

Notice an implicit but vitally important point about recoding: it requires the active involvement of the subject to recode the stimulus items into richer groups and then maintain those groups in short-term memory. The bottleneck in the system is in short-term memory's capacity, according to Miller. We can overcome that limitation by the process of recoding, but only under either of two conditions, it seems. First, we can recode if there is sufficient time to apply the recoding scheme, or more accurately, if there are sufficient mental resources such as attention still available to do the recoding.

Long-Term Memory Involvement in Recoding Alternatively, we can recode if the recoding scheme is highly overlearned, as the Morse code or binary digit schemes become with practice. Here, a well-learned mnemonic device, a rehearsal or recoding strategy is used as the basis for grouping the stimulus items to be recalled. As an example, one of Chase and Ericsson's (1982) subjects was able to recall 82 digits in order after extensive practice by recoding the digits into groups on the basis of a personally meaningful scheme. The subject was a runner, and he remembered the digits by relating them to known facts about running; 351, for instance, was remembered as "the former world record time for running the mile." This subject used his specialized long-term memory
knowledge as a basis for recoding the digits, and this assistance from long-term memory permitted him to overcome the limitations of short-term memory. In general then, both the learned and practiced recoding strategy as well as specific facts that are used for recoding are stored in long-term memory. Thus, the term mnemonic in the above quotation refers to any kind of remembering strategy, especially when long-term memory is involved.

One of Miller's soundest premonitions followed immediately from the above quotation about mnemonic "tricks": "In my opinion, the most customary kind of recoding that we do all the time is to translate into a verbal code. When there is a story or an argument or an idea that we want to remember, we usually try to rephrase it 'in our own words'" (p. 95). As you have probably deduced by now, an adult's language comprehension skills are highly overlearned and have surely migrated toward automaticity. This makes rephrasing an excellent, flexible, and overlearned recoding scheme in the present context. Indeed, it's exactly this long-term memory/language-based recoding that assisted your memory for BYGROUPINGITEMS.3

But what about situations when no automatic recoding scheme is available, such as in the relatively less meaningful situation (for most of us) of remembering numbers instead of words? What is the fate of items in short-term memory when there is insufficient time or attention available to apply a more conscious scheme? Can we merely hold the usual 7 ± 2 items?

The Brown-Peterson Task—Decline from Short-Term Memory

Under some circumstances, we can't even hold half that many items in short-term memory. The research by Brown (1958) and Peterson and Peterson (1959) provided psychology with a compelling demonstration of this, and is still viewed as trend setting for the study of cognition. We'll spend a few moments discussing the task and results, since you'll encounter the same kind of empirical hypotheses and tasks several more times in this book.

The central idea in the Brown and the Peterson and Peterson papers was that some forgetting might take place even during the course of learning new material, and that this forgetting might be due simply to the passage of time before testing—in other words, forgetting due to decay. In the experiments, a simple three-letter stimulus was presented to the subjects, followed by a three-digit number. Subjects were instructed first to attend to the stimulus, then to begin counting backward by threes from the number they'd been shown. The counting was to be done out loud, in rhythm with a metronome clicking twice per second. At the end of a variable-length period of counting, the subjects were asked to report the three-letter stimulus they had heard. The results of these studies were apparently so unexpected, and the number of researchers eager to replicate the study so large, that the task acquired a nickname that is still in use—it's the Peterson-Peterson or the Brown-Peterson task.

The surprising result was that memory for the simple three-letter stimulus was only slightly better than 70% after three seconds of backward counting, and dwindled to about 5% after 18 seconds of counting (see Figure 4–1). The essential ingredient in this finding, of course, was the distractor task, the backward counting. As the Petersons put it, "It we considered that continuous verbal activity during the time between presentation and signal for recall was desirable in order to minimize rehearsal behavior. The materials were selected to be categorically dissimilar an hence involve a minimum of interference" (p. 194).

This distractor task clearly requires a great deal of attention (if you doubt this, try it yourself from any three-digit number, making sure t

3In the oral classroom example with BYGROUPINGITEMS, a typical recall is "By grouping items together, we remember better" (QED).
count backward twice per second). Furthermore, it surely prevents rehearsal of the three letters, since rehearsal requires the same attention mechanism as the backward counting. What was surprising was that the letters were forgotten so quickly even though short-term memory was not overloaded—a 30% loss after only three seconds (assuming recall would have been perfect with a 0-second delay). On the face of it, it seemed that the Petersons had presented evidence of a simple decay function in short-term memory: with an increasing period of time, less and less information still resided in short-term memory.

**Interference Versus Decay in Short-Term Memory**

Later research, especially that presented by Waugh and Norman (1965) in their paper “Primary Memory,” questioned one of the assumptions made in the Peterson and Peterson report. Recall that the Petersons suggested that there should have been little, if any, interference from the distractor task to the memory test—from counting backward to recalling the three-letter stimulus—since letters and digits are “categorically dissimilar.” As such, the forgetting functions they observed were interpreted as evidence for simple decay of information from short-term memory. Waugh and Norman, however, felt that the distractor task might very well have been a source of interference. They noted that if the numbers spoken by the subjects during backward counting had interfered with the short-term memory trace, then longer counting intervals would have provided more opportunity for interference, since subjects would have produced more numbers during the longer interval.

Waugh and Norman’s reanalysis of several short-term memory studies confirmed their suspicion. Especially compelling were the results from their own “probe digit task.” Subjects heard a list of 16 digits, read at a rate of either one digit or four digits per second. The final item in each list was a repeat of an earlier item, and it served as the subjects’ probe or cue to write down the digit that had followed the probe in the original list. For instance, if the sequence 7 4 6 9 had been studied, then the probe digit 4 would have cued recall of the digit 6. The important part of their experiment, for the issue of decay versus interference, was the time it took to present the 16 digits. Presentation of the entire list took 16 seconds for one group, but only 4 seconds for the other group. If forgetting were due to decay from short-term memory, then the groups should have differed markedly in their recall, since so much more time had elapsed in the 16 second group. Yet as Figure 4-2 shows, the two groups barely differed at all in their recall accuracy.

The Waugh and Norman result suggested strongly that forgetting had been influenced by the number of intervening items between the critical digit and the recall test, and not merely by the passage of time. In other words, forgetting in short-term memory was due to interference. Thus, the Peterson and Peterson distractor task had not only prevented rehearsal, as it was supposed to, it had also produced interference with the critical digit to be remembered, as it was not supposed to. The short-term memory trace had experienced interference from the events that followed it during the trial.

As you’ll recall from the last chapter, it’s virtually impossible to test the simple decay theory in an adequate fashion. The Petersons’ suspicion that subjects would use a blank retention interval for rehearsal is entirely true, at least for adults. Yet introducing a distractor task to prevent rehearsal yields interference. A straightforward test of decay theory would seem to require an interval of time during which neither interference nor rehearsal takes place. Putting it bluntly, this goal can never be reached. On the other hand, the decay theory would surely have to predict the same amount of forgetting for the same interval of time, regardless of what kind of distractor task was being used—after all, the mere passage of time is the cause of forgetting according to decay theory.

A variety of experimental tests were devised to examine the relative inadequacy of simple decay explanations of short-term memory forget-
In one approach, two or more kinds of attention-consuming distractor activities were contrasted, keeping the retention interval constant. For instance, Talland (1967) used the Brown-Peterson task with two different distractor activities. One group did subtraction during the retention interval; the other group merely read the same numbers they would have spoken if doing subtraction. Not surprisingly, the group that actually had to do subtraction performed worse on recall than the reading group (see also Dillon & Reid, 1969). An alternate procedure was to test different kinds of stimulus materials and show differential forgetting based on the kind of material tested (again holding the retention interval constant). As an example, Peterson, Peterson, and Miller (1961) tested nonsense syllables versus words as stimuli. After six seconds of backward counting, word recall was significantly higher than recall of a three-letter nonsense syllable. In short, not only did different kinds of interference produce different amounts of forgetting, interference also varied with the kind of material being tested (e.g., nonsense syllables). These results are virtually impossible to explain by means of decay theory, but are clearly sensible if forgetting from short-term memory is due to interference. (In a later section, we'll reinterpret these effects as being due to competition for processing resources, with different degrees of forgetting due to different amounts of leftover resources available for rehearsal.)

**Release from PI** We will discuss one other famous line of research on this interference effect, a series of studies by Wickens (1972; also Wickens, Born, & Allen, 1963). Very shortly after the Peterson and Peterson report, Keppel and Underwood (1962) reported a startling effect that also challenged the Petersons’ interpretation of decay. It seems that subjects forgot at the dramatic rate reported by the Petersons only after they had been tested on several trials in the short-term memory task. On the first trial, memory for the three-letter stimulus was virtually perfect. Keppel and Underwood pointed out the straightforward reason for this result. As you experience more and more trials in the Brown-Peterson task, recalling the stimulus becomes more difficult because the previous trials are generating interference. This form of interference is called proactive interference (PI): the older material interferes forward in time with your memory for the current stimulus. This is distinct from retroactive interference (RI), in which newer material interferes backward in time with your memory for older items. In other words, short-term memory loses information rapidly, say within 15 seconds, when similar material has already been presented and tested. The loss of information in the Brown-Peterson task, according to Keppel and Underwood, was attributable to proactive interference.

The importance of Wickens‘ research was in his adaptation of the interference task, and especially in the way he turned proactive interference to his advantage. Wickens would present three Brown-Peterson trials; each trial used a different three-word stimulus. On the first trial, accuracy was near 90%, but it drifted down to about 40% on Trial 3. At this point, Wickens then changed to a different kind of stimulus for Trial 4; subjects who had heard three words per trial were given three numbers on the fourth trial, and vice versa. The results were dramatic. When the nature of the stimulus was changed, performance on Trial 4 returned to the 90% level of accuracy (of course, he also included a control group of subjects who received the same kind of stimulus on Trial 4 as they had gotten on the first three trials, to make sure their performance continued to dwindle, which it did). Figure 4-3 illustrates this result. The interference interpretation here is very clear. Performance deteriorates across trials because of the buildup of proactive interference. If the to-be-remembered stimulus changes, however, then you are “released” from the interference. Your performance is no longer depressed by the growing amount of interference, so you once again recall with about 90% accuracy. Wickens’ research over a lengthy period demonstrated conclusively the

![FIGURE 4-3](image)

Recall accuracy in a release from PI experiment, by Wickens, Born, and Allen (1965). Traces of letters are presented on the first three trials, and proactive interference begins to depress recall accuracy. On Trial 4, the control group gets another trial of letters; the experimental group gets a trial of digits and shows an increase in accuracy, known as release from PI.
effect of proactive interference, and then the release from PI when the
stimulus materials are changed (1972).

For now, the importance of the Wickens' research was that it showed
clearly the influence of interference in the process of forgetting informa-
tion in short-term memory. While it is possible that simple decay also
occurs in short term memory, it seems virtually impossible to give this
hypothesis a fair test. In any event, from the practical standpoint of using
short-term memory, interference from intervening material surely charac-
terizes our everyday experiences. As Howard (1983) put it, "Unre-
hearsed material is seldom allowed to remain in working memory long
enough to decay, because there is usually something else—if only some
daydreaming—to be done with the limited capacity available. To con-
vince yourself of this, try keeping your mind completely blank for 15 se-
conds" (p. 109).

Codes in Short-Term Memory

Let's consider a slightly different question about the information
stored in and lost from short-term memory. What is the form of the
stored information? If the information stored in visual memory is based
on a visual code, and the information stored in auditory memory is based
on a sound code, then what is the code for short-term memory? Are there in fact
several different kinds of codes that can be held in short-term memory? (Note that this is another way of stating
one of our seven themes, the one concerning the representation of knowl-
edge in memory.)

Verbal Codes Most of the early research on short-term memory, if
it considered this question at all, merely assumed that the information
code in short-term memory was probably an acoustic, verbal code. If the
experiment asks subjects to report letters, it seems only natural to suppose that the memory code for the letters
is related to the letter names themselves, a verbal, almost speechlike code. Several
demonstrations of the correctness of this assumption have been reported.
Conrad (1964) presented a string of letters visually to his subjects, then
recorded their errors in immediate recall. He found that when they made
mistakes, they were quite likely to "recall" a letter that sounded like the
correct one, substituting D for E, for example. Visual confusions, such as
substituting F for E, were rare. In other words, even though the letters
were presented visually, they were apparently stored in short-term mem-
ory in an acoustic, sound-based fashion. In a similar study, Wickelgren

(1965) presented four letters to his subjects, then distracted them by ha-
ing them copy down eight different letters. Finally, when asked to rec-
late the original four letters, his subjects did poorly when the eight copied let-
ters rhymed with the four target letters. (Notice here that Wickelgren
used a retroactive interference task, where the or later materials, the eig
letters, interfered backward in time with memory for the earlier fo
letters.)

It appears from this research that the code in short-term memory
verbally based, related to the spoken names of the stimulus items. A
code is usually referred to as an acoustic-articulatory code, and
the actual sound (acoustic code) or the pronunciation (articulatory code)
could be important. Subsequent research, however, has ques-
tioned the generality of this conclusion. As Lachman et al. (1979) has
pointed out, "The vast majority of experiments on short-term storage ha
used verbal materials, even though they were presented visually. If people
preferred an auditory mode for verbal material, then these experiments
would mistakenly suggest that the short-term store was only auditory" (p
249). In short, if you give only verbal-based tasks to subjects—tasks in
which some verbal or spoken response is required—they'll give you ev-
dence of only verbal-based coding. Research since the mid-1960s has
broadened our conception of short-term memory considerably. In par-
ticular, there is strong evidence for semantic- or meaning-based codes
short-term memory, visual codes, and even physical movement codes.

Semantic Codes How might we test the hypothesis that semantic
codes can be used in short-term memory? We need to devise a short-
term memory task in which the meanings of the stimulus words might influence
retention. An obvious choice is the Wickens' release from PI paralysis.
Use a Brown-Peterson task, including a distractor during the retention
interval; vary the semantic characteristics on the "switch trial," the trial
on which the nature of the stimulus is changed. Wickens and his col-
leagues performed many such experiments and commonly found that
switching word class or meaning resulted in a dramatic increase in accu-

Figure 4-4 illustrates one of the best known of these studies (Wickens
Dalezman, & Eggemeier, 1976). All subjects had four successive Brown-
Peterson trials. The control group saw triads from the fruit category as
stimuli on all four trials; the other groups saw triads from profession,
flower, or vegetable categories on the first three trials, and then were
switched to the fruit category on Trial 4. Of course, accuracy for all the
groups declined across trials, due to the buildup of proactive interference.
On Trial 4, the control group continued to decline in accuracy, since those
subjects saw yet another trial of fruit names. The other groups, however,
saw words from a different category on Trial 4, so showed higher recall on
the "switch trial." This result showed conclusively that semantic factors
can influence the amount of release from PI. Furthermore, as the semantic
Visual Codes A variety of experiments might be designed to—

Verticals. Powers, meters, and pressures.

square the number.

Figure 4.4

Short-Term Memory: A Limited-Capacity Buffer. Is a

Verbal information, power, meters, and pressures.

relationship between the short-term memory and the visual

Figure 4.3

Short-Term Memory: A Limited-Capacity Buffer. Is a

Verbal information, power, meters, and pressures.

relationship between the short-term memory and the visual

Figure 4.4

Short-Term Memory: A Limited-Capacity Buffer. Is a

Verbal information, power, meters, and pressures.

relationship between the short-term memory and the visual

Figure 4.4
Brooks' results were clearest. Requiring the subject to scan a visual image in short-term memory and to perform a simultaneous visual task, reading then pointing to the correct jagged line, resulted in very low accuracy. On the other hand, the group that scanned the visual image and simultaneously made a verbal report of yes and no responses had much less difficulty. Seemingly, short-term memory can hold visual codes, but cannot support two simultaneous visual tasks. If the two tasks require different modes, visual image and auditory response, then there is little conflict or interference. Segal and Fusella (1970) found comparable results: subjects holding a visual image in short-term memory were poor at detecting a visual signal, compared to those who detected auditory signals. Interestingly, these investigators also examined the auditory code in short-term memory. Subjects who held an auditory stimulus in short-term memory detected visual signals quite well, but auditory signals quite poorly.

Most dramatic, however, were the demonstrations of "mental rotation" by Shepard and Metzler (1971) and Cooper and Shepard (1973). In the Shepard and Metzler paper, subjects were shown a complex perspective drawing in two forms, and had to judge whether the two were the same shape. The critical factor here was that the second drawing was depicted as if it had been rotated from the orientation of the first drawing. Clearly, to make accurate judgments, the subjects had to perform some mental transformation on the second drawing, mentally rotating it into the same position as the first so they could judge it "same" or "different." Figure 4-6 displays several such pairs of drawings and the basic findings of the study.

The overall result was that people took longer to make their judgments as the angular rotation needed for the second drawing increased. In other words, a second figure that needed to be rotated 120° to bring it back to the orientation of the first drawing took longer to judge than one that needed only 60° of rotation. In the Cooper and Shepard (1973) report, subjects were shown the first figure and were told how much rotation to expect in the second figure. This advance information on the degree of rotation permitted subjects to do the mental rotation ahead of time, permitted them to prepare for the later-presented second figure.

Notice in both of these studies that subjects were performing a complex, visually based mental task—holding a mental image in short-term memory, then doing difficult, attention-consuming mental work on that image. It is almost inconceivable, especially for the shapes shown in Figure 4-6, that such performance could be achieved if subjects had only acoustic or verbal-based codes in short-term memory. (Ask yourself, what sort of verbal code would be sufficiently complex and flexible to permit such regular rotation without benefit of visual information?) Instead, the mental image and rotation studies demonstrate rather conclusively that, when we give subjects the chance, they can generate and use visual codes in short-term working memory. And, considering the kind of mental process required, it certainly seems more natural to refer to the workplace for this rotation process as working memory. Somehow, the notion of 7 ± 2 chunks of information seems quite irrelevant to the process of mental rotation.

Other Codes To conclude this discussion of short-term memory codes, notice that other formats for information storage in short-term memory are also possible. For example, most people can conjure up the "kinesthetic" image of riding a bicycle, in a manner similar to Brooks'...
capital F study, Shand (1982) has reported a fascinating set of results that demonstrate that short-term memory can hold information for physical movement. Shand’s subjects were congenitally deaf, and quite skilled at American Sign Language (ASL). He administered a short-term memory test to these people, requiring serial recall (recall in order) of five-item lists. One kind of list contained English words that were phonologically similar (SHOE, THROUGH, NEW), and one contained ASL “words” that were chonologically similar (similar in the physical hand movements necessary for forming the sign, e.g., wrist rotation in the vicinity of the signer’s face). The subjects’ recall showed confusions based on the chonological relatedness of the list items, even when the list was presented as a series of written, English words. In other words, Shand’s deaf subjects seemed to transform or recode the written words into an ASL-based code in short-term memory. Our mistaken “certainty” that short-term memory relies only on acoustic, verbal coding was truly a by-product of the kinds of stimuli we tested. In Shand’s words, arguing for a “preference for phonological coding in short-term memory processes may reflect the auditory orientation of the experimenters” (p. 11, emphasis added), rather than some inherent tendency of short-term memory.

\[ \text{v Short-Term Memory Scanning and Sternberg’s Reaction Time Paradigm} \]

The sections you’ve just read told you that short-term memory is a limited-capacity memory system, able to hold only seven plus or minus two units of information. It is unable to maintain new information for very long if other information intervenes before a test. Overcoming the bottleneck of short-term memory involves recoding, chunking or grouping processes by which more information is packed into the units that are remembered. Short-term memory is especially prone to acoustic-articulatory errors, substituting a rhyming item for the true target, but it also holds other kinds of codes as well.

These are important facts about short-term memory—there’s no doubt about that. And yet, in terms of sheer impact on the field of cognitive psychology, a series of studies in the mid-1960s by Saul Sternberg has probably had a greater influence than any of the reports already discussed. We will spend a good deal of time on the Sternberg task and results, for several reasons. Most importantly, the logic behind Sternberg’s methods and conclusions showed the way for countless cognitive studies to ask much more sophisticated questions about memory—long-term as well as short-term. Sternberg’s approach illustrated a way of studying three fundamental questions. How do we search through information stored in the memory system? How rapidly and accurately can this search be performed? What is the structure or format of the information through which we search?

Let’s begin with the logic of this whole enterprise, a logic for “inferring mental processes from reaction time measures” (Sternberg, 1966, 1969, 1971, 1975). Sternberg began by noting (1966) that the use of reaction time (RT) tasks to infer mental processes had a venerable history, dating back at least to Donders’ work in the 1800s. Donders had proposed a general method called the “subtractive method” for determining the time necessary for simple mental events. In simple terms, if you’re interested in the duration of Process B in a task that involves A, B, and C, then you must devise a second comparison task that has only Processes A and C. Test your subjects under both tasks, then subtract the time for \( A + C \) from the time for \( A + B + C \). The difference, by the subtractive method, should be the time for Process B.

Sternberg pointed out the difficulty of applying Donders’ subtractive method. It is virtually impossible to make sure that the comparison task, the \( A + C \) task, truly contains exactly the same A and C processes as the complete task. To illustrate, consider the question of how long it takes to name a letter of the alphabet, in particular how long it takes to find that name stored in memory. We’ll assume that Stage B is the name-finding stage, so it’s the duration of Stage B that we’re interested in. (For example, is Stage B faster for more common letters such as a, e, and s and slower for less common ones such as j, v, and z, or is it faster for “earlier” letters such as a and b than for “later” letters x, y, and z?) We can time subjects on the \( A + B + C \) task, presenting them with different letters and having them name the letters out loud as quickly as possible. Then we turn to the comparison task, the one containing only \( A + C \). We might suppose that the A process involves encoding the visual stimulus, that the C process is the motor response time of enunciating a letter name out loud. Can’t we merely present any letter, and have the subject shout out any letter name as soon as the letter is detected? Shouldn’t this comparison task involve only encoding time A plus motor response time C?

A moment’s reflection should reveal the problem with this method. Surely it takes longer to encode a stimulus you’re going to have to identify, as in the complete task, than it does merely to detect a flash of light. Surely it takes longer to prepare your vocal apparatus and then name the presented letter in the complete task than it does merely to shout out any

\[ \text{6Donders (1868) apparently tested the personnel at an observatory, to try to determine why some of their records disagreed. The observatory set Greenwich Mean Time by having an individual press a button when a certain star was centered on the cross hairs of the telescope sight. A few of the individuals, it seemed, responded more slowly to the “target,” so their time to press the button was longer than others’. Donders was able to convince the observatory that these individuals were not being sloppy, but that their “personal equation” was longer because of slower motor response time due to advancing age.} \]
letter name (which you had probably picked as the one you'd name even before the trial began). Thus, the time for A + C will probably be considerably shorter in the comparison task than the true A and C processes are in the complete letter-naming task. And yet the entire logic of the subtractive procedure relies on the equivalence of A and C between the two tasks.

Sternberg's solution to this knotty problem seems quite straightforward in retrospect. Apparently, at the time he proposed it, virtually no one would believe that it might work. His solution was to stop trying to eliminate one step from a sequence of processes, as the subtractive method tries to do. Instead, he suggested that the experiment be arranged so that the process of particular interest, say, Process B, would have to repeat one or more times during a single trial. Consequently, across an entire experiment there would be many trials on which Process B had occurred only once, many on which it occurred two times, three times, and so forth. Naturally, we can then examine the reaction time for these successive conditions. We can figure out how long Process B takes by determining how much time was added to the subjects' responses when an extra cycle through Process A was required. The term Sternberg chose for this elegant logical and statistical system was "additive factors logic."

The Sternberg Task

Sternberg applied his additive factors logic to the question of retrieval of information from short-term memory. To investigate this question he devised an appealingly simple task that he called "short-term memory scanning." In a typical experiment, Sternberg's subjects would be shown several hundred trials, each consisting of two parts. First, the subjects would be asked a set of one to six letters (or digits in some experiments), and would be asked to hold that set of items in short-term memory; these items are referred to as the memory set. Sternberg always presented fewer than seven items in the memory set, to make sure that all could be held accurately in short-term memory.

After a short pause, a test letter was presented to the subjects, termed the probe item; this was the second part of each trial. The subjects' task was to make a yes/no judgment as to whether the probe item was one of the letters in the memory set. While the accuracy of the subjects' judgements was of course important, the speed of their judgments, their RT as measured in milliseconds, was even more important. Thus, subjects were instructed to respond as quickly as possible while maintaining high accuracy.

Table 4-2 shows the memory sets and probe items for several trials in a typical Sternberg task and the typical sequence of events in the task. You might try a few of these, covering the probe item until you've stored the memory set in short-term memory, then uncovering it and making your yes/no judgment. Pay attention to your introspections as you do the task, so you can compare them with the actual results (for a better demonstration, have someone read the memory set, then the probe items, to you).

If you're reading carefully, you've already figured out the connection between the Sternberg task and the goal of forcing Process B to happen once, twice, etc. The connection is the memory set, the set of one to six items held_t in short-term memory. What was the subjects' task? It was to encode the probe item, then scan through the contents of short-term memory to see if the probe matched any of the letters in the memory set. If we call Process B the scanning or comparison process, then doesn't B have to happen again and again, once for each item scanned in the memory set? By comparing reaction times for trials with one, two, three (and so forth) comparisons, we should be able to determine how long the RT is for any one of them. It should be the amount of extra scanning time when one more item is added to the memory set. (If this logic is still vague to you, reread the last three paragraphs now before going any further.)
For the graphed function is about 900 msec (the psychological time)

Figure 4-7

The Forced-Choice model for short-term memory scanning, adapted from

TABLE 4-1

Methodology, Results, and Discussion

The results of Experiments 4-7 and 4-8 were analyzed using a two-factor ANOVA. The factors were memory set size and decision time. The ANOVA revealed a significant main effect of decision time, F(1, 32) = 43.2, p < .001, and a significant interaction effect, F(2, 32) = 12.4, p < .001. No significant main effect of memory set size was found, F(3, 32) = 2.1, p = .11.

The interaction effect indicates that the effect of decision time on reaction time varied with memory set size. Post-hoc analyses using the Tukey HSD test revealed that the effect of decision time was significant for memory set sizes of 1 and 2, but not for memory set sizes of 3 and 4.

In summary, the results of this experiment support the hypothesis that decision time has a significant impact on reaction time, particularly when the memory set size is small.
be scanned when no match is found? Apparently, based on Sternberg's
classic results, the contents can be scanned at a rate of 38 msec per item.
This result, a 38 msec scan rate, has already ruled out one of the logically
possible ways that short-term memory might be scanned. That is, we
might hypothesize that scanning takes place in parallel, with all items in
the memory set being scanned simultaneously: If this were the case, then
the simplest predictions would be that reaction time should not increase
at all with larger and larger memory sets: if short-term memory is
searched in parallel, then any number of scans (up to six or seven) will
occur simultaneously. This logically possible kind of search is graphed in
Figure 4-8B. Clearly, this simple parallel processing hypothesis does not
match the data, but a complex parallel process might (see the discussion
below).

True Trials

Let's turn now to trials on which the probe does match an item in the
memory set, the “true” trials when subjects decide “Yes, the probe is in
the memory set.” This is the condition in which the specific nature of the
scanning process is revealed most clearly. Consider next the kind of search
that seems most plausible, at least from an intuitive standpoint—the
“serial self-terminating search,” in Sternberg's terms. This kind of search
is the mental equivalent of a physical search, say, looking for your lost car
keys. If there are five places you normally leave your keys, then you begin
searching in the first place, continuing to the next location and the next
until you finally find your keys. Once you find the keys, then you stop
searching. In other words, you search the locations one by one, serially.
You stop your search when you find what you are looking for, in a self-
terminating fashion. Maybe short-term memory is searched in the same
way; maybe we search serially, one memory set item at a time, in a self-
terminating fashion, stopping when the probe matches the item it is com-
pared with.

The predicted results for a serial self-terminating search are graphed
in Figure 4-8C. Notice in Table 4-2 that the first three trials contain a
match between the probe and memory set. On the first trial, the probe
matches the one item held in short-term memory; on the second and third
trials, the probe matches the first and then the second position, respec-
tively. How many comparisons are necessary on Trial 1? One—the same
as if the probe letter had not matched. How many comparisons are neces-
sary on trials with two items in the memory set? One is necessary if the
probe matches in position one, and two are necessary if it matches in posi-
tion two. Sternberg was careful to design his experiments so that the
matching position on yes trials was evenly spread across all locations in
the memory set. So, for trials with two items in the memory set, half
matched after one comparison and half matched after two comparisons.
The same even spreading applied for all other sizes of memory sets as well;

one-third each for positions one, two, and three at set size three, and so
forth. Thus, across the entire experiment, how many comparisons would
be necessary for memory set size 2? It would be the average of 1 and 2,
i.e., 1.5. How many would be needed for set size 3? It would be the average
of 1, 2, and 3, i.e., 2. Notice the progression here: for false trials, 1, 2,
and 3 comparisons are necessary for set sizes 1, 2, and 3, but for true trials, 1,
1.5, and 2 comparisons are necessary on the average for self-terminating
search through the same set sizes. The rate of increase for true trials here
is exactly half the rate of increase for false trials.

Putting this rather complex idea another way, subjects must always
search exhaustively through the whole memory set on false trials, since
each position must be scanned before ultimately deciding there is no
match. But on true trials, because of the design of the experiment, sub-
jects would not have to search all positions if they were doing a self-
terminating search. Instead, they would find a match within the first half of
the memory set half the time, but would have to search further through
the memory set the other half of the time. Thus, on the average, they
would have to search through half of the memory set.7 The predicted
results for self-terminating search, therefore, are that true reaction times
should increase at one-half the rate of false reaction times.

If you've already compared these predictions to the obtained data in
Figure 4-8A, you've realized that this sensible, serial self-terminating
search is not what Sternberg found. Instead, Sternberg found essentially
no difference in the search rate between true and false trials (figure 4-8A
and D). We know that subjects had to search all positions on a false trial
(you have to look in all five locations for your keys before you're sure
they're not there). Therefore, finding the same search rate for true as for
false trials suggests pretty strongly that subjects search all positions on
true trials as well. Even if a match occurred in an early position, subjects
apparently continued scanning through the remaining positions before
making their decision.

Serial Exhaustive Search

However ridiculous this kind of search for your car keys would be,
Sternberg argued persuasively that this serial exhaustive search,
scanning all positions for all trials, might in fact be more efficient in the
world of short-term memory. Consider the search rate of 38 msec per item.
This is incredibly fast, after all—it's less than 1/20th of a second. Stern-

7 An analogy that has worked with my classes involves catching the bus. Imagine a city bus that
comes every 20 minutes. If you never pay any attention to the schedule or the time and merely show
up at the bus stop, then how long will your average wait be? Most people realize that sometimes
they'll have to wait only a few minutes, and sometimes longer, and that across many weeks the aver-
age wait will be about 10 minutes. Half the time you'll wait 10 minutes or less, and half the time more
than 10 minutes. Just as in self-terminating search, then, your average wait for the bus will be one-
half the total time between buses.
In a recent study, normal adults were given four tasks, Figure 4-9 for illustration of these.

1. To determine the duration of the match, where the time in this case could be found by observing the reaction times and physical signs. The data were collected from the microsecond to the millisecond range, showing the fine-tuned response times and the efficiency of the brain's memory system. This range was also used in the study of computer memory systems. It was found that the human brain can process information at a rate comparable to that of computer systems.

2. To determine the accuracy of the match, where the time in this case could be found by observing the reaction times and physical signs. The data were collected from the microsecond to the millisecond range, showing the fine-tuned response times and the efficiency of the brain's memory system. This range was also used in the study of computer memory systems. It was found that the human brain can process information at a rate comparable to that of computer systems.

3. To determine the effects of aging on the match, where the time in this case could be found by observing the reaction times and physical signs. The data were collected from the microsecond to the millisecond range, showing the fine-tuned response times and the efficiency of the brain's memory system. This range was also used in the study of computer memory systems. It was found that the human brain can process information at a rate comparable to that of computer systems.

4. To determine the effects of medication on the match, where the time in this case could be found by observing the reaction times and physical signs. The data were collected from the microsecond to the millisecond range, showing the fine-tuned response times and the efficiency of the brain's memory system. This range was also used in the study of computer memory systems. It was found that the human brain can process information at a rate comparable to that of computer systems.
results. In a very different use of the Sternberg task, Darley, Tinklenberg, Hollister, & Atkinson (1973) found that search rate was unaffected, although overall reaction time was slower, for subjects under the influence of marijuana; the fundamental memory process of scanning was unaffected by the drug but other processes such as encoding, decision, and motor responses were altered.

As stated in chapter 2, there have also been detractors of the Sternberg method, in particular of the notion that increasing reaction times necessarily mean serial exhaustive search. For instance, one proposal explains this pattern of results as the product of a parallel search, where each additional item to be scanned slows down the rate of scanning for all items (much as a battery will run several motors at once, but each will run more slowly if fewer motors were connected; see Baddeley, 1976, for a review of such criticisms). Others have objected to a different aspect of Sternberg's work, the embedded assumption that the several stages or processes are sequential, and that one must be completed before the next one begins. In a general way, our earlier discussions of automaticity and parallel processing should suggest the nature of this criticism to you. With practice, a process becomes more automatic, thus releasing attentional and processing resources to be devoted to other mental processes. Such outcomes, of course, suggest that the assumption of sequential and independent stages of processing is incorrect, or at best, incomplete.

Disputes such as these indicate an active, probing science. It's a bit disconcerting to students that cognitive psychology doesn't have the solid answers they were expecting (one of my professors in graduate school routinely commented, "Hey, you chose psychology. You're just going to have to learn to live with uncertainty"). On the other hand, balancing out Sternberg's critics, note the following: the fact that we might interpret his results as parallel rather than serial search is a tremendous advance over the former state of affairs, never having conceived of short-term memory search in the first place.

▼ Short-Term Memory and Recall

We've covered a great deal of material on short-term, working memory so far, but haven't yet focused precisely and fully on an obviously important question—what are the functions of short-term, working memory? What is this limited-capacity system for?

Of course, we've nibbled at the edges of this question, and you've encountered some indirect answers to it already. Rehearsal is a term that has been tossed in occasionally throughout the chapter, for instance in the form of Miller's (1956) recoding, but it has not yet been really defined or explored as a vital, short-term memory process. Furthermore, if you remember the topic of rehearsal from your introductory psychology course, you may have wondered why you've read this far into a chapter on short-term memory without yet running into a serial position curve, a graph of item-by-item accuracy on a recall task. The term serial position simply refers to the original position an item had in the list that was studied. I wanted to save this discussion until last, since it meshes nicely with current research on the characteristics of working memory, and since it provides the connecting bridge to the next chapter, in which we consider long-term memory processes. But now the time has come to talk about serial position. Figure 4-10 shows several time-honored, traditional serial position curves.

Free Versus Serial Recall

Before studying the evidence in these serial position curves, let's consider the two basic tasks we use to test subjects, free recall and serial recall. In free recall, subjects are free to recall the list items in any order, whereas in serial recall we ask subjects to recall the list items in their original order of presentation. Not surprisingly, serial recall is the more difficult task to perform—in recall the items in order, subjects must rehearse the items as they are shown, trying to store not only the stimuli but also its position in the list. As more and more items are shown, subjects are less and less able to do this rehearsal, so they tend to show poorer performance later in the list. In contrast, free recall provides the opportunity to recall the items in any order. As Atkinson and Shiffrin (1968, 1971) argued, this final recency portion of the list is generally held only in short-term memory, and is "spewed out," so to speak, as soon as the signal to recall is given to the subjects. This recall strategy works because the recency of those last items ensures that they are still in short-term memory. Clearly, you cannot capitalize on recency in a serial recall task; you must start recalling with the first item in the list. Since you cannot rely on immediate recall for any of the items in serial recall, you must rehearse them as they are shown, in order to store them in a more enduring form.

Serial Position Effects

We generally refer to the early positions of the list as the "primacy portion" of the serial position curve; these are the early serial positions plotted across the bottom of the figure. "Primacy" here has its usual connotation of first—it's the first part of the list that was studied. The term primacy effect, then, always refers to the accuracy of recall for the early list positions. A strong primacy effect means good, accurate recall of the early items on the list, usually due to rehearsal, whereas a weak primacy effect, low accuracy on the early items, is usually due to insufficient rehearsal. The final portion of the serial position curve is known as the "recency portion." A recency effect refers to the level of correct recall on the final items of the originally presented list. "High recency" means high accuracy, and "low recency" means that this portion of the list was hardly recallable at all.
As Figure 4–10A shows, a strong recency effect is obtained across a range of list lengths (Murdock, 1962); these lists were presented at a rate of one item per second. Note further that there is a slight primacy effect for each list length, but that the middle portion of the lists showed very low recall accuracy. Apparently, the first few items were rehearsed enough to make them recallable from long-term memory, but not enough time was available for rehearsing the items in the middle of the list. For all lists, though, the strong recency effect can be attributed to recall from short-term memory.

The experimental manipulation that eliminates the recency effect should sound quite familiar to you by now. Glanzer and Cunitz (1966), for instance, showed their subjects 15-item lists, required them to do an attention-consuming counting task for either 10 or 30 seconds, and then finally asked them to recall the items. In contrast to the group that was asked for immediate recall (0 second delay), the groups that had to perform the counting task before recalling the list showed very low recency (Figure 4–10B). On the other hand, the primacy portion of the list was essentially unaffected by the counting task. The early list items, in other words, must have resided in a more permanent, long-lived memory store for them to endure the 30 seconds of counting that was interpolated between study and test. These items seemed quite immune to the interference effects of the distractor task. The most recent items, however, were dramatically susceptible to interference, so they must have been stored in a shorter-term, more fragile memory—STM.

Other manipulations, summarized by Glanzer (1972), showed how the two portions of the serial position curve are indeed influenced by different factors. For our consideration of short-term memory, notice that providing more time per item during study (3 versus 6 versus 9 seconds), had virtually no effect on the recency portion of the list, but did alter the primacy portion to a significant degree (see Figure 4–10C; from Glanzer & Cunitz, 1966). Additional time to rehearse enabled subjects to store the early items more strongly in long-term memory, it seemed. On the other hand, additional time was not necessary or even helpful for the sort of immediate recall used for the most recent items. These items were presumably held in short-term memory and recalled rapidly before interference could take place.

**Rehearsal Buffer**

The notion of short-term memory as a "rehearsal buffer," a mental recycling system for holding information temporarily, was clearly a dominant idea through the 60s. Waugh and Norman's (1965) model explicitly showed rehearsal as a recirculating loop within primary (short-term) memory. The typical interpretation was that rehearsal was an optional control process invoked by short-term memory. Rehearsal was thought to have two properties; it could maintain information in short-term memory, via recirculating it through the rehearsal buffer, and at the same time it
The study described above...

Figure 4-11 shows two kinds of serial position curves within the results to study the biased in the use of the information presented the subjects... produce a significant difference between Knew and Knew, and there is more difficulty of course, that does this...

In the next section, the data of the study performed by K-L... the position of the focus on the focus portion... the other difference from their previous... the findings are the differences in the kind of previous subjects' section during the presentation of the data is researcher provided...
advantage of the rapid, "spewing out" kind of immediate recall. Indeed, the fact that they could begin their recall with these last items affected the way they studied—as if they had said to themselves, "I don't need to spend much time on the last items, since I can name them first." This is, of course, an illustration of metacognitive awareness on the part of the subjects, a tailoring of their rehearsal strategy to the particular task. (How often have you tailored your study time and habits to fit the kind of exam you're going to have?)

A final kind of support for the notion of two kinds of STM rehearsal comes from developmental studies of children's learning and short-term memory performance. A second study by Kellas, McCauley, and McFarland (1975a) examined performance of children in third, fifth, and seventh grades. In support of several earlier studies, their results showed an increase in laborious rehearsal across the grade levels: seventh-graders rehearsed much more than fifth-graders, and fifth-graders rehearsed more than third-graders (see also Flavell, 1970). The important point here, however, concerns the recency effects that were found. As Figure 4-12 shows, there were virtually no differences among the grades in the recency items in the lists—immediate recall from STM did not differ. However, the more deliberate kind of rehearsal responsible for primary effect differences did vary with ages.

It seems very clear from these several studies that two distinct kinds of rehearsal can be performed in short-term memory, a deliberate kind that transfers information to long-term memory, and a simpler, less effortful kind that is responsible for recency effects. The deliberate, strategic rehearsal responsible for primary effects will be discussed further in the next chapter, since its effect seems to be one of transferring information to long-term memory. For our consideration of short-term memory, however, notice two things: first, the constancy of the recency effect across ages and across differing amounts of study; and second, the elimination of the recency effect under conditions of interference, either by distraction from rehearsal (the counting task) or by the need to recall other information first (the serial recall task).

What is short-term memory for? Part of the answer is rehearsal—rehearsal that can transfer information to long-term memory and rehearsal that maintains a short-term memory trace for a brief period of time. While both of these functions are obviously important, it still seems that something is missing in this answer. James, after all, suggested that primary memory is related to attention and consciousness. This certainly suggests that short-term memory is more than just a "rehearsal buffer," however correct that conclusion may be. Demonstrations such as the Shepard and Metzler (1971) mental rotation study make a similar suggestion: a conception of short-term memory as "the rehearsal place" is too limiting, too inflexible to account for the complex mental activities people routinely perform. To anticipate just a bit, the final section of this chapter will conclude that short-term, working memory is not only "the rehearsal

![Figure 4-12](image)

**Figure 4-12**

Recall accuracy across serial positions for free recall, subjects from grades 3, 5, and 7. Notice that the primary effects differ by age, but that recency is nearly the same for all three groups.

place," it is also the "place" where comprehension and reasoning take place. We need a broader conception of short-term memory, one that does justice to all our mental activities and capabilities.

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**Working Memory**

A significant advance in our understanding of this memory system has been provided by the careful and insightful work done by Baddeley and his colleagues (Baddeley, 1976; Baddeley & Hitch, 1974; Baddeley & Lieberman, 1980). Baddeley and Hitch began their paper with a rather startling statement: "Despite more than a decade of intensive research on the topic of short-term memory (STM), we still know virtually nothing about its role in normal human information processing. This is not, of course, to say that the issue has been completely neglected: The short-term store (STS) . . . has been assigned a crucial role in the performance of a wide
range of tasks including problem solving ... language comprehension ... and most notably, long-term learning. However, despite the frequency with which STS has been assigned this role as an operational or working memory, the empirical evidence for such a view is remarkably sparse (1974, pp. 47–48).

These authors quickly pointed out that they were not questioning the fact that learning, recall, reasoning, and so forth make demands on an information processing system that is limited in capacity or attention. Nor were they questioning the “span of immediate memory” result that so many have obtained, that only about seven items can be recalled immediately without error (Miller, 1956). Instead, they were suggesting that the short-term memory system we are accustomed to thinking about was considerably richer than simple ideas such as 7 + 2 and the recency effect. They suggested that working memory was a more appropriate term for this rich and important system. Critically, they demonstrated in their research that this working memory system was a more interesting cognitive component than the studies of memory span and recency effects had implied.

To document their position, they described a particularly dramatic case study, reported by Warrington and Shallice (1969; also Shallice & Warrington, 1970; Warrington & Weiskrantz, 1970). A series of reports by these authors described a patient “who by all normal standards, has a grossly defective STS. He has a digit span of only two items, and shows grossly impaired performance on the Peterson short-term forgetting task. If STS does indeed function as a central working memory, then one would expect this patient to exhibit grossly defective learning, memory, and comprehension. No such evidence of general impairment is found either in this case or in subsequent cases of a similar type.” (Baddeley & Hitch, 1974, pp. 48–49, emphasis added; also Vallar & Baddeley, 1984.) In short, how can working memory and short-term memory be the same, when a patient with grossly defective STM performance exhibits no memory deficiencies in other tasks attributed to STM? To anticipate the conclusions in Baddeley and Hitch’s paper, the problem lies with the theory of an undifferentiated STM. In Baddeley’s view, traditionally defined STM is but a small component of a larger, more elaborate working memory.

The Dual Task Method

Let’s spend some time reviewing the evidence that Baddeley and Hitch presented to support this novel view. To begin with, they noted that evidence about short-term memory has typically come from two quite different results: first, the limited memory span, and second, the recency effect in free recall tasks. They noted that the one common characteristic between these results was the notion of limited capacity, that memory span and the recency effect both imply a memory system with rather severe limits. Of course, this idea has been common at least since Miller’s characterization of short-term memory as an information processing “bottleneck.” They then designed a series of experiments based on the dual task procedure. In general, they asked subjects to perform two tasks at a time, both of which were thought to make significant demands on the limited-capacity working memory system. Most commonly, one of the tasks was a memory span task—to hold some number of items in a short-term buffer, then recall those items after the other task has been completed. The critical aspect here is that some amount of processing is necessary to maintain the items in the recycling buffer. With many items, i.e., a heavy memory load, enough mental resources may be used that performance on the other task will deteriorate. Thus, as in all dual task settings, Baddeley and Hitch were interested in the competition or interference effects that might be produced when two attention-consuming tasks had to be performed simultaneously. See Table 4–3 for a description of the condition in Baddeley and Hitch’s experiments.

As you read, remember the purpose of the dual task procedure and the kind of interpretations it permits. Any two tasks that are performed simultaneously may show either complete independence, complete dependence, or some intermediate level of dependency. If neither influences the other, then we infer that the two tasks rely on separate mental mechanisms, or on separate pools of mental resources. If one task always disrupts the other, then the two tasks presumably require the same mental resources while they are being performed. That is, some common memory component or pool of capacity is being tapped by both. Finally, if the two tasks interfere with each other in some circumstances but not others, then there is evidence for partial overlap between the two, partial sharing of mental resources (see chapter 13 for an elegant application of this reasoning to the topic of neurocognition).

Working Memory and Reasoning In the Baddeley and Hitch experiments, subjects were asked to hold from one to six randomly chosen letters or digits in the short-term “buffer,” the system responsible for the memory span. Naturally, subjects’ recall for those items was always tested. The other activity in their dual-task procedure varied; in some experiments, it was a reasoning task, in others it involved language comprehension, and still others used a free recall learning task. Baddeley and Hitch’s first three experiments used a concurrent (simultaneous) reasoning task. That is, while a number of items were being held in short-term memory, subjects also had to do a mental reasoning procedure. Stims such as AB were presented, and subjects had to respond true or false to an accompanying sentence. For a stimulus such as AB, true sentences might be “A precedes B,” a passive-voice “B is preceded by A,” a negative “B does not precede A,” one using the alternate verb “B follows A,” any combination of these (e.g., passive negative “A is not preceded by B”...
Table 4-3 DESCRIPTION OF THE CONDITIONS TESTED IN BADDELEY & HITCH (1974).

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hold 1 or 2 items in buffer.</td>
</tr>
<tr>
<td></td>
<td>See AB, and decide true or false to sentence “B does not precede A.”</td>
</tr>
<tr>
<td></td>
<td>Recall items in buffer.</td>
</tr>
<tr>
<td>2</td>
<td>Hold 6 items in buffer.</td>
</tr>
<tr>
<td></td>
<td>See AB, and decide true or false to sentence “B follows A.”</td>
</tr>
<tr>
<td></td>
<td>Recall items in buffer.</td>
</tr>
<tr>
<td>3</td>
<td>(control condition)</td>
</tr>
<tr>
<td></td>
<td>Hold 0 items in buffer.</td>
</tr>
<tr>
<td></td>
<td>(same concurrent task)</td>
</tr>
<tr>
<td></td>
<td>Recall 6 items for memory span task.</td>
</tr>
</tbody>
</table>

Experiment 3

<table>
<thead>
<tr>
<th>Articulatory suppression task</th>
<th>then</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control condition—no articulation</td>
<td>See AB, and make same kind of decision.</td>
</tr>
<tr>
<td>Condition 1—repeat “the the the” out loud for duration of trial</td>
<td>Simultaneously see AB, and make same kind of decision.</td>
</tr>
<tr>
<td>Condition 2—repeat “one two three four five six” out loud for duration of trial</td>
<td>See AB, and make same kind of decision.</td>
</tr>
<tr>
<td>Condition 3—hold 6 randomly ordered digits and repeat out loud for duration of trial</td>
<td>See AB, and make same kind of decision.</td>
</tr>
</tbody>
</table>

As you would expect, the time it took to make the true/false judgments increased as the test sentence became more complex. The slowest and most difficult sentence type to judge was the passive negative type.

More to the point, however, was the way reasoning speed depended on the memory span task. In Experiment 1, only one or two items were “preloaded” into memory—stored and held in the short-term rehearsal buffer throughout the reasoning task. There was no interference under these conditions (see Table 4-4). Subjects’ recall of the “preloaded” letters was essentially perfect and did not depend on hearing versus seeing the preloaded letters. In Experiment 2, however, subjects were preloaded with either zero or six letters; in the “zero preload” condition, subjects were given the six letters after they had answered the reasoning question, thus placing no memory demand on them during the reasoning task. When correct recall of the letters had been stressed, reasoning time jumped from 2.7 seconds to 4.7 seconds with the six-item memory load. And not only was reasoning speed slower in this condition, but recall of the six letters also suffered. In contrast, the “equal stress” group, whose instructions did not stress memory at the expense of reasoning, showed only a small increase in reasoning time when they held six letters in working memory—but their recall dropped to only 3.7 items on the memory span task.

Table 4-4 REASONING TIMES AND LETTER RECALL UNDER VARIOUS MEMORY LOAD CONDITIONS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Memory load (number of letters held in memory)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Reasoning times</td>
<td>3.20 sec</td>
</tr>
<tr>
<td>Letter recall</td>
<td>essentially perfect</td>
</tr>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Reasoning times</td>
<td>3.27 sec</td>
</tr>
<tr>
<td>Letter recall</td>
<td>5.5</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>5.8</td>
</tr>
<tr>
<td>Reasoning times</td>
<td>2.73</td>
</tr>
<tr>
<td>Letter recall</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Note: In both experiments, a memory load of 0 was a control condition. In these conditions, subjects performed the reasoning task, and only then were they given the set of letters for the memory span task. Thus, letter recall of 5.8 in the 0 Memory load condition means that 5.8 letters were recalled immediately after their presentation, where presentation followed the reasoning task.

Adapted from Baddeley & Hitch, 1974

The Working Memory Interpretation. Overall, it seemed that holding six items was a significant drain on working memory. If you were holding six items, there was insufficient extra mental capacity for doing the reasoning task “up to speed.” Subjects could sacrifice reasoning speed and manage to do well on the memory span task, or could sacrifice memory span and do well on reasoning speed. But they seemed unable to do well on both tasks unless the span task made minimal demands on the working memory system. Baddeley’s interpretation here is quite important. It seemed that the reasoning task was dependent on the capacity of working memory, a limited resource system. One- or two-item memory loads caused no disruption in working memory, so holding these memory loads was probably dependent on a different component of the overall working memory system. On the other hand, the component that was used
for memory span performance could be overloaded by asking it to hold six items. Under these overloading circumstances, Baddeley suggested that the memory span component tends to drain mental resources from the larger, multipurpose working memory system. Baddeley called the component responsible for memory span the articulatory loop (e.g., Salame & Baddeley, 1982). The articulatory loop seems to be a subcomponent of working memory, specialized for the verbal-based recoding of items that can prevent forgetting. Under small memory loads, the articulatory loop functions independently, and does not disrupt working memory. With heavy memory load, however, it shows partial overlap with the general working memory component used for reasoning. This partial overlap is evidenced by the interference between memory span and reasoning speed.

Let’s read a description of Baddeley’s proposed working memory system, so that the later studies will fit into an appropriate context (a diagram of the proposed working memory system is shown in Figure 4–13). A particularly apt description of this system appears in Salame and Baddeley (1982): “The articulatory loop [is] part of a broader conceptualization of short-term memory … termed Working Memory. The Working Memory system was assumed to comprise a central executive which was responsible for initiating control and decision processes, and which was assisted by a number of subsidiary slave systems. The articulatory loop was one of these, and was assumed to comprise a modality-free store which used the process of articulatory rehearsal in order to maintain items in short-term storage” (p. 151).

Notice first that working memory was a multicomponent memory system, the main part of which was an executive control system. This executive was in charge of directing attention and mental resources, of starting the rehearsal procedure when it was necessary, and of making decisions. It also carried out the bulk of the reasoning task. An assistant to the executive, a “slave system” in Baddeley’s terms, was the articulatory rehearsal loop, the component responsible for memory span performance (another so-called slave system was the visuo-spatial scratch pad, described by Baddeley and Lieberman, 1980). The slave systems can operate on their own, once triggered by working memory, without disrupting the central executive’s functions at all; such is the situation with only one or two memory span items. On the other hand, if the slave system is asked to do too demanding a task, such as holding six items in a memory span task, it has the option either of doing poorly on the task or of draining off some of the executive’s resources for itself. Of course, when the slave drains resources from the executive, we would then expect the task being performed by the executive to suffer.

The Articulatory Loop To test the characteristics of the articulatory loop, Baddeley and Hitch conducted a third experiment. In this study, they asked subjects to perform the standard reasoning task while doing one of three “articulatory suppression” tasks (there was also a control task that required no other processing). One of the articulatory suppression tasks required fast repetition of the word “the.” The idea here was that saying “the the the” would not require memory, per se, but would consume the articulation resources of the articulatory rehearsal loop. As such, saying “the the the” should suppress any articulation that is a normal part of the reasoning process. The second suppression task required rapid repetition of the sequence “one two three four five six.” This form of articulatory suppression might be a bit more difficult than “the the the,” Baddeley and Hitch reasoned, but still not as difficult as a true memory span task. Finally, the last suppression task involved a genuine digit memory procedure, with strings of six digits. In this task, sub-

FIGURE 4–13 A DEPICTION OF BADDELEY’S WORKING MEMORY SYSTEM

<table>
<thead>
<tr>
<th>WORKING MEMORY</th>
</tr>
</thead>
<tbody>
<tr>
<td>EXECUTIVE CONTROL SYSTEM</td>
</tr>
<tr>
<td>(Central pool of mental resources)</td>
</tr>
<tr>
<td>Activities:</td>
</tr>
<tr>
<td>Initiate control and decision processes</td>
</tr>
<tr>
<td>Reasoning, language comprehension</td>
</tr>
<tr>
<td>Transfer information to long-term memory via rehearsal, recoding</td>
</tr>
<tr>
<td>Recency effects</td>
</tr>
</tbody>
</table>

| ARTICULATORY REHEARSAL LOOP |
| ("Short-term buffer") |
| Activities: |
| Recycling items for immediate recall |
| Articulatory processes |
| Executive’s resources are drained if articulation task is difficult |

| VISUO-SPATIAL “SCRATCH PAD” |
| Activities: |
| Visual imagery tasks |
| Executive’s resources are drained if imagery task is difficult |

The executive control system supports reasoning, language comprehension, and other such tasks by using resources from the central pool. Both the articulatory rehearsal loop and the visuo-spatial scratch pad have their own mental resources, but these are insufficient for especially demanding tasks. When necessary, each of these can drain resources from the central pool in the executive control system.
Subjects had to repeat aloud the digit string over and over while answering the reasoning sentences—obviously, a combination of articulation and memory span. Notice how the amount of articulation in the three suppression tasks was about the same (a speaking rate of four to five words per second was enforced), but the demands on memory steadily increased from “the the” through the digit recycling task.

The reasoning speed results for different sentence types are presented in Figure 4-14. In general, reasoning time increased as the sentences became more complex. Further, reasoning time also increased as the suppression task grew more difficult. It seemed clear that both the reasoning and the articulation tasks could share the same pool of mental resources or attention if necessary. Enough resources were available for a minimal memory load of one or two items while reasoning (Experiment 1), but certainly not enough were available for a heavy memory load task combined with reasoning (Experiment 2). And when an articulatory suppression task to be performed aloud was required, then the great drain on working memory slowed down the reasoning task even more (Experiment 3). By far the most dramatic condition in the figure is that last group, passive negative reasoning problems (“A is not preceded by B”). When no other task was required (control condition), these sentences took slightly over 3 seconds to judge. But if a randomly selected string of six digits had to be recycled through memory at the same time, these difficult sentences required nearly 6 seconds to judge.

Language Comprehension The results found by Baddeley an Hitch on language comprehension tasks were largely the same as those for reasoning problems: holding six digits in memory significantly disrupts comprehension scores and also significantly impaired the subjects’ memory span performance. In companion experiments, reasoning and comprehension speed were tested when the stimulus sentences were phonetically similar (“B precedes P”; “Redhead Ned said Ted fed in bed”) versus dissimilar (“M precedes C”; “Dark-skinned Ian thought Harry ate in bed”). Of course, the fact that short-term memory often relies on a phonetic-articulatory code means that phonetically similar items should be more difficult to process (recall the acoustic confusion results describe earlier). This was exactly what happened.

The general conclusion from Baddeley’s research is that working memory is a more suitable name for the attention-limited “workbench” or “scratch pad” system of memory. Working memory is responsible for the active mental effort of reasoning and language comprehension, as well as for the transfer of information into long-term memory by means of rehearsal. Aside from the central executive of working memory, there is separate articulatory loop component. The articulatory loop is partial autonomous, in that it can recirculate a small amount of information with out interfering with the central executive’s performance. When ove loaded, however, it begins to drain extra mental resources from the executive component. This disrupts the ongoing executive activity, whether is reasoning, comprehending, or learning. An overall limitation in the amount of mental resources available to working memory is implied quite strongly here—the extra resources that are drained by the articulatory loop are not replaced into working memory by some other component. Instead, working memory merely suffers along with insufficient resources for its own work. But, of course, as processes become more automatic fewer of working memory’s resources are consumed by the task (see Hin & Kalmar, 1987, for an analysis of the “pools of resources” metaphor).

A particularly interesting implication of this work, as yet not tested in a thorough fashion, concerns the growth of automatic processing in children. Presumably, any conscious process will use working memory, an will consume some of its limited resources. As a child’s mental process
become more automatic, however, we imagine that fewer and fewer conscious resources are necessary for performance. It would be very interesting to see experiments that use Baddeley’s dual task procedure with children to observe how interference between mental processes changes with age. For children just learning to read, for instance, we might expect that a letter detection task and simultaneous digit span task might produce great interference. At later points, when letter detection is more automatic, we would expect little, if any, interference between those two tasks, but still might predict interference between word recognition and digit span.

A Working Memory Interpretation of the “Classic” STM Effects  A final strength of Baddeley’s proposed working memory system is that it can accommodate most, if not all, of the standard short-term memory effects you read about earlier in the chapter. For instance, a working memory reinterpretation of simple memory span would suggest that the articulatory loop can hold about seven plus or minus two units of information, but a heavier load is not possible because of restrictions in the available pool of mental resources. Likewise, interference in STM, say, in the Brown-Peterson task, can be attributed to insufficient mental resources. Backward counting uses enough resources that those remaining are insufficient for recycling the three-letter stimulus in the articulatory loop. Similarly, because holding three words in working memory should drain fewer resources than holding three letters, the superior recall of words after an attention-consuming distractor task is understandable. Notice also that counting backward at a rapid rate was enforced in all of the experiments that used the Brown-Peterson task. This means that the other task, remembering the stimulus, would suffer instead of the counting performance. Clearly, if subjects had been permitted to slow down their counting, recall would have improved.

Finally, Baddeley’s dual task has been applied to a study of primacy and recency effects (Baddeley & Hitch, 1974). Increasing the memory load from 0 to 3 to 6 items depressed primacy effects in free recall, but, rather surprisingly, did not alter the recency effect. Apparently, the articulatory loop responsible for memory span performance is a separate system from the one that generates the recency effect. As such, recency effects may provide evidence of a separate recall mechanism, one not tied to the active rehearsal and recycling that is characteristic of the articulatory loop.

We’re not done with working memory by any means; we’re just taking a brief pause. You’ll encounter the working memory system again when we discuss language comprehension, problem solving, decision making, and so forth. Of course, this shouldn’t be a surprise—this chapter has suggested that whatever conscious attention is, it’s closely related to working memory, the place where conscious mental effort is expended. Just as a preview, you’ll find working memory implicated in the process of fluent reading (e.g., Baddeley, Logie, Nimmo-Smith, & Brereton, 1985), in the difficulty of reasoning (e.g., Scribner, 1975), and in the nature of our contributions to a conversation (e.g., Norman & Rumelhart, 1975). At the beginning of this chapter, a five-year-old “abused working memory.” Why was the father’s working memory abused? What would you have added to the child’s last remark—the question, “So, can I?”—to avoid the confusion? And what does that tell you about your sensitivity to someone else’s working memory?

CHAPTER SUMMARY

1. Short-term or working memory is an intermediate memory system between the sensory memories and long-term memory. Its capacity for holding information is rather severely limited, on most accounts to only 7 ± 2 units of information. The process of recoding, grouping more information into a single unit, is the means of overcoming this limitation or “bottleneck” in the information processing system.
The multipurpose system known as working memory:

STM research is the articulation loop, neocortex complex, of the work of learning, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. STM research is the articulation loop, the main processor of the brain. 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