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Chapter 7

The Development of Working Memory

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Working memory refers to ideas that are thought of, or made available to the mind, just when they are needed in order to carry out a mental task or solve a problem. A simple example is remembering a phone number so you don't have to keep your eye on the exact spot in the phone book while entering the number. As a slightly more complex example, suppose you need to add 39 and 46 without using paper or a calculator. To do so, you must keep in mind both of the numbers to be added while bringing to mind the procedure you will use to do this sort of addition. In the conventional procedure, after you add the numbers in the right-hand column, 9 and 6, you must remember to decompose the answer (15) into a 5 that goes in the right-hand column of the sum and must be remembered, and a 1 that is added to the left-hand column's numbers, making $1 + 3 + 4 = 8$ in this second column. Then you must remember to adjoin the numbers in the two columns, forming the answer (85).

Two things may set these examples apart from memory as discussed in most places within this book: capacity limits and time limits. In contrast to the vast capacity of the human mind to learn information and retrieve it on occasion, the amount that one can bring to mind all at once, to perform a task or solve a problem, is quite limited. (To appreciate this, just ask a friend to get you seven unrelated items, as long as he or she is going into the kitchen anyway. You are more likely to get a confused or irritated reply than you are to get all seven items.) Moreover, this limited amount of information that is brought to mind at any one time can be kept in mind only briefly (say, less than about 1 minute) unless the person devotes intense effort to the task of retaining the information. (Remember the things you wanted to say to someone but forgot while that person was talking to you? How about the errand you forgot to run because something more interesting caught your attention first?)

Because this working memory is so important in daily life, it would be very helpful to know how it changes with development in childhood. If we knew that, we would know a lot about particular limitations on thinking and problem solving in children of various ages. A child could not solve a problem that required more working memory than he or she could muster.

It is clear that young children do not do as well as older children on tasks that directly measure aspects of working memory. One of the most basic, often-replicated findings is that older children are able to repeat back verbatim a longer list of words than younger children; that is, they have a higher "memory span" (for a review see Dempster, 1981). However, we still must ask, what is the basis of developmental differences in working memory such as this one? Do they reflect a developmental increase in working memory capacity, or perhaps of the persistence of working memory across time? Do they instead just reflect the use of better knowledge and strategies in older children?

Before examining these developmental questions, however, it is important to ask how working memory operates in general. This is a complicated, unresolved issue that involves many different

processes. There are multiple views of how working memory operates, and they have implications for what type of developmental change is theoretically possible. As a result of this unresolved debate, I believe, there has not been a recent comprehensive review of what we know about working memory development. Baddeley (1986) provided a review of working memory from one theoretical vantagepoint, and Gathercole and Baddeley (1993) updated it from a similar perspective, with more developmental information included. This chapter will cover some of the same material but will place greater emphasis on highlighting some controversial issues that arise from a comparison of opposing theoretical viewpoints. A single chapter on this issue cannot be fully comprehensive, but this chapter will at least surf across a wide range of relevant topics in an attempt to organize and explain them.

<a>Theoretical views of working memory

The traditional view of working memory (Baddeley, 1986) has been that it depends in part on an older concept, "short-term storage." The concept of short-term storage states that there is a part of the mind that is capable of holding a small amount of information for a limited period of time. It is contrasted with "long-term storage," the vast store of information accumulated throughout one's life.

In order to use short-term storage within a working memory system, the right information must be placed in the store, kept active in the store until it is needed, and then retrieved in a timely fashion. For example, to remember a phone number until it can be dialed, according to Baddeley's (1986) model, one would save the phonetic sequence corresponding to the digits in short-term storage; keep the phonetic sequence active as long as necessary by silently rehearsing it (i.e., repeating it to oneself); and then mentally read out the contents of the short-term store while dialing. In an arithmetic problem, the same working memory mechanisms might be used. One might, for example, need to store the phonetic sequence "carry a one" in short-term storage; keep it active in this memory store for as long as needed using covert verbal rehearsal; and then retrieve it when the operation is to be carried out.

Recently, though, some researchers have questioned whether working memory does have to depend on a short-term store after all. The essential defining property of a short-term store is that information in the store has a limited capacity, which theoretically might occur either because it can only hold so many items at once (see Miller, 1956) or because whatever information it holds decays over time (see Baddeley, 1986). An alternative possibility described by Cowan (1995, Chapter 4) and Ericsson and Kintsch (1995) is that information in long-term memory has properties that just make it *seem* as if a short-term store is involved. According to that view, chunks of information are stored in memory with contextual markers that point out the situations in which the information is relevant. New information concerning the problem one is presently working on would be stored with the most relevant contextual markers, and therefore would be, for the time being, easier to retrieve than most other information in memory.

According to this description of “long-term working memory,” the information would not decay over time. However, it could become harder to retrieve over time for two other reasons: (1) because the context does not remain the same as it was, and (2) because subsequent information may interfere with retrieval. For example, suppose you wanted to carry out an addition problem ($42 + 39$) in your head. Suppose further that the numbers represented the dollar prices of items to be purchased, and you wanted to figure out the sum while standing in the store’s checkout line. This requires having the numbers available in memory while carrying out the operation. Even if you were able to meet this requirement with no problem, it might be impossible for you to report the numbers or their sum a few minutes later, while driving away from the department store. According to the view in which there is no short-term storage, the reason might be that the sights and sounds of the store helped you remember how much each item cost. Without that context, the sensory information corresponding to the price tags might be harder to retrieve from memory. Still another reason might be that, in the meantime, you have thought of the prices of several other items that you wish to buy in another store, or decided not to buy. These numbers in your memory are stored with contextual cues similar to the ones in the addition problem, and when you try to retrieve those numbers again the new numbers might interfere. This is just one example of how a change in context and inter-item interference can reduce the chance of correct recall.

We don’t know what all of the relevant contextual markers and aspects of interference really are. If the contextual changes and interference occurred quickly and strongly enough, there might be enough forgetting to make it look as if information must have been lost from a quickly-decaying short-term store.

So, despite many reliable findings in the working memory literature, different theoretical views still remain viable. As an analogy to these possibilities, we might consider libraries with several different types of organization. First, in a library with a decaying short-term memory, you can telephone in a request for a book and it will be retrieved from the stacks and held at the checkout desk (the short-term store) for you. You can request as many books as you want; the library will find a way to accommodate you. However, each book will only be held for a certain period of time (say, 1 week) and then will be reshelved.

Second, in a library with a capacity-limited short-term memory, the books you request are held indefinitely, provided that there are not too many books requested. When the holding area is full, though, the older requests that have not yet been picked up are sent back to be reshelved. The holding time will depend on the demand for the space. If there is an extremely heavy book-holding demand, your book might not even be held for an entire day, and you might not have time to pick it up!

Third, in a library without a short-term store, the books you request are not moved from their original storage locations, but a little flag is placed sticking out of the book, making it easier to retrieve when you

arrive. The flag is color-coded for the date, day of the week, season, and year. So if you come in soon or recall exactly what flag was used on that day, the retrieval process could be easy. That will be true especially if not many books received similar flags. However, if you wait too long (so that the flag that was used is no longer exactly clear to you) or if too many books were tagged at around the same time, retrieval will be difficult.

One shouldn't take the analogy too literally. It breaks down, for example, in that memories may not exist in discrete locations like books but, rather, may be distributed across large, overlapping areas of the cortex, and almost certainly would not disappear from their long-term memory locations when they were placed in short-term storage. However, the analogy can help to clarify how different working memory systems might operate.

Let us now examine the evidence for and against a distinct short-term memory in a little more detail, on the basis of some of the relevant research.

The basis of short-term forgetting, part 1: Is there decay?

The fundamental question of whether "short-term memory storage" really exists as a separate entity is an old one (Conrad, 1967; McGeoch, 1932; Melton, 1963), but it is more alive in the field today than some popular summaries would lead one to believe. An opposing view, the "unitary memory" view, is that the same rules of learning apply to all memory tasks, from those lasting a few seconds to those lasting hours or days (Crowder, 1993).

According to the "dual-storage" view, which states that the human mind includes separate short- and long-term storage mechanisms, the basic distinguishing property of short-term storage is that it is based on a temporary memory representation that deteriorates or decays within, say, a minute or less. Long-term storage would be subject to forgetting from contextual changes and interference, but not decay. The unitary memory view holds that memory in any task is not susceptible to decay, just retrieval failures owing to other factors (contextual shifts, interference).

Some of the evidence that used to be viewed as strongly in favor of a short-term memory store has had to be reinterpreted in light of more recent evidence. In one classic study, Peterson and Peterson (1959) presented three spoken consonant letters on each trial and then imposed a distracting task, counting backward by 3 or 4 from a particular number, lasting between 3 and 18 seconds. After that distraction, the participant was to recall the letters. Even though it did not seem likely that there would be much interference from the numbers with the letters, the recall of the consonants fell off dramatically as the period of distraction lengthened. It was assumed that consonants could not be rehearsed during the distracting period and that the short-term memory representation of those consonants decayed during that time.

Keppel and Underwood (1962) re-examined performance in Peterson and Peterson's procedure, and found something disturbing to the view that the dropoff of memory performance as a function of the distractor period resulted from short-term memory decay. They found that there was very little forgetting in the first trial or so, regardless of the distractor period. It was only after several trials that long distractor periods within a trial hurt performance much. This suggested that long-term memory was involved in the task, and that memory loss occurred only if there was the possibility of interference from the letters presented on previous trials. The dual-storage theorists still could suggest that the distractor period was effective because it allowed short-term memory decay, and that this decay would hurt performance only if there was enough interference from previous trials to prevent a more durable type of memory storage from forming. However, the unitary memory theorists could explain the results without decay, by suggesting that good recall depends upon remembering the context in which the last set of consonants was presented, and that a distractor period reduces the distinctiveness in memory of that most recent set of consonants, allowing its consonants to become more easily confused with consonants presented on previous trials. It is as if one is standing near the last telephone pole in a row, which would look very large and distinct in comparison to poles farther down in the row. As one moves away from the row of poles (i.e., as the duration of the distracting period increases), the last pole appears to merge closer to the other ones (i.e., distinctiveness of the most recent consonant set in memory decreases).

Another classic type of evidence for short-term storage came from "free recall" procedures, in which a list of words was presented in either written or spoken form on each trial and was to be repeated with the words in any order that the participant found convenient. That type of procedure results in a U-shaped recall function, with much better recall of the words presented near the beginning and end of the list, and poorer recall of words presented in the middle. The superior recall at the beginning of the list, or "primacy effect," was thought to occur because the first few words can be attended and rehearsed without competition from other items. In contrast, the superior recall at the end of the list, or "recency effect," was thought to occur because the short-term memory representation of the last few words has not yet decayed much by the time of recall. Seeming to support this interpretation, Glanzer and Cunitz (1966) found that a distracting task interposed between the end of the list and the participant's recall attempt left the primacy effect unaltered, but greatly reduced the magnitude of the recency effect.

Bjork and Whitten (1974) carried out a procedure that challenged the dual-store explanation of the recency effect in free recall, much as Keppel and Underwood's (1962) study challenged the dual-storage explanation of Peterson and Peterson's (1959) study. Bjork and Whitten presented pairs of words with a distracting period before and after each pair. The final distracting period occurred just before the recall test and was long enough (12-42 seconds) that it should have allowed the short-term memory

representation of the list to be eliminated, or nearly so. Nevertheless, a recency effect emerged. It could be attributed to the greater temporal distinctiveness of the last few pairs of items, given that they were separated by distracting periods. It is as if the poles in a row were greatly separated, which would allow one to stand further back from the end pole without losing a sense of its special distinctiveness from the other poles.

This "continual distractor procedure" that Bjork and Whitten used has been extended to a situation with distractor periods between individual items rather than item pairs (e.g., Koppenaal & Glanzer, 1990), again resulting in the "long-term recency effect." The procedure also has been extended to produce long-term analogs to other effects that previously had been taken as indices of short-term memory at work, including an advantage of memory for words presented in a spoken as compared to a printed modality (Gardiner & Gregg, 1979) and a disruptive effect of an interfering spoken word, or "suffix," placed directly after a spoken list to be recalled (Glenberg, 1984). All of these findings opened up the possibility that a unitary memory account could explain the basic short-term memory findings (forgetting across distractor periods; recency, modality, and suffix effects in free recall) without any need to make reference to a decaying short-term store. The principle that the temporal distinctiveness of an item in memory aids its recall would be sufficient.

Nevertheless, there are findings in the research literature that seem difficult to account for without the notion of memory decay (for reviews see Healy & McNamara, 1996; Cowan, 1988, 1993, 1994, 1995). Perhaps foremost among them, Reitman (1974) tested memory for lists of five monosyllabic nouns (presented visually and read aloud by the participant) that were followed by a distracting period filled only with tones to be detected in noise, and included an elaborate system for finding out if a particular participant was likely to have been rehearsing the words while carrying out the detection task. There was little forgetting of words in participants who rehearsed, but there was considerable forgetting in those who did not rehearse. It is possible that the rehearsal just served to counteract interference from the intervening noise and tones, but they are so unlike the verbal items to be remembered that it seems more likely that the rehearsal served to counteract decay. There was little in the intervening stimulation that could have interfered with the items, so this suggests that the rehearsal process prevented words from decaying in memory. (For other evidence that appears to pose a problem for unitary memory theories, see Conrad, 1967; Cowan, Wood, & Borne, 1994; Craik, 1970; Craik & Birtwistle, 1971; Vallar & Baddeley, 1982; Watkins, Watkins, Craik, & Mazuryk, 1973; Wingfield & Byrnes, 1972).

There also is recent physiological evidence of neural aftereffects of tone stimulation in the temporal lobe lasting several seconds, which is easy to explain on the basis of memory decay but might be difficult to explain without decay (e.g., Lü, Williamson, & Kaufman, 1992; Mäntysalo & Näätänen, 1987; Sams,

Hari, Rif, & Knuutila 1993). It has been assumed that these neural responses are related to behavioral components of memory, and there is evidence to support that. For example, the "mismatch negativity" component of the event-related potential occurs basically for any physical change in a repeated sound that the participant would be able to detect if he or she were listening, even though the mismatch negativity is recorded while the participant ignores the sounds. Thus, it has been assumed that the mismatch negativity occurs when a sensory trace of a standard sound is compared to a deviant sound in the brain and found to differ from the standard (Näätänen, 1992). However, the mismatch negativity does not occur if the sounds are further apart than about 10 seconds (Sams et al., 1993).

Cases of neurological damage also seem to support the notion of memory decay (Squire, Knowlton, & Musen, 1993). One relevant phenomenon is damage to the hippocampus, an area embedded within each temporal lobe of the brain, and to closely surrounding areas (typically through strokes, disease, or operations to cure severe epilepsy). This does not affect performance on short-term memory tasks (or memory for about a 10- to 30-second period), but in severe cases of bilateral damage it prevents the patient from learning anything new in a way that can be deliberately, consciously recalled later. In contrast, damage to certain other areas of the brain can severely impair short-term memory for a particular type of information (e.g., spoken verbal information). That also has the effect of impairing long-term memory for the same kind of information, presumably because the information does not get a chance to be encoded well in long-term memory; but it does not produce a general long-term memory impairment. Thus, different types of brain injury selectively impair short- versus long-term memory.

Still, objections could be raised. For example, a unitary memory theorist might argue that the hippocampus is needed to link an event to its context for the sake of memory encoding. It would have to be assumed that within a matter of seconds, the context has changed and the event therefore no longer can be consciously retrieved (though it has left a mark on memory that can affect procedural or indirect tests of memory). However, proposing that a contextual change depends on a fixed brief period seems somewhat arbitrary.

A final type of evidence for memory decay is an indirect one, having to do with Baddeley's (1986) notion of a verbal "articulatory loop," a system in which verbal information is presumably held temporarily and, until it decays from storage, can be refreshed from time to time through covert verbal rehearsal. A strong impetus for the formation of this theory was research on the word length effect by Baddeley, Thomson, and Buchanan (1975). They found that immediate memory for sets of short words was superior to memory for sets of longer words. They also conducted a separate task in which participants received short subsets of the items that had appeared in the memory test, either in spoken or in written form, and were to read or repeat these items as quickly as possible. This task was meant as an

estimate of the rate at which covert verbal rehearsal could take place. It was found that there was a linear relation between the rate at which items of a particular type could be repeated and immediate memory for those items. Specifically, it seemed that people remembered about as much of a particular type of item as they could repeat in about 1.8 seconds. This relation between rapid speech rate and immediate memory performance has been replicated many times, with diverse means of varying the repetition rate including manipulations of word length, individual differences, age differences, or differences between one language and another (Baddeley, et al., 1975; Cowan, Keller et al., 1994; Gathercole, Adams, & Hitch, 1994; Hulme, Thomson, Muir, & Lawrence, 1984; Naveh-Benjamin & Ayres, 1986; Nicolson, 1981; Schweickert & Boruff, 1986; Standing, Bond, Smith, & Isely, 1980; Stigler, Lee, & Stevenson, 1986). This relationship is illustrated schematically in Figure 7.1.

{Insert figure 7.1 here }

The explanation (Baddeley, 1986) has been as follows. The phonological representation in each word in a list to be recalled is saved in a short-term memory store, or "buffer." In order to be retained in the store, each item must be rehearsed before it is totally lost from storage through decay. Assuming that overt repetition and covert rehearsal can take place at about the same rates (not a bad assumption; see Landauer 1962), it seems that one can recall as much as can be rehearsed in about 1.8 seconds. This suggests that the persistence of information in the buffer without rehearsal is only about that long -- about 1.8 seconds.

An alternative theory is that more slowly rehearsed words hurt performance not because they allow more decay, but because they cause more interference with memory. One problem with that account is that it does not explain the 1.8-second constant. When rehearsal speeds up, the rate of interference also speeds up (at least in terms of the number of phonemes rehearsed per second). Therefore, the memory performance should not go up with rehearsal speed. It does just that.

Nevertheless, the relation between speech rate and memory span is just a correlation. We do not know the true cause of the correlation, so the unitary memory account cannot be ruled out definitively.

In sum, for the sake of the simplicity and parsimony of theory, it has seemed attractive to some investigators to have a unitary theory of memory with as few explanatory principles as possible and no concept of memory decay. However, there are important aspects of the evidence that the unitary memory theorists have yet to explain. These types of evidence seem to be more readily explainable using the concept of memory decay. Still, this is a fundamental unresolved question in need of further evidence.

The basis of short-term forgetting, part 2: Is there a capacity limit?

A possibility that requires more attention is that memory is limited not by time per se, but by the quantity of information. Miller (1956) was an early proponent of this view when he observed that short-

term recall in many circumstances seemed to be limited to about 7 items (plus or minus two).

If there is such a limit, its nature is still in question. The old interpretation is that there is a limited number of fixed "slots" in short-term storage and when too many items are presented, some items are bumped out of the slots they occupy. A unitary memory theorist might argue that the limit occurs because of interference between items in memory generally, not in a special short-term store. Perhaps over seven or so items presented in immediate succession cannot all be remembered because they are not distinct enough from one another, having been presented close to one another in time and with little opportunity for very meaningful, coherent encoding.

Some researchers have proposed that there is a capacity limit in short-term memory, but that it is inflated by other contributions. There can be recall from long-term memory even in what is viewed as a short-term memory task; and recall can be enhanced by mnemonic processing strategies, such as covert verbal rehearsal, that help one to hold more items than would be possible through effortless, automatic processing alone. Techniques in which rehearsal is minimized and the performance levels are corrected for the presumed contribution of long-term memory have resulted in the revised estimate that two to four items can be held passively in memory (e.g., Glanzer & Razel, 1974; Watkins, 1974).

Time and capacity limits considered jointly

One important question that has not been answered yet by research in the field is how the short-term memory time limit that Baddeley et al. (1975) observed is related to the capacity limit that other have observed. Zhang and Simon (1985) suggested that both limits exist. They examined short-term memory in Chinese, for sets of monosyllabic characters, disyllabic words, and idioms consisting of four syllables. In terms of the number of units, the average observed memory spans were 6.6 characters, 4.6 words, and 3.0 idioms. However, consider that this amounts to 6.6 syllables for the character spans, 9.2 syllables for the word spans, and 12.0 syllables for the idiom spans. To account for these results, they developed a model in which there was a time limit in recall (similar to the model of Baddeley, 1986) but in which this limit consisted of a constant amount of time to retrieve each unit plus an extra amount of time to unpack the unit into its syllables and process them individually.

Even if one accepts Zhang and Simon's proposal, a remaining question is whether the capacity and time constraints operate similarly. Specifically, assuming that the phonetic information is lost over time, is there information in a limited number of nonphonetic "slots" that remains until it is bumped out by additional information, or is the nonphonetic information lost through the passage of time, as well? The answer to this question may depend on exactly what "capacity limits" are. They could reflect a limit in automatically held information. Indeed, that seems to be the spirit in which researchers such as Miller (1956) thought of short-term memory slots. In this case, it seems reasonable that these automatically held

slots might be susceptible to memory decay, in addition to the severe interference from additional information. Theories of memory have rarely considered the possibility of a form of memory representation that has both capacity limits and time limits.

Alternatively, the capacity limit that has been observed (just 2 to 4 items, according to the literature we have discussed) could reflect the amount that can be held in awareness or the "focus of attention" at any one time. It does not seem that attention to an item just fades away; it is maintained on the item or items for a while and then abruptly shifts to other matters depending on such things as task demands and the person's motivation.

A working model of working memory

The purpose of the discussion above was to make the point that we still do not really know exactly what the limits on memory are. In a situation like that, in which much basic research remains to be done, it often reduces confusion if one assumes that a particular tentative or "working" model of the processing system is correct. People tend to hold to such models implicitly, even if they are not fully aware of doing so; and stating a model explicitly may just bring one's assumptions out in the open.

One simple model of memory was suggested by Cowan (1988, 1993, 1995). The essence of this model is reproduced in Figure 7.2. In it, only a subset of the vast information in an individual's memory is in an activated state at any one time, making that information easy to access if it should be needed. The activated information can be sensory, phonological, or semantic in nature. Moreover, only a subset of this activated information is in the individual's current focus of attention. The attentional focus is controlled in part by the central executive, which represents the individual's voluntary processing strategies, and in part by shifts of attention to abrupt changes in the stimulus (e.g., loud noises, color changes) and possibly pertinent words in it that sometimes appear to be analyzed automatically (e.g., one's own name spoken by someone trying to get your attention).

{Insert Figure 7.2 about here }

According to this model, any amount of information could be activated at once, but the information decays. Based on various types of evidence, it has been suggested that the decay is most severe for about 2 seconds and continues at a continually decreasing rate for about 15 or 20 seconds (Cowan, 1984, 1988). In contrast, information in the focus of awareness does not decay, but there is a capacity limit on how much information can be in the focus. Thus, in this model, the time and capacity limits apply to different aspects of short-term memory. Retrieval of information of both kinds also might be affected by interference.

Not shown in the diagram, there could be differences between types of activated memory (e.g., the separate verbal versus spatial stores described by Baddeley, 1986). However, the simplicity of the

diagram is meant to suggest that these different modules could operate in a similar manner. It also is meant to suggest that we do not yet know all of the relevant subdivisions of memory. For example, are tone and speech memory handled together, or by separate modules? It is not yet clear (Jones & Macken, 1993).

If one removes the time limit on activation, the model shown in Figure 7.2 also would turn into one version of the unitary memory model. Unitary theorists do not deny that there is a capacity-limited focus of attention; they only deny that there is a time-limited aspect of memory.

Thus, although there are many theoretical possibilities that have not been ruled out, Figure 7.2 can serve as a device to simplify our perspective as we move on to other issues. It is similar in spirit to the prior model suggested by Baddeley (1986), except that the “active memory” of the present figure is a short-term storage device that includes any type of processed information (e.g., sensory, phonological, or semantic information), and thus is more inclusive than the distinct phonetic and visuospatial short-term stores depicted in Baddeley's model.

There are some neurophysiological findings with positron emission tomography in humans (Awh, Jonides et al., 1996) and individual neural cell recordings in monkeys (Miller & Desimone, 1994) that provide general support for a model like Baddeley (1986) or the model shown in the figure. These studies show that there are separate areas of the brain that are involved in the passive, automatic retention of information for a short time (e.g., in the temporal lobe), versus the active, effortful processing that can be used to prolong short-term memory (e.g., in the frontal lobe).

<a>Developmental changes in working memory

Working memory can be involved in various ways in almost any mental task, ranging from memory to problem-solving to comprehension. It would be overwhelming to try to summarize developmental changes in each of these tasks individually. Instead, the following discussion focuses on what the underlying changes in the processing system may be. There are some changes that clearly do occur, and others that are still tentative.

Focusing on the basic processes that appear to change is important for two reasons. First, it can lead to a better appreciation of development in general. Second, the developmental changes can be relevant to the theoretical model of working memory that is favored. In turn we will consider apparent developmental changes in (1) knowledge, (2) processing strategies, (3) processing speed, (4) the use of attention, (5) passive memory loss over time, and (6) passive memory capacity.

Changes in knowledge

Since the beginning of cognitive psychology, it has been clear that knowledge aids in immediate memory tasks, in which the participant tries to recall a list of items presented on each trial. Miller (1956)

discussed the short-term memory limit in terms of "chunking," which is a grouping together of items on the basis of knowledge. For example, one can remember and repeat back a list of nine unrelated letters (e.g., "sdc-rqb-ltz") only with great difficulty. In contrast, it is easy to repeat back a list of 9 letters that can be grouped into 3 meaningful three-letter chunks (e.g., "usa-cia-bbc"). In the latter case, the relevant real-world knowledge greatly helps to reduce the load on memory.

If there is one mental attribute that is sure to increase with age, it is knowledge. However, it is often difficult to decide if a developmental improvement in the use of working memory occurs because of an increase in knowledge, or because of other reasons. Ordinarily, the developmental change in knowledge is also accompanied by a developmental change in the brain and an improvement in other aspects of mental functioning. Therefore, it is difficult to know what improvements are due to knowledge per se.

Some work of Chi (1978) occurred in a special situation in which the effects of knowledge are evident. They tested memory for chess board setups in adults who were relative novices at chess, and in children who were experts. In this test, each participant inspected the chess board and then had to reproduce the setup without looking at the original board. Other short-term memory skills also were tested. In general, the children's short-term memory was inferior. When it came to legitimate chess game setups, however, the expert children were superior to the novice adults. The children's knowledge of chess presumably allowed them to chunk the board into larger configurations of pieces that were easier to remember.

In general, knowledge aids working memory because it reduces the effective memory load. To the extent that one has the knowledge to link items together into a meaningful pattern, and to the extent that these patterns are in fact noticed, the stimuli no longer have to be remembered as separate, arbitrary elements.

Some studies have been useful in distinguishing knowledge contributions from other contributions to working memory. For example, Roodenrys, Hulme, and Brown (1993) studied the development of memory span for words (of which one can have lexical knowledge) and nonword strings of sounds (of which one cannot have such knowledge). Older children's short-term recall benefitted from the lexical factor more than younger children. This finding will be discussed in greater detail later on, when the aim will be to distinguish knowledge from other possible sources of development in working memory.

Changes in processing strategies

The way in which a person approaches a working memory task, or any other task for that matter, is far from automatic or consistent. Instead, the individual has various choices of processing methods or "strategies" from which he or she can choose. This topic is not totally separate from the previous topic, knowledge, because the use of a better strategy may depend partly on the individual's knowledge of

which strategy is best (and partly on the individual's ability to use the strategy effectively when that knowledge is present).

To illustrate strategy use, consider a child's means of solving a simple addition problem such as $9 + 3$ (Geary, 1990; Geary, Bow-Thomas, Fan, & Siegler, 1993). If the child knows the answer, the fastest way to solve the problem is usually to retrieve it from long-term memory. If the child does not know it (or, at least, does not know it with sufficient confidence), another method will be preferred. The child might rearrange the numbers. By transferring 1 from the second number to the first, it can be seen that they are equivalent to $10 + 2$, which the child may recognize as 12. If the child cannot decompose the numbers in this way, a third method is to start at 9 and count up to 12. If that ability is not present, the child may have to count all the way from 1 to 12. Sometimes, especially for problems with sums less than 10, fingers are used as a working memory aid. A problem such as $5 + 3$ can be solved by the child uplifting 5 fingers on one hand and 3 fingers on the other, and counting the uplifted fingers.

A child may not use a developmentally new strategy consistently at first. Instead, work by Siegler (1994) has shown that the use of strategies varies from trial to trial. A new strategy may be used only on a small proportion of the trials, and that proportion tends to grow as the value of the strategy becomes clear and the child becomes better at using it effectively. All the while, the older, less desirable strategy becomes less and less frequent.

Strategies that are used to assist in a memory task are termed "mnemonic strategies." One might think of general, commonsense guidelines such as writing down the information or ignoring potential distractions as mnemonic strategies. However, most mnemonic strategies would fall under the rubric of "rehearsal," or going over the information in one's mind. Rehearsal, in turn, can be subdivided into "rote" and "elaborative" rehearsal. Rote rehearsal means going over the information exactly, whereas elaborative rehearsal means forming new, meaningful connections between items to be remembered.

When the material permits elaborative rehearsal, it is by far the more effective means of remembering. However, the ability to carry out elaborative rehearsal is more a reflection on the knowledge structure and inventiveness of the individual than of his or her working memory capacity per se. Therefore, tasks that are intended to measure working memory capacity are often designed in such a way that it is difficult to carry out elaborative rehearsal. For example, in memory span tasks, often the items are drawn from the same small set on every trial and do not form a meaningful pattern. This is the case, for instance, in the digit span task used in tests of intelligence. The participant hears a short sequence of digits and repeats it back, and the sequence length is made longer until the participant makes an error on several trials in a row. The longest length successfully repeated is one estimate of the participant's span. Without intensive training, it would be very difficult to do more than rote rehearsal in

this type of task. There isn't much time to make up a story about the sequence of numbers.

The use of the strategy of rote rehearsal is one that is known to improve with development. This topic is examined in much more detail within the following chapter (on strategy development), so it will just be briefly summarized here. Flavell, Beach, and Chinsky (1966) examined children's lip movements during a delay between a short list of items and the memory test, relying on the observation that, in young children, even "covert" rehearsal could not be entirely covert but would produce movements of the lips. It was found that the lip movements did become more frequent in older children, who remembered more. Subsequent studies have shown that the absence of rehearsal is not just a matter of knowledge that this strategy would be useful; very young children can be instructed to rehearse at the age of about 5, but it still does not improve their recall. Older children benefit more from rehearsal, and that is at least partly because they come to rehearse in a more useful, cumulative fashion in which more items in a row are strung together in rehearsal. This plays an important role in the development of short-term memory. For example, Cowan, Cartwright, Winterowd, and Sherk (1987) found that a rehearsal-blocking task in adults (whispering the alphabet while listening to a spoken list of words to be recalled) resulted in short-term recall levels very similar to what 5-year-olds ordinarily attain without any rehearsal-blocking task.

There also is a developmental trend in the tendency to use rehearsal spontaneously. Even though young children's performance sometimes benefits from instructions to rehearse, they typically do not continue to rehearse when they are no longer explicitly instructed to do so. Ornstein, Naus, and Liberty (1975) and Naus, Ornstein, and Aivano (1977) found that sixth-grade children rehearsed spontaneously whereas second- and third-grade children did not. This might be accounted for on the grounds that rehearsal is more effortful, and therefore probably more aversive, in younger children. Guttentag (1984) showed this using a secondary probe task in which children were to repeatedly tap on a plastic key connected to a computer while engaging in a memory task with instructed cumulative rehearsal. The logic of the experiment was that the more effort is needed for the rehearsal process, the less effort will be available for tapping, which therefore will be slowed relative to a control condition in which tapping is carried out by itself. It was indeed found that there was more interference in younger children, amounting to a tapping slowdown of 41% in second-graders, 31% in third-graders, and only 17% in sixth graders. All ages managed to rehearse in sets of about three items together in a rehearsal cycle. (They were to include the word just presented along with at least two words presented previously. For example, while hearing the list *car, bear, house, desk*, a child in compliance might be heard to repeat, "car...bear, car...house, bear, car...desk, house, car..." and so on). This rehearsal set of three was no higher than the normal, spontaneous rehearsal sets of older children when simply asked to rehearse out loud, whereas the younger children spontaneously rehearsed in smaller sets of one or two items in a cycle.

It is not really known whether “cumulative rehearsal” is exactly the way that words are rehearsed silently, when overt rehearsal is not required; it could be, for example, that people are able to covertly rehearse several words at once in a parallel fashion, which they logically are unable to do in overt rehearsal.

In sum, it seems certain that working memory strategies improve with development. What is less clear is why they improve. There is evidence of improvements in (1) the knowledge or understanding of what strategies would be useful; (2) the ability to implement the strategies; (3) the ability to use the strategy without expending undue effort; and (4) the ability to use better versions of the strategy. These changes come at different points in development, making the entire developmental sequence a complex and fascinating one.

Changes in processing speed

Until this point, we have discussed developmental changes in knowledge and strategy use, both of which are very complex and must involve the acquisition of additional information in older children. The next topic, changes in speed of processing, could occur more directly because of the maturation of brain tissue. Brain maturation is completed gradually, with some changes occurring as late as adolescence (Rabinowicz, 1980). Some of this maturation, for example, involves completion of the myelin layer that serves as insulation for some nerve cells and speeds up the transmission of impulses. It is perhaps for this reason that various processing speeds increase with development (Kail & Salthouse, 1994; Hale & Jansen, 1994). This speedup can have important implications for how working memory operates.

Theoretically, there are at least two ways in which processing speed could matter. One way is simply that faster processing could allow a task to be completed more quickly. This could be especially important because a task that takes too long may be discouraging, and a child may give up before completing it. Faster processing minimizes the chances of that happening.

Second, faster processing is especially important if information is lost over time. This could occur either if the premise of “memory decay” is correct, or if the situation is one in which there is continuing interference that is imposed as a function of time. By speeding up processing, it becomes more likely that the necessary processing will be completed before the information upon which that processing must operate becomes unavailable.

As we have seen, one process that depends on speed is just what we considered in the strategy section, covert verbal rehearsal. According to Baddeley's (1986) model, faster rehearsal is more effective because it allows more items to be refreshed in short-term storage before they are lost from storage, and therefore allows more items to be held in short-term storage at the same time. As discussed above and depicted in Figure 7.1, a great deal of research has suggested that the rate at which the to-be-remembered

items can be pronounced is important. Older children not only know their words, letters, and numbers better; they also can pronounce these items faster than younger children, and therefore might reactivate items in short-term storage through rehearsal at a faster rate (Baddeley, 1986).

More recent research has suggested, though, that this cannot be the entire story. Based on the earlier research by Flavell et al. (1967), Henry (1991), and many others, children as young as 4 or 5 years of age do not use rehearsal at all, so "the speed of rehearsal" would not be a meaningful parameter for these children. Sure enough, when one looks at pronunciation speed and memory span in individuals within an age group, rather than averaged across individuals, one finds that the correlation holds up fairly well for older children (e.g., 8-year-olds) and adults, but not for younger children (Cowan, Keller, et al., 1994; Gathercole, Adams, & Hitch, 1994). This, then, leads to a puzzle. Rehearsal speed might explain why there is a linear relationship between speaking rate and memory span in children 8 or older, but it does not explain why the same relationship holds for age group means including even younger children. One possibility is that the speaking rate task correlates with some important property of cognition in addition to covert rehearsal speed. For example, the sophistication of the rehearsal strategy might be correlated with the rate of speech, as both of these things improve with age. It will take some very careful analyses of individual differences to determine the full reason why speech rate and memory span are correlated.

Research in my laboratory (Cowan, 1992; Cowan et al., 1994) has discovered another process that is faster in children with a better memory span and speeds up with development. We measured the timing of children's correct repetitions of lists of words in a memory span task, using a computer program that is capable of measuring individual segments of speech and pauses. The duration of words in the response did not differ depending on the memory ability or age of the child; at least between the ages of 4 and 8, the age range of children in these studies, words are spoken at a relatively constant rate regardless of how fast the child *could* pronounce individual words. What varied much more, however, was the duration of silent pauses between words in the responses. These silent pauses were shorter in older and mnemonically more advanced children.

These inter-word pauses in the spoken responses also were longer for longer lists, which helps to clarify what process may be occurring during the pauses. During these periods, the child may be trying mentally to sift through the words in the entire list to determine which word to pronounce next; the words were to be pronounced in the order in which they were presented. This process could be termed "memory search" and has been discussed in related studies in adults (Sternberg, Monsell, Knoll, & Wright, 1978; Sternberg, Wright, Knoll, & Monsell, 1980). For correctly repeated lists of an approximately fixed length (about 3 to 3.5 items), 4-year-olds produced an average inter-word pause of 0.38 seconds, whereas 8-year-olds produced an average pause of only 0.23 seconds.

If these inter-word pauses do reflect memory search, as we suspect, then it is important that there are converging reasons to believe that memory search changes with age. This kind of result has been obtained in the simple procedure developed by Sternberg (1966). In this procedure, participants receive a list and then a probe item, the task being to indicate whether the probe comes from the list or not. In adults, each item in the list adds an additional 20 to 40 milliseconds to the reaction time, suggesting that participants mentally search for the probe in their mental representation of the list items, in a rapid manner. However, this search process is several times slower in young children (e.g., Keating, Keniston, Manning, & Bobbitt, 1980). It also is intriguing that Sininger, Klatzky, and Kirchner (1989) found much slower than normal memory search in children with language impairment.

Is there an explicit explanation of why memory search rates would be expected to affect memory span, similar to speaking rates? Perhaps the reason itself is similar. Information can be lost from short-term storage while either speech articulation processing or a rapid memory search are ongoing, and the faster these were to be conducted the less time there would be for short-term memory loss to take place. Thus, it appears that the speeds of at least two processes, speech and memory search, contribute to working memory. (Our ongoing work suggests, moreover, that they are not highly related to one another.)

Nevertheless, a possibility that must be considered carefully is that some factor that changes with development other than processing speeds may be responsible for the correlation between processing rates and memory span. This remains possible because we only have correlations between processing speeds and memory span, which is not the same as an experimental demonstration that processing speeds determine span. For example, it is theoretically possible that the causal factor is knowledge. Older children and adults know words better than younger children, and this may allow them both to process the words faster and to recall more of them than younger children. In fact, Case, Kurland, and Goldberg (1982) supported this possibility. They showed that adults who were to repeat nonsense words could only do so at a rate that was equivalent to 6-year-olds producing words, and that the levels of recall for these two situations were comparable also.

There is no way to rule out such an explanation definitively at this point, but at least one recent study (Roodenrys et al., 1993) did address it. This study examined memory for sets of short, medium, and long words, and also for sets of short, medium, and long nonwords (e.g., “glof” is short, “spigdub” is medium, and “prelafoon” is long). When one plots memory versus speeded speaking rate for words of different lengths, one finds that they are linearly related; sets of shorter words can be pronounced more quickly and recalled better than sets of longer words, as shown in Figure 7.1. The same is true for nonwords, but these do not fall on the same line as words. They fall at a lower level of recall for a particular speech rate.

This suggests that recall may be affected by speech rate and word knowledge separately, with speech rate determining the slope of the relation between word length and memory span, and word knowledge affecting the intercept or overall height of the line depicting that relation (Hulme, Maughan, & Brown, 1991). Roodenrys et al. used this technique with children 6 and 10 years old. The difference between performance on words versus nonwords was greater in the older children, so they appear to have benefitted more from word knowledge. However, a more striking effect was that if one drew a straight line through all of the word data in a plot comparable to the present Figure 7.1, younger children would be lower down on that line than older children (with slower speech and smaller spans). The same is true for nonwords. So the speech rate change seems separate from the word knowledge change, though more work on this topic is needed.

Until now, the types of developmental change that have been pointed out could be expected according to almost any reasonable theory of working memory. They all could attribute importance, for one reason or another, to knowledge, strategies, and processing speed. However, that may not be the case for the possible changes to be considered below. Theories of working memory that do not emphasize the role of attention and how it is employed would not predict that differences in the allocation of attention would lead to different working memory ability. Theories with no decay would not predict what looks like decay differences across ages, and those without a memory capacity limit would not predict a developmental difference in that limit. The findings of the relevant studies therefore may be of use in helping to determine what theory of working memory is most apt.

Changes in the use of attention and processing capacity

In the model of Cowan (1988, 1995) shown in Figure 7.2, one important aspect of working memory is the focus of attention. There could be developmental differences in the functioning of this focus of attention that would be seen as working memory differences. For example, there could be a difference in how much material can be subsumed within the focus of attention at one time. This amount of useful information in the focus of attention can be termed “processing capacity,” under the assumption that a larger amount of attended information permits a larger amount of information processing. There also could be a difference in how efficiently attention is kept focused on the relevant stimuli and tasks. Finally, there could be a difference in how well attention can be used to prevent the activation of irrelevant information. That is, there could be a difference in the inhibitory function of attention. All of these will be discussed in turn.

<c>Attention as processing capacity.

One possible individual difference in the focus of attention has been proposed by Just and Carpenter (1992). In their model of working memory, there are individual differences essentially in how much

information can be in the focus of attention at any one time. They use a slightly different terminology, however, stating that there are differences in the amount of memory that can be activated at any one time. When they use the term “activation,” though, they mean “kept active by attention,” without considering a role for information that might be activated automatically, without attention.

Daneman and Carpenter (1980) developed a measure of working memory span that seems closely related to this emphasis on attentional limits. The measure is based on the idea that there are two separable aspects of working memory, storage and processing. Daneman and Carpenter suggested that adequate performance in complex tasks requires that storage and processing be used together, and their measure was developed to stress both of these. On each trial, a participant must do two things. The first is to comprehend a series of sentences, and the second is to repeat the last word of each of the sentences after the sequence of sentences is completed. This requires that the subject hold the sentence-final words in mind throughout the time that the comprehension task is being conducted. Given adequate comprehension, the number of sentence-final words that can be remembered serves as the measure of “working memory span.” This working memory span correlates rather well with performance on verbal comprehension and reasoning tasks; much better, for example, than does a simple memory span. Turner and Engle (1989) have shown that this finding is not specific to the use of sentential material. One can use a working memory span measure in which the processing portion of the task is arithmetic instead of sentence comprehension, and the results still correlate with performance on verbal tasks.

Some correspondence between working memory span tasks and the focus of attention seems likely, even though the exact correspondence is still uncertain. If one individual is found to have a higher working memory span than another, the explanation could be that the first individual is able to keep more information in the focus of attention at any one time. That might help the individual to store more information during the working memory task, and it also might help the individual to attend to the processing that needs to be done despite the load on memory.

What I have described is the notion that attention or its usefulness in performing tasks (processing capacity) has to be shared between storage and processing. This idea has been proposed before (Case et al., 1982) and will be examined a little later on. Case et al. suggested that an important difference between younger and older children is that the older ones can do processing more efficiently, leaving them more processing capacity to use for storing items.

There have been at least a few developmental studies with this type of working memory span task. Swanson, Cooney, and Brock (1993) tested third and fourth grade children’s ability to solve word problems and collected a number of other measures including working memory span. A small (less than .30) but significant correlation between working memory span and problem solving ability was obtained.

Walczyk and Raska (1992) studied children in second, fourth, and sixth grades and, not surprisingly, found an increase in working memory span across those ages. Within each age group, working memory span correlated with high-level reading skills including the detection of errors in reading and the ability to draw inferences about the reading. These correlations were substantial, generally in a range of about .4 to .6. Swanson (1996) carried out a wide range of working memory, intelligence, and achievement measures on individuals from 5 to 19 years of age and found correlations between measures in a range of magnitudes similar to Walczyk and Raska. Verbal and visual/spatial measures of working memory were found to be correlated with each other and both correlated with the same intelligence and achievement measures, suggesting that it is a very general resource that develops.

Whether this developmental difference in active processing can account for differences in short-term memory is another question. It should do so if memory storage relies on the same pool of attention or processing capacity that active processing does. To examine this, Case et al. (1982) used a "counting span task," which is similar to the working memory span task of Daneman and Carpenter (1980). In the counting span task, participants counted the number of items on each card and then tried to recall the series of card totals. The longest series resulting in correct serial recall is the counting span. According to the theoretical framework of Case et al., older children's better counting span is to be explained on the grounds that they used less processing capacity for counting, leaving more capacity for the storage of the totals.

Towse and Hitch (1995, Experiment 2) reported results of a study with a modification of the counting task that run counter to this processing capacity account of Case et al. (1982). The participants were children 5 to 11 years old. The counting task was modified so that the targets on each card could or could not be identified by a color feature. In either case, the targets to be counted were blue squares. When they shared a card with orange triangles, the targets could be identified on the basis of either color or shape. However, when they shared a card instead with blue triangles, the targets could be identified by shape only. (The latter were called "conjunction" cards based on the notion that the combination of shape and color was relevant, but that was not quite accurate given that all objects on these cards were blue so that only shape was relevant.) The latter cards produced far more errors in counting and were slower to be counted than the cards that provided a color cue. According to the processing capacity account, therefore, these uniform-color cards should take more capacity away from storage, which should result in lower counting spans. This is in fact what was found, in all age groups.

However, Towse and Hitch noted that there was an alternative hypothesis to be considered. Because the more difficult counting task took longer, it allowed more time for memory of the totals to be lost before the recall task. To control for the effect of time, they included a third condition in which the color

cue was present, but in which more time was needed anyway (roughly comparable to the time needed in the uniform-color condition) because the number of targets per card was higher than in the other two conditions. Even though there were far fewer counting errors in this third condition than in the uniform-color condition, it produced a counting span that was about as low as in the uniform-color condition. This suggested that it was the amount of time taken by counting that was important for counting span, not the amount of attention, processing capacity, or effort.

Actually, the results of this experiment are not so simple. Another reason for the counting span to be reduced in the third condition (the one with a color cue but more targets per card) is that it involves memory for higher numbers, which are well known to be more difficult to process than lower numbers. A figure in which the counting time was matched across conditions (Towse & Hitch, 1995, Figure 5) does show the counting span decreasing markedly as a function of the time taken in counting, but it also suggests that memory was nevertheless poorer in the uniform-color (conjunction) condition than in the other two conditions. There may be separate effects of both the amount of time and the processing capacity used in the task. One might well expect that, if counting span is based on a system in which there is both passive storage and active processing of the material to be recalled (Baddeley, 1986; Cowan, 1988). It remains possible that developmental changes in either the passive persistence of information across time or the efficient use of attention and processing capacity accounts for the developmental change in counting span.

Halford, Maybery, O'Hare, and Grant (1994, Experiment 3) modified the card counting span task in an interesting way. Instead of having to remember the total for each card, a series of numbers was presented first as a memory "preload." Next the cards were presented for counting, and then the preload was to be recalled. The results were consistent with those of Towse and Hitch (1995) in that memory declined as a function of the number of cards counted.

If the same processing capacity were shared between the memory load and the counting task, then the cost of counting should be greater in younger children because they would have to expend more processing capacity in order to count. However, Halford et al. found that the decline in memory as a function of the number of cards counted was very comparable for children who were 5, 8-9, and 12 years old. This, along with other results of this study, suggested that the main source of forgetting was the result of interference or decay of the representation of items in memory, with only a very small effect of the difficulty of the processing task that was carried out along with the memory task.

So, in sum, although it is clear that older children use attention better than younger ones, this does not translate into a commensurately large gain in short-term memory as Case et al. (1982) would have expected. There is a developmental gain in short-term memory ability in these tasks, but it does not seem

to have very much to do with a developmental change in processing capacity or processing efficiency.

This, in turn, leads to a puzzle. If, in working memory span and counting span tasks, the span doesn't depend much on the difficulty of processing, then why does working memory span correlate with performance in comprehension and problem-solving tasks more highly than ordinary memory span does?

One answer is that it could be the ability to carry out two tasks concurrently that is the critical variable distinguishing among individuals and changing with age. This ability to manage different concurrent streams of information would depend upon how adeptly the focus of attention could be switched between tasks, or perhaps split between tasks. This ability probably is closely related to what Baddeley (1986) has termed the "central executive" function. Individual differences in working memory span apparently do not have much to do with varying *amounts* of information in the focus of attention, however. Clearly, more work on this important topic is needed.

<c>Maintaining the focus of attention.

A pioneering study conducted by Maccoby and Hagen (1965) illustrates well that changes in maintaining the focus of attention do affect memory performance. They studied first-, third-, fifth-, and seventh-grade children, using both intentional and incidental memory tasks. On each trial, the child saw a series of colored cards with a picture of an animal or common object on each card. The task that the child was instructed to carry out (the intentional task) was to remember the sequence of colors. After all of those trials were completed, however, a surprise (incidental) memory task was administered. In it, the child was to identify which pictures had been presented with which colors. This was incidental in the sense that the children had not been asked to remember the pictures or their relation to the background colors at the time that the cards were seen. Whereas performance on the intentional task increased with age, performance on the incidental task actually decreased; it was lower in seventh grade children than in the younger children. The older children apparently had learned to focus attention on the relevant aspects of the materials to be remembered, and to ignore distractions, more effectively than younger children did. A similar followup study by Hagen (1967) suggested that the tendency of older children to shut out the irrelevant information increased when an additional distracting task, listening for a deviant low tone within a high-pitched melody, was to be carried out concurrent with the intentional memory task. It appears, then, that older children are more able to focus attention on relevant information, which may increase the likelihood that this relevant information is encoded adequately and recalled.

How would this developmental difference in the deployment of attention contribute to working memory performance? Possibly in a very simple, straightforward way. Within the model shown in Figure 7.2, it is assumed that some of the correct answers that a participant produces on a working memory task are made possible precisely because the information was held in the focus of attention

throughout the duration of the test trial. If a child's attention wanders away from the task-relevant material, fewer of those correct answers can be produced.

<c>Attention and inhibition.

Attention is used not only to activate relevant elements of memory, but also to suppress or inhibit irrelevant aspects, which sometimes appear to become activated automatically and could cause the focus of attention to wander from the relevant information or topic. In the experiment by Maccoby and Hagen (1965), inhibition might have been needed to suppress the urge to attend to the pictures on the cards, which would have detracted from learning of the relevant stimulus dimension (which was the card color). Along these lines, Hasher and Zacks (1989) suggested that working memory may be less efficient when some of the available storage space is taken up by irrelevant information that was not inhibited adequately. They applied this view to changes that occur in aging, but Bjorklund and Harnishfeger (1990) discussed how the same principles might be extended to child development.

There is good reason to suspect that the ability to inhibit irrelevant information would change with age. For example, maturation of the frontal lobe of the brain is not complete until adolescence (Yakovelev & Lecours, 1967). Judging from the behavior patterns of individuals with frontal lobe damage, some areas of the frontal lobe are essential for brain operations in which one holds information in mind and inhibits irrelevant information (Fuster, 1989; Goldman-Rakic, 1992).

One additional type of procedure illustrates that older children do use inhibition more effectively within working memory. It is a variety of the test used to examine Jean Piaget's notion of "object permanence." In the simplest version of the object permanence test, an object such as a toy is covered with a cloth or other obstruction. Infants who are advanced enough to be physically capable of moving the obstruction still will not do so in order to retrieve the toy, presumably because the memory of the toy has faded. Infants who are advanced enough to pass this test still will fail to retrieve the object in another, slightly more sophisticated task with two containers, A and B. After the desirable object has been hidden and retrieved from Container A a few times, the object is moved to Container B. Even though the infant sees the adult place the object under B, often he or she still will search for it once more under A. Apparently, the short-term memory representation of the object under Container B is weak enough that the influence of this memory is overwhelmed by the recently learned habit of looking for the object under Container A. This is termed the "A not B" error.

How do we know that inhibition is involved in this type of error? Consider a situation in which the Containers A and B are transparent (e.g., clear drinking glasses). In this situation, infants sometimes still make the error (Butterworth, 1977). In this situation, it appears that the learned habit can be stronger than even the perception of the object under the obstruction. With age, there is a greater tendency to inhibit

the irrelevant response, allowing the current correct perception or memory to control the response.

Then how do we know that working memory is really involved? There are two reasons to believe that it is. First, far fewer errors are made when the obstruction is transparent than when it is opaque. At least some of the errors have to do with memory of the object being weaker than perception of the object. Second, in one experiment (Diamond, 1985) the obstructions were opaque but a delay was imposed between the time when the object was hidden and the time when the infant was allowed to find it. In this situation, more errors were made at longer delays. Apparently the memory of the hidden object became weaker during the delay, allowing the learned habit of searching at A to predominate more and more as the delay increased. Moreover, this increase in errors with delay time was greater for the younger children. The mean delay at which the A-not-B error first occurred was about 2 seconds in 7.5-year-old infants, and it increased steadily to about 10 seconds by 12 months of age.

This pattern suggests that as the short-term memory of the object in Container B fades, at some point the learned habit of looking in Container A becomes more compelling, and that control of behavior by the learned habit occurs at shorter delays for younger infants. It is still not clear, however, if the developmental change that accounts for this pattern is an increase in short-term memory persistence or an increase in the ability to inhibit the inappropriate learned habit.

We have focused on an example of inhibition in infancy, but it seems likely that the use of inhibition continues to improve throughout childhood (Bjorklund & Harnishfeger, 1990). An experiment by Tipper, Bourque, Anderson, and Brehaut (1989) demonstrates this in an interesting way, using a task known as “negative priming.” The basic task comes from Stroop’s (1935) procedure in which color words are presented in conflicting colors of ink. (For example, the word “blue” might be presented in red ink.) The task is to name the color of ink, but there is a tendency to want to read the word aloud instead, which slows down the color naming and results in errors. The children in the study by Tipper et al. were susceptible to this effect also, though they were slower and made over twice as many errors as the adults.

In the negative priming procedure, Stroop’s task was modified further through a relationship between one trial and the next. The irrelevant word of one trial was used as the relevant color of the next trial. For example, if the irrelevant word was “blue” on trial n , the relevant color and correct response would be “blue” on trial $n+1$. Previous research with adults had shown that this condition results in even slower color-naming than for Stroop’s procedure. The explanation offered was that people inhibited responses to the irrelevant word on each trial. In the case of negative priming, the word that was just inhibited in one trial had to be brought back out of inhibition for the very next trial, which presumably took extra time. However, Tipper et al. found that second-grade children responded differently. Unlike the adults, the children were not slowed down further in the negative priming condition than in the Stroop condition. It

is as if the children did not carry out as much inhibition in this circumstance, and so neither reaped the reward nor suffered the consequence of this inhibition.

Although it thus does appear that there are important developmental changes in inhibition, more work is needed to determine how this developmental change affects various working memory tasks. More work is needed also to determine if this change in inhibition is specific, or if it is just one example of a more general developmental trend toward a more efficient control of the focus of attention through central executive functioning.

Changes in passive memory loss over time?

We have reviewed evidence that there are many developmental changes in knowledge, strategies, and the use of attention that may affect the way in which working memory tasks are carried out. In scientific thinking, it is always wise to begin with the simplest theory possible, and then to complicate the theory only insofar as the evidence demands. It is simpler to believe, for example, that there are at least some aspects of working memory that do not change developmentally. It is in this context that researchers often have suggested that there does not appear to be a developmental change in the period for which of information is passively held by the brain; that is, information of the type referred to by Cowan (1988) and in the present Figure 7.2 as “activated memory,” or the kinds referred to by Baddeley (1986) as the “passive phonological buffer” and the “visuospatial sketch pad.” However, there is no evidence that this memory remains fixed with age; there just has been no evidence that it changes. A change in this type of memory would be important simply because it would mean that older children could hold information in memory longer without even trying.

There is evidence that it is not only the frontal lobes that matures slowly during childhood; there also are appreciable change in other lobes of the brain (Rabinowicz, 1980), which are likely to be involved in the passive storage of information.

Recently, two studies have shown that at least for auditory stimuli, there in fact *is* a change in how long information remains in short-term storage. Keller and Cowan (1994) examined participants' ability to compare two different tones and determine if they are the same or different in pitch. There was a silent period between tones that could vary from trial to trial, and the actual difference between tone frequencies could vary. (“Frequency” is the primary tone characteristic that determines the pitch that one hears.) In order to make the task sufficiently difficult, the tone frequencies were rather close together, generally less than a musical note apart. In this situation, correct performance depends on whether the participant still remembers the first tone in the pair in sufficient detail at the time when the second tone is presented, so that the two tones can be compared. Performance in this situation declines as the inter-tone interval increases from a fraction of a second to about 20 seconds, usually leveling off by that time. The

hypothesis under investigation was that younger children would lose tone pitch memory more quickly over time. Participants in three age ranges were tested: 6-7 years, 10-12 years, and adults.

The developmental difference in tone pitch memory loss over time can be examined fairly only if the age groups are not different at all inter-tone intervals. If, for example, older children are better no matter what the interval, then differences in the loss of information across intervals could be explained with the uninteresting hypothesis that memory loss can be observed better at some levels of performance than at others. To rule out that uninteresting type of explanation, Keller and Cowan adjusted the difference between the tone frequencies for each individual, in order that each age group would perform at about the same proportion correct (.84) when there were about 2 seconds between tones. However, then the groups were tested also with longer inter-tone intervals using these same tone differences. It was found that the younger children performed at a particular fixed level of performance (.71) with 8 seconds between the tones on the average. The older children, however, could perform at this same level with about 10 seconds between the tones, and the adults could do so with about 12 seconds between them.

One interpretation of this age difference is that older participants' brains automatically preserved the tone memory longer, but another possibility is that older participants were better able to use attention to continue to preserve the tones. To examine this, Keller and Cowan conducted a second experiment using only adults. In one condition they were allowed to think about the first tone during the inter-tone interval, just as in the previous experiment. In a second condition, however, they were required to imagine a familiar melody during the inter-tone interval and mark the contour of the melody. Even though there was ample evidence from the contour marks that the adults were faithfully imagining a melody, they did about equally well in the tone comparison task under these two conditions. It appears that memory for the exact tone pitch is held in the brain rather automatically, and is not influenced much by what the participant does intentionally to remember it. Therefore, it seems unlikely that active mnemonic strategies during the inter-tone interval could account for the superior performance of older participants in this procedure. There instead appears to be an age difference in how long tone memories persist automatically before they fade away.

There is one way in this conclusion could be questioned. Our musical imagery task effectively prevented rehearsal, but it could not totally control the way in which the tones were encoded in the first place. Perhaps older children and adults are more attentive at the time that the first tone is presented, and this in some way results in a memory trace that is more persistent over time.

Another recent experiment (Saults & Cowan, in press, Experiment 2) helps to rule out that possibility because the sounds were ignored at the time that they were presented. Participants, who were first-grade children, third-grade children, and adults, played a silent video game that involved matching each picture

in the center of the computer screen to one of four surrounding pictures, whichever one had a name that rhymed with that of the central picture. Meanwhile, random repetitions of the four words bee, tea, bow, and toe were presented at irregular intervals over headphones. Once in a while, without warning, the video game was suddenly replaced by pictures of the four items that had been heard over headphones. The task then was to select (with a mouse click) the item that had been presented most recently. This most recent item had been presented 1, 5, or 10 seconds ago.

The speed and accuracy on the video game could be monitored, and they were found to be the same in this dual-task situation as when no sounds were presented at all, which suggests that the sounds did not take attention away from the video game. Also, in another control condition in which participants were to pay attention to the spoken words and identify them, all age groups did extremely well on these words. However, there was an interesting pattern of memory for ignored words. At a 1-second test delay, all groups did about equally well. Nevertheless, the amount of forgetting across test delays was greater in younger children. This was the case no matter whether one looks at recall of the correct word as a whole, recall of the correct initial consonant (*b* vs. *t*), or recall of the correct vowel (*ee* vs. *o*). Figure 7.3 shows the results for the consonants, which seem particularly interesting. By a 5-second test delay, extreme memory loss had occurred in the youngest group only. By a 10-second delay, considerable loss occurred in the older children also, but little forgetting had yet occurred in adults.

{Insert Figure 7.3 about here}

There still are ways in which one might account for these findings on the basis of subtle shifts of attention that we were unable to measure. At this point, however, the likelihood that there is a developmental difference in passive memory storage seems much greater than it once did. We intend to continue to pursue this avenue of research until it is clear if passive memory loss changes with development or not.

Changes in passive memory storage capacity?

Another way in which passively held memory storage theoretically could change with development is that it could increase in amount. In the terms of Figure 7.2, there could be a limit in how much activated memory one can have at any one time, and that limit could increase with age in childhood.

That kind of idea has been proposed by Pascual-Leone (1970), who has conducted a number of experiments in which the number of items that must be kept in mind are varied, under circumstances that would discourage rehearsal. The amount that can be kept in mind, termed the “M-space” in the theory, is found to increase with age. However, alternative explanations of such findings are certainly possible. The main alternative has been the notion of Case et al. (1982) that the efficiency of mental operations increases with age. If the efficiency increases, this could leave more room for the storage of information,

even if M-space does not change with development. It is going to be difficult to separate these two hypotheses.

Changes in complex tasks

The previous discussion is organized around basic processes within working memory that could change with development. To proceed with this discussion, we have had to assume that particular tasks that have been used are indicative of these specific processes. In reality, most tasks are not pure and a particular task could indicate more than one process.

This point can be illustrated with a discussion of one task that has played an important role in the recent literature. Gathercole and Baddeley (1989, 1990) have developed a task in which young children (e.g., 3-, 4-, and 5-year-olds) hear a multisyllabic nonsense word on each trial and are to repeat it. As long as they succeed, progressively longer and more complex nonwords are given. Older children are able to repeat longer and phonologically more complex nonwords than younger children. This task is clearly interesting because it predicts the acquisition of vocabulary and reading in preschool children; children with a better-than-average nonword repetition scores generally acquire a vocabulary words and beginning reading faster than other children. What process is involved?

Theoretically, it could be any of the six types of process we have examined. First, it could be a difference in knowledge. Older children's superior knowledge of English could make it more likely that a nonword would sound like a word, which would ease the phonological memory load. However, this possibility has been addressed by Gathercole (1995). She divided the nonwords in her experiment into those judged more versus less word-like. It was the less word-like nonwords that best predicted vocabulary acquisition and reading ability. Still, knowledge could play a role in a different way. The more advanced children may have better knowledge of English phonological rules, which could allow them to divide the nonwords into fewer, larger multiphonemic chunks to be stored in memory.

Second, nonword repetition could depend upon strategies. Older or more advanced children may be more likely to rehearse the nonword while it is being presented, making recall more likely. This would be expected according to the research of Flavell et al. (1966), Henry (1991), and others.

Third, nonword repetition may depend upon speed. For example, older children may be able to rehearse nonwords faster, helping to prevent rapid memory loss until the word can be repeated. This would be expected according to the theory of Baddeley (1986). If this is the case, one might expect tests of articulation speed to predict vocabulary acquisition. Perhaps it will.

Fourth, nonword repetition could depend on the versatility of attention. Perhaps older children can begin to plan their articulatory response while still listening to the nonword stimulus, which would ease the demand on memory. Younger children may be less able to do so because it is a type of dual task.

A fifth possibility is that it is a difference in the rate of passive memory loss. Younger children may be more likely to lose phonological information from the passive store before they get a chance to repeat it.

Sixth, and finally, older or more advanced children may simply have more room in phonological memory for multiple phonemes to be held simultaneously. This was the hypothesis that first came to mind when I read about the nonword repetition task, but there is no firm evidence for it.

Thus, as in this illustration, any of the six bases of change in working memory development that have been discussed above remain possible. Any of the six may account for developmental changes in a complex task. It should be clear that more research is needed to determine which of these processes is relevant in particular situations of special importance.

<a>Implications for working memory and its development

The research we have discussed has important theoretical and practical implications. Studies of the development of working memory processes may have implications for what theoretical interpretations of working memory tasks are correct even in adults. For example, we mentioned that the studies showing a limit in memory span, approximately equal to the number of items that the individual can pronounce in 2 seconds, may be difficult to explain if the unitary memory theorists are correct in asserting that there is no specific time limit to memory, only the results of interference and retrieval conditions. The finding of age differences in the persistence of memory for ignored speech may also prove to be awkward to explain from a unitary memory standpoint.

The recent research also has important theoretical implications for memory development in general. It now seems likely that the working memory changes in more ways than any of the current theories have proposed, and this changes the way in which memory development is viewed. The recently discovered factors (changes in the persistence of memory and the rate of memory search) seem likely to be strongly rooted in biological maturation and not very amenable to training, unlike the factors that were most often discussed previously in the field (changes in knowledge and strategy use). However it still is unclear how much of a role training plays. For example, could the rate of memory search or rehearsal be increased through training? Results so far are mixed (Hulme & Muir, 1985; McCauley, Kellas, Dugas, & DeVellis, 1976).

Although we have focused on the development of working memory in childhood, there also are important developmental changes in working memory in the aging process (e.g., Pratt, Boyes, Robins, & Manchester, 1989; Tun, Wingfield, & Stine, 1991). A comparison of the bases of development in children and in aging can be of considerable use because there must be both similarities and differences between the two. The efficiency of processing in the brain is likely to be below the normal young adult in

both children (because of immaturity) and the elderly (because of the deterioration of brain processes), and in this way they are similar. However, a big difference is that the experience and knowledge of an elderly individual should be, in many ways at least, as good or better than that of a young adult, whereas children have less experience and knowledge. If a child does not carry out a mnemonic strategy that young adults use, it is not clear if that is because the strategy is too difficult or because the child did not think of using the strategy (or did not have enough specific knowledge to use it well). When an elderly adult does not use a strategy that young adults use, that is much more likely to be because the strategy is too difficult given the deterioration in brain processes.

Similarities in results obtained with children and the elderly suggest that some very similar processes are important in both cases. In particular, much of the deviation from young adults can be explained on the basis of slower brain processes (Baddeley, 1986; Cowan, 1994; Hale & Jansen, 1994; Kail & Salthouse, 1994; Salthouse, 1994). Relative slowness in brain processes may make it difficult to carry out as effectively many of the strategies that young adults use, and it may permit more memory loss before the individual's mental task at hand is completed.

Finally, there are important practical implications of the development of working memory in childhood for various types of cognitive delay and impairment. Types of task that measure various short-term and working memory processes have been found to be related broadly, across many different situations, to the rate of language acquisition and comprehension ability (Gathercole & Baddeley, 1989, 1990; Gillam, Cowan, & Day, 1995; Lincoln, Dickstein, Courchesne, Elmasian, & Tallal, 1992; Montgomery, 1995); the quality and complexity of language production (Adams & Gathercole, 1995; Blake, Austin, Cannon, Lisus, & Vaughan, 1994), and reading ability (Apthorp, 1995; Bowers, Steffy, & Tate, 1988; Mann, 1984; Farmer & Klein, 1995; Siegel, 1994; Sipe & Engle 1986). The relation between verbal short-term memory and intellectual functioning is further illustrated in that one type of short-term memory task, the spoken digit span, is included in intelligence tests and is related to verbal intelligence (Cantor, Engle, & Hamilton, 1991). If we gain a better understanding of working memory tasks and their development, we may be better able to diagnose, interpret, predict, and eventually treat serious cognitive developmental problems.

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<a>Author notes

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<a>Figure Captions

Figure 7.1. A schematic illustration of the linear relationship that has been observed between the maximal rate at which words can be pronounced and the memory span for sets composed of those words. As shown, the variations in pronunciation rate and span have been obtained either by varying the characteristics of the participant groups' abilities or by manipulating the length of the words.

Figure 7.2. A simplified diagram of the relationship between memory faculties suggested by Cowan (1988). The focus of attention is only a subset of the activated elements in memory because there also is the possibility of automatic activation of memory elements.

Figure 7.3. Recall of the correct vowel in memory for ignored speech at three different silent test delays, for first-graders, third-graders, and adults. Data from Saults and Cowan (in press).

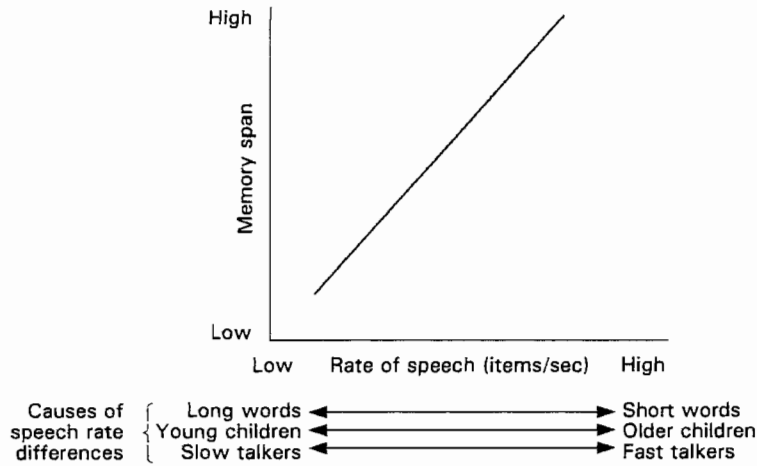


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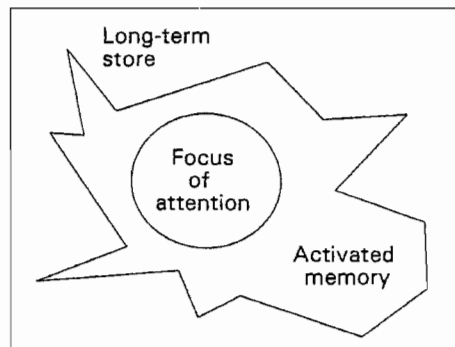


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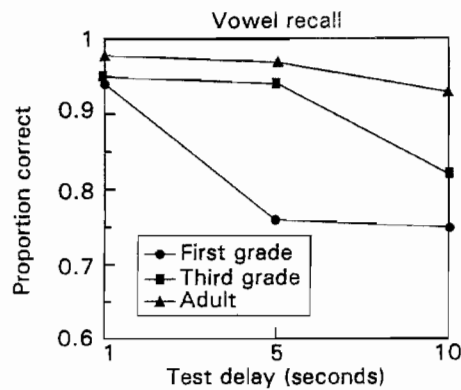


Figure 7.3 Recall of the correct vowel in memory for ignored speech at three different silent test delays, for first-graders, third-graders, and adults. (Data from Saults & Cowan 1996.)