Short-term and Working Memory in Childhood

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Short-Term and Working Memory: What are they All About?

It might be fun to back into the topic at hand, indirectly. Have you ever wondered why young children are so adorable? I can see some connections to my academic specialization, short-term and working memory. (We'll get to these soon.) Often, a child seems cute because of a failure to understand a social situation in the depth that an adult would. When my son was 2 years old, he wandered from the house into the garage and I asked him to come back in and put his shoes on, after which he could go back out there with me. Not receiving a response, I called, "Can you hear me?" To that he replied, "No, I don't hear you!" It seems that he did not want to come in but did not calculate that his response would give him away. When he was several months older, in all earnestness he asked if my wife and I would read two separate books to him at the same time. He had inadvertently re-invented a psychological task known as dichotic listening and was fully surprised and amused to learn that, although we could comply, he could not dually listen. He had been unable to imagine all the cognitive elements of the situation in advance. Recently, my 3-year-old granddaughter was asked why she had not taken a nap during day care, to which she sighed and replied, matter-of-factly in one word, "Problems…" From our viewpoint, using an adult expression without realizing that it did not quite match the adult frame of mind was somehow hilarious. Cognitive failures of this sort can be amusing even when adults produce them. Have you ever planned to drive with a friend (or spouse) to pick up a car from the repair shop, only to have the friend suggest that the two of you drive separate cars to meet at the shop? It seems adorable that the friend did not anticipate the 3-car, 2-driver problem, even though all of the necessary information was right there to be considered.

Short-term and/or working memory is needed to hold in mind the information that would produce a more mature, complete perspective in the above examples. Collectively, it refers to a small amount of information that is most easily accessible to the conscious mind at a given moment, in contrast to the vast amount of information that one has learned over a lifetime. Elements from the lifetime of information often can be coaxed from memory through long periods of thought. For example, if you sit and reflect upon your high school experience, you probably will remember more and more names of classmates. At any one moment, though, only a small subset of the class can be on your mind, readily accessible (that is, brought to consciousness within, say, a few seconds), and usable to solve problems and perform tasks.

The amount of information that can be kept in mind may change with age, and that, according to one view, may be a fundamental reason why children seem so different from adults in their thought processes (Halford, Cowan, & Andrews, 2007). The ability to understand a complex thought depends on how many elements of thought can be kept in mind at once and interrelated. For example, truly understanding the concept of a “little red caboose” depends not only on knowing and remembering the words but also on attaching both adjectives, *little* and *red*, to the noun, *caboose*. It also depends on knowing and keeping in mind that the term *little* is defined relative to other train cars, not to objects in general. (After all, it is a real train car, not a toy one, that is presumably under discussion.) All of these things must be understood and kept in mind simultaneously to get a true impression of what is meant by the phrase. In language comprehension generally, one must keep in mind the information already received until it can be more fully interpreted on the basis of information yet to come. Even the simple instruction, *Put on your warm socks* requires that the verb, possessive pronoun, and adjective be kept in mind, perhaps as separate little ideas, until one hears the noun that ties them all together, *socks*. Similarly, working memory is needed in language production in a process that involves holding the message in mind while figuring out how best to express it as a series of words. In arithmetic, one often must hold information in mind while performing calculations on it.

The amount of information that can be active in working memory at once may also determine how much presence of mind a child seems to display. Whereas a sophisticated older child on Halloween (and I am writing this paragraph on Halloween) standing at the door often remembers to say *Trick or treat*, *Thank you*, and *Goodbye*, a younger child might only remember *Trick or treat*, or might just stand there silently in front of you, not recalling what to say (Berko Gleason & Weintraub, 1976); or might even forget the mission entirely, barging on ahead into the house. The sophistication of an individual's response to a situation is assumed to be related to the amount of relevant information the individual can cull and hold in mind concurrently, from the present environment and from the vast store of past experience.

In this chapter, we will consider some more precise definitions of the terms and concepts that we have bandied about and will get into issues regarding some key processes of the mind, and how they change throughout childhood. Understanding childhood development not only is helpful for raising and educating children, but also provides insights about adult mental function, in much the same way that understanding history helps in appreciating the current political climate. We also consider individual differences in working memory and their implications.

The Differences Between Short-term and Working Memory

People have a lot of confusion about two terms that are widespread in the research literature, *short-term memory* and *working memory* (a distinction relevant also to chapters by Oakes & Luck, and by Reznick, this volume). Yet, both terms have links to the same individual, George Miller. In 1956, he published an article that is one of the most widely cited in all of psychology and became a cornerstone of the cognitive revolution that overturned the behaviorist school of psychology. In the cognitive revolution, an emphasis was maintained on empirical evidence, but a new tenet was that this evidence could be used to reach conclusions about the structure of the mind. Miller's article fit this mold. He was asked to deliver an hour-long invited address but did not feel that he had enough to say on any one topic. After some pleading by the conference organizer and some soul-searching of his own, Miller decided to cobble together a talk based on superficial similarities between several phenomena that he was working on or reading about, all showing that people could remember about seven items at once. (He surrounded the magic number seven by a confidence interval for humorous effect, which also nicely indicated the rough nature of the constancy.) Despite his superficial motive for the article, it helped establish the cognitive notion that there is a limited short-term storage faculty in the mind. This limited faculty also was anticipated in a book by Broadbent (1958). It used behaviorist terminology, but surprisingly including an information processing diagram as a footnote. The diagram basically showed a large quantity of transient sensory information in the mind, from which a small amount of conscious information was culled and from which, in turn, new permanent memories were made. Both Broadbent's and Miller's contributions later served as launching points for various better-developed models of human information processing, including a well-known one by Atkinson and Shiffrin (1968), in which the limited-capacity faculty was termed a *short-term store*. This store was an abstract entity (not necessarily a single part of the brain, but quite possibly some kind of brain ensemble) that was said to hold a few items concurrently. This memory was measured, for example, by the length of a list of items that could be repeated without error (which Miller called immediate memory).

In a thoughtful little book, Miller, Galanter, and Pribram (1960) seem to have coined the term *working memory*. By this they referred to the memory for plans that one had to keep mentally accessible in order to pursue a goal or a set of goals. There was no strong indication that this working memory would depend on the seven plus or minus two items of Miller (1956), but there could well be a relation between them, and many researchers probably thought as much. On the other hand, working memory so defined might also depend on a part of long-term memory within which there is special marking of information that is likely to be needed. Similarly, if one wants to remember the name of a student in class, there are at least two ways to do so. First, one can encode that student's name with some sort of mnemonic aid, thereby improving the ability to retrieve it any time later from memory (e.g., imagine an image of a red-breasted bird with a baker's cap on in order to remember Robin Baker). Second, one can actively think of the name and hold it in the conscious mind while coming into class (e.g., say the name to one's self at precisely the right time). Only the latter method appears to depend on the short-term memory concept of Miller (1956) as refined by Atkinson and Shiffrin, but either method potentially might fit Miller et al.'s (1960) definition of working memory.

The definition of working memory of Miller et al. (1960), did not become wildly popular. A bit later, Baddeley and Hitch (1974) revived the term and used it with a different connotation, which became predominant in the field. They found that models like that of Atkinson and Shiffrin (1968) are too simple because there is more than one short-lived kind of memory. One kind of memory might hold the items being consciously considered, whereas other kinds might hold information for a few seconds even after it is no longer consciously considered, the noted examples being speech sounds (even those imagined on the basis of written input) and images (even those formed on the basis of a verbal description of objects in space). On the basis of a great deal of relevant evidence, Baddeley (1986) discussed a *working memory system* that included a *phonological store* (holding mechanism for speech sounds) and a *visuospatial sketchpad* (holding mechanism for pictures); and also a *central executive* (decision-making mechanism) comprising the mental processes that determine what information gets in and out of the phonological and visuospatial stores, and how the information is manipulated and rearranged. The part of information that was in conscious storage had an ambiguous status: it seemed to be mentioned by Baddeley and Hitch (1974), disappeared from Baddeley (1986) for the sake of parsimony and was possibly reborn as the *episodic buffer* (holding mechanism for ideas) of Baddeley (2000). The episodic buffer was postulated to explain how one could retain, in short-term memory, abstract ideas and associations between very different types of information (e.g., a face associated with a name).

There is the danger of the number of terms and definitions proliferating beyond anyone's control. To make matters worse, laymen seem to use the term short-term memory differently, to refer to information that is held in the long term but with an organized structure making the particular information not too difficult to remember. An example is the knowledge of where one parked one's car this morning. One cannot retain that information all day and simply recall it without first reminiscing for a moment to retrieve it. Laymen and some clinicians often say that amnesic individuals have lost their short-term memory, whereas a cognitive psychologist would say that they have lost the ability to form new long-term memories.

Definitions of psychological processes tend to become associated with the procedures that are used to test them. Daneman and Carpenter (1980) proposed that individual differences in reading comprehension would be related to a more active type of working memory task that required the involvement of both storage and processing of information, taking their leads from the work of Baddeley and Hitch (1974) and others (LaBerge & Samuels, 1974; Newell, 1973). In their *reading span test*, sentences were to be processed and the final word of each sentence was to be remembered. Subsequently, many authors adhered to the notion of working memory tasks as those that included both storage and processing components (in contrast to short-term memory tasks, which had no processing component). This definition of working memory was expanded to include other aptitudes and other processing domains. For example, in the *counting span test*, items within a series of displays must be counted and the sum of items in each display must also be remembered (Case, Kurland, & Goldberg, 1982). In the often-used *operation span test*, arithmetic problems were to be solved and an item (like an unrelated word) was presented after each problem for later recall (Engle, Cantor, & Carullo, 1992; Turner & Engle, 1989). In each of these procedures of what has come to be termed *complex span*, the main measure is the length of the trial yielding successful performance, including both successful processing and correct subsequent recall of the memoranda. For a while, working memory was thought to be uniquely measured by these complex span tasks. It now seems likely that other tasks are aligned with complex spans. Cowan et al. (2005) argued that this is the case for any short-term memory task that requires attention for its solution and does not allow verbal rehearsal as a way to reduce the load on attention. This logic is very similar to the logic that Case et al. used for their counting span measure, which they considered as one measure of the basic working memory capacity or *M space*. They indicated about children (p. 395) that “While they are often observed to engage in relatively simple strategies such as rehearsal, tests of M space are designed so as to make these strategies difficult to apply.” Cowan et al. investigated other such measures that did not include a dual task, such as running memory span and array memory, and found that they predicted aptitudes in a manner similar to complex span.

Definitions and Concepts for This Chapter

So as not to leave you, the reader and secret hero of this chapter, sifting through the history of the field to decide what I mean by my terms, here I will define them in a manner consistent with my own work. Cowan (1988) tried to ask what we know about human information processing that could be stated without saying too much about the qualities of which we are unsure. The conclusion was that we did not know for sure that the distinction between phonological and visuospatial information was the only one of importance, so both of them were represented as different types of features among the activated portion of long-term memory, which also could include semantic, acoustic, orthographic, tactile, and other types of features. This concept can be traced back to the notion that a certain assembly of neural cells may remain activated to represent ideas for a short while, even without any attention to the ideas (Hebb, 1949). Within this activated memory, there would be a subset of information that is in a more organized state and is held within the focus of attention, a concept that can be traced back to what James (1890) called *primary memory,* and to the short-term memory of Atkinson and Shiffrin (1968). There were some other concepts that are not relevant here but the model also included the central executive processes of Baddeley and Hitch (1974), which helped to control the focus of attention, sometimes struggling to wrest it away from stimuli that can automatically recruit attention because they are so flashy, loud, or interesting. This model is shown in Figure 1, and the following definitions help to clarify it.

Short-term memory can be considered the temporarily activated information from long-term memory. It can become activated either through the current presentation of stimuli, or from reminiscing about knowledge and events that occurred in the past. Based on information that we will discuss, I assume that the information that enters short-term memory depends on how attention was used. If stimuli are attended, then semantic features become active; semantic activation happens much less often, if at all, for unattended stimuli. Physical features, in contrast, easily can be activated even without attention. At some level, you hear the birds or traffic while you work, and would detect an abrupt change in their sounds even if you were ignoring them (cf. Cherry, 1953). I also assume that particular information in short-term memory remains active for several seconds, or until subsequent information with similar types of features causes too much interference.

Working memory will be used here to refer the collection of information that is held in a temporarily accessible state through any means. The term *working* refers to the fact that when an individual encounters a real-world problem, he or she usually throws at it any combination of mental strategies and processes that may help, and that seems likely to be the case with the memory necessary to solve various problems. Defined in this way, working memory *includes short-term memory*, but with emphasis on the special role of the focus of attention, which presumably can prolong and enrich the representation of several meaningful items at a time; and with emphasis on various mnemonic strategies that depend on central executive processes, and help to enhance the temporary activation and persistence of information.

If short-term memory is narrowly defined as temporarily activated information then it can include only basic storage properties whereas, if working memory is defined as temporary retention of information through any means, it must include not only storage, but also control processes that help to extend the time for which information can be kept in storage. It has been proposed that this can occur through several different means, which differ in how much effort and attention is involved and also in the durability of the memory. Let’s discuss the storage limits and then the mnemonic control processes. Later, we will see that storage and processing both are relevant to working memory development.

Limits and Capabilities of Working Memory

In science it is always preferable to provide the simplest explanation for a set of phenomena. Although most researchers accept a distinction between short-term or working memory and long-term memory, there are some who attempt to account for all of memory with a single set of rules (e.g., Nairne, 2002). In order to support separate short- and long-term systems, it is necessary to show that some property differs for these systems. One possible distinction is the loss of information as a function of a relatively short amount of time in short-term or working memory, or decay, unless that information is rehearsed. Another possible distinction is a limit in how many items can be present in short-term or working memory at the same time, a capacity limit. Neither of these properties apply to long-term memory, which is presumed by all to last a very long time (possibly a lifetime) and to have a vast capacity. It must be acknowledged, though, that the existence of decay and capacity limits have not been easy to prove. In each case, it is theoretically possible that certain kinds of interference between the mental representations of different stimuli can account for memory loss in the short term, as Nairne suggested. Given these challenges, it is important to discuss some of the reasons why I, and many others, continue to divide memory into at least two subcategories, short- versus long-term categories with different properties.

Storage Limit Type 1: Decay and/or Interference in Short-term Memory

Decay, the loss of memory information as a function of time, is a concept that used to seem simple but has provoked controversy for over 50 years. The basic issue is whether forgetting occurs just because time elapses, or because of events that occupy that time. Think, for example, of the analogy to radioactive decay. For a given type of radioactive material, decay occurs at such a predictable rate that it is used to calculate the age of the material. Nevertheless, I imagine that this type of decay occurs because of atoms and subatomic particles knocking into one another in a quasi-random manner that cannot be predicted, in about the same way from one time and place to another. In the same way, there might be random physiological events in the brain that are unpredictable (for all practical purposes) and that cause memory loss over time. If, however, those events cannot be modified by stimulus conditions, we still might be justified to think of the result as time-based decay, as in the case of radioactive materials. That kind of conception would be a justifiable, useful simplification.

Decay of this sort is still not easy to prove. If an experimenter presents information to be retained and then does not follow it with distracting information, there is typically no forgetting, presumably because covert verbal rehearsal can maintain the information. In a classic experiment, Peterson and Peterson (1959) presented three consonants to be remembered (a trigram) followed by a very distracting task, counting backward from a given number by threes, and found dramatic forgetting as the distracting task increased from very short to 18 seconds. The problem is, this forgetting could be explained in two ways. It could be that the distraction prevents some mnemonic process, such as covert verbal rehearsal. Another possibility, though, is that the distraction task causes interference on some level. Perhaps it interferes because some of the same speech sounds making up the numbers would be produced also if one were to pronounce the consonants to be remembered.

One well-known attempt to distinguish between explanations of the results that Peterson and Peterson (1959) obtained provides insight, but at the same time further underscores the difficulty in distinguishing among hypotheses (Keppel & Underwood, 1962). They found that in the first few trials a participant carried out, there was little forgetting of the consonant trigram even if the retention interval filled with counting backward lasted for 18 seconds. There are two explanations of this finding, one that does not require decay and one that does. Both explanations depend on a phenomenon known as proactive interference, or interference from the material preceding the information to be remembered. In this case, it is interference from the consonant trigrams in the experiment in the few trials preceding the current trial. The participant presumably sometimes cannot remember which consonants were current and which were presented previously. (1) In one explanation, at short retention intervals the information of the most recent trial is especially distinct in memory, helping to overcome the proactive interference; at long retention intervals, this distinctness is lost, like telephone poles that seem closer together as they recede into the distance. (2) According to the alternative explanation, at short retention intervals, the participant can use long-term memory to retain the consonants, and this long-term memory information does not noticeably decay across 18 seconds; but this long-term memory cannot be used efficiently after there is much proactive interference. Then, only short-term memory can be used, and the information decays quickly with increasing retention intervals.

This research debate continues up to the present time. On one hand, Lewandowsky, Duncan, and Brown (2004) found no loss of memory with time. They presented lists to be recalled with variable intervals between recalls, filled with one or three repetitions of the word "super" to prevent rehearsal. The number of repetitions, which affected the delay before recall of each word, did not matter. Oberauer and Lewandowsky (2008) reported this same absence (or near-absence) of loss of memory as a function of time even when attention was occupied by a demanding tertiary task along with rehearsal prevention. On the other hand, Ricker and Cowan (2010) observed forgetting without any retroactive interference at all. They presented arrays of three unfamiliar characters at once, followed by a pattern serving as a mask so that the items could not be preserved in sensory memory. The mask was followed by a 1.5-, 3-, or 6-second blank retention interval and then a probe item to be judged the same as one of the array items or different from all of them. They found substantial forgetting of the characters with increasing retention intervals. A few other recent studies suggest that decay occurs not only to unfamiliar characters, but also to visually-presented digit lists when an irregular timing pattern has to be remembered, which may prevent efficient rehearsal (Cowan & AuBuchon, 2008); and to arrays of easily-categorized colors (Woodman, Vogel, & Luck, in press, Figure 5).

Some popular theories of working memory depend on decay. Baddeley, Thomson, and Buchanan (1975) found that people can retain about as much list information for serial recall as they can recite in about 2 s. The theoretical explanation was that information is lost from a phonological buffer over a few seconds unless it is refreshed by covert verbal rehearsal. Barrouillet, Portrat, and Camos (2011) suggest a similar mechanism but find that refreshment of items (maintenance of their presence in working memory) does not have to be verbal in nature; attention can be used to refresh items. This is proposed in order to account for the finding that the number of items that can be retained declines in a linear fashion with increasing cognitive load, the proportion of time taken up with an attention-demanding task, regardless of the domains of the stimuli (Barrouillet, Portrat, Vergauwe, Diependaele, & Camos, 2011).

In contrast to the hotly debated effects of time, everyone seems to agree that there are effects of interference from items with similar features. For example, visual activities interfere with working memory for visual items more than phonological activities do, whereas phonological activities interfere with working memory for phonological items more than visual activities do (see Baddeley, 1986 for a review). The role of decay and interference will come into play when we examine developmental trends.

Storage Limit Type 2: Capacity Chunk Limits

Within the brief but voluminous history of research on working memory, a large part can be characterized as a detour from capacity limits to time limits. Miller (1956) focused on item capacity limits, suggesting that people can remember seven plus or minus two items in a list, with an item defined as a unit meaningful to the participant, or *chunk*. For example, the letter series *IRSCIAFBI* is easy to remember if one recognizes three chunks representing U.S. government agencies.

Baddeley et al. (1975) shifted the focus to time limits. The implication was that item capacity limits occur indirectly as a result of time limits; thus, memory is poorer for lists of longer words. Occasionally, however, other researchers departed from this view. Atkinson and Shiffrin (1968) were working from a view in which item limits were important, and Baddeley and Hitch (1974) included in their model not only phonological and visuospatial buffers that could be time-limited, but also a central, abstract buffer that was said to be attention-related and might well be item-limited. This central buffer was viewed superfluous and removed by Baddeley (1986), but was restored as the episodic buffer by Baddeley (2000, 2001). One researcher who had contributed some of the earliest work in cognitive psychology already in the 1950s, Donald Broadbent, held the view that there is a capacity limit of 3 items that applies when rehearsal strategies are eliminated (Broadbent, 1975).

Cowan (2001) elaborated upon Broadbent's (1975) view and updated it on the basis of a large subsequent literature. The theoretical view showed that an item-capacity-limited memory was just part of the working memory system. That review concentrated on cases in which it was considered impossible to use rehearsal to remember the items, and it was considered impossible to combine items to form larger chunks of information. Examples included arrays of brieflypresented colored squares and lists of verbal items in the presence of articulatory suppression (repetition of a single word over and over to prevent covert rehearsal). In such cases, normal young adults could remember 3-5 items on average.

Subsequent work confirmed and extended that general finding, with the estimate toward the low end of the range suggested by Cowan (2001). An example is the finding of Chen and Cowan (2009), which was the culmination of a series of studies published previously. Chen and Cowan trained individuals to know two-word chunks such as *door-fish*, well enough that they could produce the second word in response to the first with 100% accuracy. They also presented singletons in order that these would have a familiarity equal to the learned pairs. After this training, lists of singletons or learned pairs of various lengths were presented for serial recall. When the results were scored for recall in order and participants were free to rehearse, the results matched what would be expected on the basis of a time-limited store; performance was poorer for lists of learned pairs than for lists of singletons, presumably because the learned pairs took longer to rehearse. However, the results were different when the procedure was changed in two ways: (1) repetition of the word *the* twice per second during the list presentation was required in order to prevent rehearsal, and (2) in the scoring of results, the serial order of responses was ignored. With rehearsal prevented, the results fall remarkably near 3 chunks recalled regardless of the list length or chunk length; this means 3 singletons or 3 learned pairs recalled (Table 1). This study shows that the item limit is for Miller's (1956) chunks, units composed of highly associated elements (in this case, learned pairs of words). The capacity limit is quite close to what is found for arrays of visual objects to be remembered in order to be compared to a probe display within which one object may have changed (e.g., Luck & Vogel, 1997; Cowan, 2001).

The explanation for the chunk capacity limit was unclear but Cowan (2001) suggested that this limit occurs in the individual's focus of attention. This notion has been assessed by requiring that items of multiple types be retained at the same time. The focus of attention presumably does not include features that are specific to a particular domain (such as the way a spatial design looks or the way a spoken word sounds) but, rather, an abstract representation of any stimulus, akin to an assembly of its distinctive features. One such study is the fifth experiment by Saults and Cowan (2007, Experiment 5), illustrated in Figure 2. The top half of the figure shows the method. On each trial, there was an array of 6 colored squares accompanied by 4 digits spoken all at once, in different voices from 4 loudspeakers. This arrangement was used in order to prevent verbal rehearsal without actually using a separate rehearsal-prevention task; we previously showed that visual arrays of colored squares do not benefit from rehearsal (Morey & Cowan, 2004). In the study of Saults and Cowan, depending on the trial block, the participant had to remember only the colored squares, only the spoken digits, or both. When the test arrived, it was a repetition of the array but one item in the attended modality may have changed; the color in a particular location may have changed or the digit associated with a particular voice may have changed. Spatial information of the digits was not preserved between study and test arrays, so it could not interfere with the use of spatial information about the colored squares. Only items in an attended modality could have changed, and the task was to indicate whether there was a change. The bottom half of Figure 2 shows the result.

If the visual and acoustic stimuli were stored separately, then requiring retention of both modalities should have resulted in a total of 6.33 items retained in working memory; that is the total of unimodal visual and acoustic conditions. Instead, in the bimodal attention condition they retained only 4.21 items. Apparently, there was competition of attention for 6.33-4.21=2.12 items that could not be retained because other items were being retained. This appears to be a rough estimate of the capacity of the focus of attention, the amount of overlap between tasks that have little in common. It may be an underestimate because there were not very many acoustic items that could be perceived.

We do not yet have a clear understanding of why capacity without rehearsal is limited to 3 to 4 items in both the visual-spatial and verbal domains. According to the model shown in Figure 1 as conceived by Cowan (2001), all of the capacity to hold 3-4 items in the absence of rehearsal supposedly comes from what can be held in the focus of attention. Another possibility, however, is that representations within a particular domain interfere with each other when there are more than about 4 chunks active at once in that domain. In that case, the focus of attention might only hold a subset of the active items in each domain. More research is needed to distinguish between these possibilities.

Mnemonic Control Processes

There are many ways in which information theoretically can be kept alive in working memory. An individual might repeat the items verbally, or might form a visual image of the items. An individual also might make an attempt to recognize patterns that exist among the items, or form new groups so that a large set of items can be broken down into several smaller sets. The focus on control processes in working memory can be traced back to a relatively early point in the emerging field of cognitive psychology (e.g., Atkinson & Shiffrin, 1968; Baddeley & Hitch, 1974).

There appears to be a difference in the devotion of attention that is required to use each type of rehearsal of items to be remembered. For example, there is evidence that verbal rehearsal uses attention for the first few repetitions of an item, at most, after which the repetition process becomes more automatic and less dependent on attention (Naveh-Benjamin & Jonides, 1984).

Participants repeated a pair of words 1, 4, or 10 times while trying to remember three two-digit numbers and, with increasing numbers of repetitions, the words showed three signs of becoming more automatic. First, they became more stereotypical, in that they did not vary as much in duration from one pronunciation to the next; second, the word recitation became harder to interrupt by a probe signal indicating that a different vocal response should replace word recitation; and third, when a manual response to the probe could be made instead of interrupting word recitation, that manual reaction time became faster across successive recitations of the same words, as recitation required less attention.

In contrast to verbal rehearsal, there is evidence that the refreshment of visual information (keeping the information active in working memory by thinking about it) continues to use attention. In a brain imaging study, Raye, Johnson, Mitchell, Greene and Johnson (2007) found that the left dorsolateral prefrontal cortex was activated when participants were asked to “refresh” as opposed to verbally rehearse a visually-presented word. They discuss other neuroimaging studies of refreshing, including some in which there were visual images to be attended.

In at least one study there has been a behavioral comparison of refreshing and rehearsing using the same methods. It appears that participants can decide to use refreshing, an attention-based mnemonic method, or rehearsal, a method that is not as demanding of attention. In a word list recall task, Camos, Mora, and Oberauer (2011) found they could discourage the use of refreshing by inserting a demanding secondary task (choice reaction time rather than single reaction time). Conversely, they found they could discourage the use of rehearsal by making the words phonologically similar, in which case rehearsal would lead to mistakes. The results further suggest, though, that participants used attention even when they used rehearsal.

Specifically, even when participants were instructed to use rehearsal no matter what, the choice reaction time secondary task interfered with memory. It is not yet clear if this occurred because attentional refreshing was used along with rehearsal, or because there is a residual cost of rehearsal (e.g., in the process of forming the motor program for rehearsal; see Naveh-Benjamin & Jonides, 1984). It is also not yet clear what participants do when asked to refresh; the most obvious assumption is that they use a mental image of the stimulus, but it is possible that it is some kind of more abstract idea that is being refreshed.

Clearly, the attention demand of verbal rehearsal seems less than the attention demand of other kinds of refreshment of memory, as illustrated for example by the results of Vergauwe, Barrouillet, and Camos (2010). They paired a visual or verbal memory span task with visual or verbal processing between the items to be remembered. The tasks were letter span or location span, paired with semantic categorization or a visuospatial fit judgment. As in other studies from this group, it was found that span was an inverse linear function of the cognitive load, the proportion of time taken up doing the processing task. For visual storage, the linear function was the same regardless of the nature of processing, as shown in the top panel of Figure 3. For verbal storage, however, visual processing impeded storage less than than verbal processing did, as shown in the bottom panel of Figure 3. It appears likely that verbal storage is helped by a verbal rehearsal process that does not take much attention, but is impeded by verbal processing. This is in addition to the concurrent use of attention as in visual storage, which is impeded by either verbal or nonverbal processing.

It is also possible to remember information in the short term by making up an elaborate scheme or story that ties together the items so that they can be memorized, so that they take up fewer chunks in working memory (cf. Miller, 1956). For example, if you remember the letter string “IWTQCP” by making up the sentence, “I wish to question certain pronouncements,” it becomes a single chunk in working memory, and also a new entry into long-term memory.

In sum, there is an arsenal of processes at the service of working memory but they are not neutral with respect to the domain. A verbal rehearsal process sometimes can relieve some of the burden on attention that otherwise can occur with the refreshing of any kind of material.

Short-term and Working Memory and the Brain

Understanding of the role of the brain in short-term and working memory can come from studies of lesions, as well as studies of electrophysiology and neuroimaging, in normal humans and other species. An example comes from Baddeley and Warrington (1970). They examined free recall of lists of 10 words in amnesic individuals who were unable to remember new information for very long, because of brain damage affecting temporal lobe structures. Amnesic individuals had preserved memory for the end of the list, presumably through a preserved short-term memory, whereas the memory for the beginning of the list was much smaller than in normal control individuals, presumably through a deficient long-term memory (for this distinction in normal adults see Glanzer & Cunitz, 1966)

These kinds of results, however, are susceptible to reinterpretation. Bjork and Whitten (1974) show that when distracting periods are placed between pairs of words in a list to be recalled, the recency effect re-emerges despite a distracting period at the end of the list. This *long-term recency effect* could suggest that the recency effect occurs because of the temporal distinctiveness of the most recent list items relative to earlier items, not a special working memory for these items (e.g., Lewandowsky, Ecker, Farrell, & Brown, 2011). In contrast to this reinterpretation, though, Davelaar, Goshen-Gottstein, Ashkenazi, Haarman, and Usher (2005) showed that the long-term recency effect is not the same thing as the ordinary recency effect.

The striking brain lesion results still have not answered the theoretical questions. More recent work using methods to take images of the functioning brain also have been unsuccessful to date in determining whether information decays from short-term memory or is lost through interference or temporal distinctiveness (e.g., Jonides et al., 2008).

In contrast, though, other aspects of working memory have found clear signatures in the brain. At least the last item in a list to be remembered is retained without the activation of the hippocampus that is a signature of long-term memory processing, according to a functional magnetic resonance imaging (fMRI) study by Öztekin, Davachi, & McElree (2010). Öztekin et al. saw the absence of hippocampal activity as a signature that the information was held in the focus of attention, not retrieved from long-term memory at the time of recall. Their actual results, however, seem to show that the first list item also may have been processed with reduced hippocampal activity, and perhaps there is a third active item that is not at a consistent serial position; see Cowan (2011).

Other studies have shown that when there is a visual working memory load, it activates the intraparietal sulcus. It activates frontal lobe areas as well, but the intraparietal sulcus activity is different in that it levels off when the capacity limit is reached. The notion is that the intraparietal sulcus actually represents the information, whereas frontal areas of the brain are involved in maintaining that activation (Todd & Marois, 2004; Xu & Chun, 2006) like a flashlight shining on a screen. Cowan, Li et al. (2011) pointed out that the intraparietal sulcus is known for other functions related to focusing attention, and they showed that it was the sole brain area that responded to a working memory load regardless of its visual-spatial versus acoustic-verbal nature (for signatures of the focus of attention, cf. Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012).

Putting these studies together, there is evidence that items that are held in working memory using attention involve distinct brain areas. As noted, the intraparietal sulcus is involved in representing attended items in working memory, and other brain areas represent domain-specific information in working memory, such as language areas involved in holding phonological representations (Jonides et al., 2008). When attention is needed to hold goals in mind, there is activity in the dorsolateral prefrontal cortex (Kane & Engle, 2002), and distinctive brain activity has been observed for rehearsal versus attentional refreshing as different mnemonic activities (e.g., Raye et al., 2007). Overall, brain evidence has been helpful in strengthening the conclusion that storage and maintenance of working memory is partly general across domains and partly domain-specific. Uncertainties, such as the evidence for or against decay, illustrate that our understanding of working memory in the mind and brain of adults is a lively and rapidly-evolving field, to which developmental evidence can contribute.

How do Short-term and Working Memory Develop?

It has been known for many years that there is a developmental increase during childhood in memory span, or the length of list that can be repeated back from memory (e.g., Bolton, 1892). For example, a 4-year-old child may only be able to repeat back a series of two or three digits correctly, whereas an adult typically can repeat a series of six or seven digits. For simple tests like this, capability increases in a brisk, near-linear manner from about 3 to 8 years of age, with a more gradual increase beyond that; 3-year-olds have only about 60% of the capability of 8-year-olds, whereas adults having about 110% of what 8-year-olds have. For more complex tasks in which one must process information while storing it, such as listening spans in which sentences must be comprehended and the final word of each sentence remembered, the developmental path is steady and steep from about 6 to 13 years (Gathercole, 1999).

It also is clear that there is an involvement of long-term memory in working memory tasks and, in that light, the basis of developmental differences must be considered cautiously. For example, the serial position functions shown by amnesic adults, with preserved recency effects despite degraded earlier list portions when compared to normal adults, look similar to what is found for younger children when compared to older children (e.g., Cole, Frankel, & Sharp, 1971; Spitzer, 1976).

More recent research has shown that a wide variety of short-term and working memory task performances improve with age in childhood (e.g., Cowan & Alloway, 2009). It seems likely that the age difference in working memory ability contributes to age differences in the ability to comprehend language and solve problems. Information that can be kept in working memory at the same time can be combined to form more complex concepts (Halford et al, 2007). For example, in order to understand the concept of a bat, one must keep in mind the fact that it is a mammal and the fact that it nevertheless flies, unlike most mammals. To understand the command *Put the red square on top of the green circle*, one must remember not only the features but also their bindings, or else risk, say, incorrectly putting a green square on top of a red circle if those choices are available.

It is still unknown exactly why developmental growth in working memory capability occurs. The basic difficulty of cognitive developmental research comes from the fact that brain growth is organic. For our theorization, it would be nice if all of the parameters of cognitive functioning stayed the same except one of them, which then could be used to predict the child’s cognitive developmental level and which tasks he or she can carry out. Indeed, one theory of cognitive development termed neo-Piagetian relies on developmental changes in the amount of information that can be stored in working memory at one time, or the amount of cognitive energy to be divided between tasks (e.g., Case, 1972; Pascual-Leone & Smith, 1969; Pascual-Leone & Johnson, 2011). If multiple basic skills or processes improve with development, though, it will be difficult to pinpoint the contribution of any one of them.

With a fine-grained analysis of working memory, it might be possible to build up a more detailed understanding of how working memory changes with age and what cognitive effects the changes should create. This fine-grained understanding seems important not only for theoretical reasons (that is, to understand the nature of the human mind) but also for practical reasons. By understanding what processes contribute to normal performance at each age, we should be able to optimize educational materials so as to make the best use of working memory, and perhaps help its functioning to grow. Toward this better understanding, we will discuss the processes that were highlighted within the review of the adult functioning of working memory.

Development of Decay

We saw above that there is a long-persisting, spirited debate about whether there is such a thing as decay, the loss of information from short-term or working memory as a function of the absolute amount of time that has passed since an item has been encoded or rehearsed. If decay does exist, then it would be possible that the developmental improvement in working memory could occur in part because there is faster decay in younger children.

In order to observe decay, it is necessary to prevent rehearsal or to equate it across age groups. This is not easy to accomplish because older participants could rehearse items even at the time they are encoded. To prevent all rehearsal, Cowan, Nugent, Elliott, and Saults (2000) examined memory for lists of spoken digits that were to be ignored during their presentation and thereafter, with a retention interval of 1, 5, or 10 s past the end of the list until a memory test. Participants played a silent picture-name-rhyming game that occupied their attention and speech sound phonological encoding processes during the presentation of the lists. There was no test of most spoken lists but, occasionally, the rhyming game was interrupted with a screen asking for keypress recall of the digits in the most recent list. Difficulty was equated across participants by presenting each participant with lists of a length equal to his or her memory span. In a control procedure, participants were allowed to pay attention to the lists as they were presented, with no rhyming game. The top panel of Figure 4 shows several things about the results of this procedure. First, it shows that, for all three age groups, there was substantial forgetting of the ignored lists with increasing retention intervals (solid squares). The absence of forgetting across retention intervals for attended lists (open circles) shows that there is a profound benefit of attention for memory. Second, the figure shows that there was no significant age difference in the pattern of responses overall; there was no overall age difference in decay of ignored lists.

The bottom panel of Figure 4 shows that there was, nevertheless, an important but limited age difference, restricted to the final serial position of the list. Younger children (Grade 2, about 8 years old) and older children (Grade 5, about 11 years old) both were at about 70% correct with a 1-s retention interval. As the retention interval increased, though, the older children retained much more of the information than the younger children. (It is not possible to compare the adults to the children fairly because adults performed so much better for this serial position even with a 1-second interval.) This difference between childhood age groups suggests that there is a developmental difference in decay for a kind of memory confined to the last serial position. As Cowan et al. (2000) explained, the memory confined to this position is likely to be a form of auditory sensory memory, with each list item overwriting the sensory memory representation of the previous items. Although this finding warrants further research, for working memory overall the more important conclusion is that developmental differences in decay cannot explain developmental improvements in memory span or working memory performance.

Development of Capacity

A deceptively simple possible difference between age groups is that older children could have more slots in working memory than younger children, i.e., more basic capacity. This possibility, however, has been difficult to establish because there are other possible differences between age groups that would mimic an increase in slots.

One possibility is that the number of slots in working memory stays the same across age groups but with more efficient use of the slots in older children. It is well known that increasing the efficiency of encoding can produce larger chunks, increasing the amount of information that can be stored and recalled. The epitome of this approach is a study by Ericsson, Chase, and Falloon (1980) involving an individual who knew a large number of athletic records. Over the course of a year, this individual was given training on digit span and was able to increase his span from the usual 7 or so digits to about 80. He did this first by forming chunks of about 3 or 4 digits corresponding to known athletic records or other concepts (e.g., *789* could be re-coded and retained as one chunk, such as *78.9, the age of a rather old man*). This re-coding process brought the individual's span up to about 20 digits in a matter of months. Then the individual learned to combine sets of 3 or 4 adjacent chunks to form super-chunks, bringing the span up to about 80. Although we do not totally understand how this amazing performance was possible (and it has been duplicated in a few other participants), there is evidence that re-coding was indeed involved. After a year of training with digits, for example, performance on lists of letters was still only about 7.

Gilchrist, Cowan, and Naveh-Benjamin (2009) were able to address the possibility of chunking by presenting sets of simple, unrelated spoken sentences for verbatim recall. In a trial within a 4-short-sentence condition, the participant might hear, *Our neighbor sells vegetables…Flag football starts soon…Take your paper and pencil…She prepared a cheese sauce*. There was also an 8-short-sentence condition. In other conditions, short sentences were combined to form 4 longer, two-clause sentences (e.g., *Our neighbor sells vegetables but he also makes fruit juice*) or words were presented in randomized order to form control pseudo-sentences (e.g., *Lightning paper we bees take*). No one set of words was presented in more than one condition for a participant. Gilchrist et al. judged the efficiency of chunking by assessing how well the words in a clause hung together. Thus, the efficiency question was, if a participant recalled at least part of a clause (that is, if the clause was *accessed*), how much of that clause was recalled? The results showed that, for these materials, there was no age difference in this efficiency, or conditional proportion of clause materials recalled. In first grade (children about 7 years old), sixth grade (children about 12 years old), and college students, the proportion of a clause recalled, conditional on at least some of the clause being recalled, was just under 80%. Nevertheless, there was still a striking age difference in the number of clauses accessed (i.e., recalled at least in part). This difference in clause access for materials for which there was an absence of an increase in chunking efficiency with age was taken to indicate developmental growth in the number of slots in working memory.

Another popular theory is that the developmental growth of working memory reflects a different kind of increase in efficiency, namely the ability to concentrate on items relevant to the task and to exclude irrelevant items. Cowan, Morey, AuBuchon, Zwilling, and Gilchrist (2010) examined that possibility by presenting more-relevant and less-relevant items in a visual array to be remembered. For example, the participant might be instructed to attend to the colors of the circles and ignore the colors of the triangles. In a critical condition, the participant would be tested on an item of the shape that was to be attended on 80% of the trials, and tested on an item of the shape that was to be ignored on only 20% of the trials. It turned out that participants remembered more of the colors for the attended shape than for the ignored shape, to an extent that did not differ across the three age groups tested (Grades 1-2, Grades 6-7, and college students). However, the youngest group nevertheless recalled far fewer items than the older groups. Thus, the age difference in recall could not be accounted for by an age difference in the ability to concentrate on the more-relevant items. This finding was replicated using slow-paced sequences of items rather than rapid arrays (Cowan, AuBuchon, Gilchrist, Ricker, & Saults, 2011).

At least, this was the result when there were only 4 items in each display. When there were 6 items in each array, the younger children indeed became overwhelmed and were unable to concentrate on the more relevant items, a finding that accounted for some, but certainly not all, of the age difference in performance (Cowan et al., 2010). This suggests that overwhelming working memory with items to be stored diminishes attentional filtering ability, rather than the other way around. Thus, by ruling out various alternatives, it now does seem likely that there is a developmental growth in the number of slots in an individual's basic working memory capacity, or what Case (1972) referred to as M-space.

One unknown about capacity is the role of binding between features of an item. In order to get an item correct in a working memory task, it is often important to know how features are bound; one may need to know not only that a red object is present in the display, but also its location, or which color was associated with which shape. Children in the elementary school years do not appear to have a particular difficulty in remembering the binding between colors and locations, whereas older adults with an equivalent working memory for simple items have more problems with this sort of binding (Cowan, Naveh-Benjamin, Kilb, & Saults, 2006). However, when the task involves associating multiple features at once, it appears that younger children can associate fewer features together. For example, understanding a proportion requires the coordination of four quantities (e.g., 2/3=6/9) and that concept is typically not mastered until about 11 years of age (Halford et al., 2007). It may be that each unit within the relation must take up a separate slot in working memory in order for the items to be properly associated to form the concept.

Development of Mnemonic Processing

Without a doubt, one of the most important changes in the child development of working memory is the increasing sophistication in the use of mnemonic strategies (see also chapters by Larkina and Güler, Roebers, and Schneider, this volume). Flavell, Beach, and Chinsky (1966) showed that children younger than about 7 years typically do not try to remember a list of objects by repeating the list to themselves; when children first begin to do so, their mouths can be observed to move, but that was not observed in younger children. When Cowan et al. (2006) asked second-grade children and adults how they remembered a list of digits, participants in the older group usually said that they tried to group items together, whereas the children almost never said that. In fact, until the middle of the elementary school years, children do not even take full advantage of grouping cues present in a list in the form of pauses between subsets of the items (Towse, Hitch, & Skeates, 1999). Ornstein and Naus (1978) showed that mnemonic strategies include much more sophistication in terms of cumulative rehearsal as children progress through middle childhood.

One method of eliminating rehearsal in adults is to require articulatory suppression, consisting of the repeated pronunciation of a single word or sound. That repetition makes it difficult or impossible for participants to repeat the memoranda covertly. Several studies have shown that adults under articulatory suppression show patterns of results resembling younger children (Cowan, Cartwright, Winterowd, & Sherk, 1987; Cowan, Saults, & Morey, 2006).

One recent study illustrates the impact of changing mnemonic strategies on the pattern of performance in working memory tasks. Camos and Barrouillet (2011) used a procedure in which animals to be remembered were separated by colors to be named, with the color-naming occurring at a certain rate and for a certain duration. When children were old enough to rehearse the animals (at 7 years of age), what was detrimental to memory was a higher cognitive load, which was defined by the rate of color-naming. Thus, naming two colors rather than one in the same amount of time had a detrimental effect, presumably because rapid color-naming prevented rehearsal and refreshment of the animals and therefore allowed the memory traces of the animals to decay. In contrast, when children were too young to rehearse, the cognitive load did not matter and, instead, it was the duration of color-naming that made a difference to memory. Presumably, young children remembered the animals passively and this memory decreased as a function of time, regardless of the rate of color-naming because rehearsal of the animals was not taking place.

There might also be mnemonic strategies for working memory that are not yet clear. We know that greater knowledge makes it easier to chunk together items, but the effect of this better chunking in older children is situation-specific and has not been systematically examined. There are studies showing that in free recall, older children make better use of the ability to sort a series of list items into their semantic categories (e.g., Cole et al., 1971). Given the variety of strategies that can be applied, it is often difficult to predict age differences in performance on a novel task. In everyday life, knowledge plays a very important role in working memory. For example, if one wants to remember the ingredients to bake a cake (oil, flour, sugar, chocolate, topping) it helps great deal to be familiar with the ingredients themselves and the process of cake-baking, and undoubtedly this accounts for a lot of working memory development. Nevertheless, there are cognitive tasks that must depend on basic working memory capabilities with little help from prior learning, and these too may change as the brain develops. Learning new mathematic concepts might be one example in which sufficient working memory capacity is essential; another is following conceptually simple but lengthy directions.

Speed of processing. It is important for development that mnemonic processing not only changes qualitatively, but also increases in speed. This change in speed may account for developmental changes memory loss or memory retention. Regarding decay, it is quite clear that older children carry out various processes more quickly than younger ones (e.g., Kail & Salthouse, 1994). If there is such a thing as decay, this rapid processing is important because it allows refreshment of the items to be remembered before their decay from working memory is complete and they therefore can no longer be accessed in order to be refreshed. Evidence for this sort of model recurs several times in the recent history of developmental research. Baddeley et al. (1975) found that adults could remember as many items as they could verbally recite in about 2 s, which produced a linear relation between recital rate and number of items recalled. This result was later applied across age groups in childhood, with older children reciting items faster and remembering commensurately more, preserving the linear relation between speech and number of words recalled (e.g., Hulme & Tordoff, 1989). Case et al. (1982) reported that word-identification speed (measured through repetition of a spoken word) and counting speed were related linearly to the span using the same word and number materials, with younger children showing slower speeds and commensurately lower spans. Hitch, Towse, and Hutton (2001) proposed that there is decay and that attention must be switched between tasks in complex span to protect memoranda from decay, which is accomplished better by more mature participants. Barrouillet, Gavens, Vergauwe, Gaillard, and Camos (2009) found that the process of attentional refreshing was slower in younger children, and that this speed accounted for much of the variation in complex span tasks in which letters to be remembered were separated by numbers to be repeated, or animal pictures to be remembered were separated by colors to be named. The ages of participants in these studies that yielded linear relations between various processing speeds and working memory recall ranged from 4 or 5 years old to young adults.

The developmental increase in capacity, as well, might emerge indirectly because of a developmental increase in processing speed. We do not yet know the basis of capacity limits. It could be that different parts in the brain (such as sub-areas of the intraparietal sulcus) concurrently hold information about different items in the focus of attention. Alternatively, though, the focus of attention could circulate between items and, at a sub-second scale, each item could be activated in a repeating cycle. There is some neuroscientific evidence in favor of the first of these hypotheses (Anderson, Ferguson, Lopez-Larson, & Yurgelun-Todd, 2010), but also evidence in favor of the second one (Siegel, Warden, & Miller, 2009). If the latter is correct, there could be age differences in how quickly attention circulates between items (cf. Barrouillet et al., 2009, 2011) and this potentially could explain age differences in capacity.

Development of the Brain and Working Memory

It is clear that multiple areas of the brain mature at different rates (Rabinowicz, 1980; Sowell et al., 2003; Yakovlev & Lecours, 1967). What seems most important is that the latest-maturing areas of the brain are the frontal-parietal areas, including those that mediate the attention-related functions of working memory (Scherf, Sweeney, & Luna, 2006; Thomason et al., 2008). The frontal areas have long been regarded as more involved in executive functions, whereas closely linked parietal areas are more involved in the experience of attention. Thus, frontal damage often results in dysexecutive syndrome, or the inability to plan and carry out activities in an organized and self-initiated manner, whereas parietal damage often results in abnormalities in consciousness such as hemispatial neglect or anosognosia, the inability to realize that one has a disability (for a review see Cowan, 1995). Given that the frontal-parietal network is not fully mature until the mid-twenties, continued maturation in multiple working memory processes is to be expected.

Individual Differences in Ability Within an Age Group

Whereas this chapter focuses on the development of working memory with age, it must be emphasized that there are very important individual differences that feed into learning problems. Many times, a perceived discipline problem or learning disability can be traced back to a poor working memory that is below age group norms and may even make it hard for a student to follow directions (Gathercole, 2008).

Studies of individual differences can help us to understand what working memory processes are important. For example, Gathercole, Pickering, Ambridge, and Wearing (2004) found that the same factor structure could account for working memory task performance including a wide range of tasks from 4 to 15 years of age, a factor structure matching the model with phonological, visual-spatial, and central executive components. Cowan et al. (1998) found that two different speeds were important for digit span performance, the speed of covert rehearsal (measured in a separate speeded task) and the speed of retrieval (the latter measured by the duration of pauses between words in a list of a fixed length during recall itself). These two speeds were not correlated with one another, but together they accounted for so much variance that after they were both subtracted out, the effect of age on memory span was no longer significant. Later work showed that pauses in the responses of complex span tests supplement span itself in accounting for aptitude and achievement test scores (Cowan et al., 2003; Towse, Cowan, Horton, & Whytock, 2008).

The relevant processes depend on age. Cowan et al. (2005) found that when children were too young to rehearse, simple digit span was rather highly predictive of intelligence test scores. In older children and adults, however, the correlation between digit span and intelligence test scores disappeared. Presumably, the ability to rehearse reduced the need to use attention and basic working memory capacity to carry out digit span, and thus the digit span test had less in common with intelligence tests in the older participants.

Working memory tests can reveal specific disabilities as opposed to general mental deficiency. For example, Gillam, Cowan, and Day (1995) found that children with specific language disabilities in middle childhood had trouble in serial recall only when the test was scored for serial order; they were not deficient in knowing the items that were presented, just their order. Gillam, Cowan, and Marler (1998) showed that they also tend not to use verbal rehearsal unless the test situation strongly encourages it. Thus, when the input and response modalities were manipulated, the children with specific language impairment had trouble only when visual inputs were paired with nonverbal (pointing) responses. They had no problem if the input was spoken and/or the response was verbal. This may seem counterintuitive, but the combination of visual input and nonverbal response did not force children to form a phonological code of the information. Typically-developing children in middle childhood nevertheless tend to form this code and rehearse the items, to their advantage compared to children with specific language impairment.

Just as important as finding specific working memory impairments is finding that different clinical populations in childhood show different working memory impairments, which may be diagnostic of their disabilities. For example, Jarrold, Cowan, Hewes, and Riby (2004) found different patterns in children with William's syndrome versus Down syndrome. Both groups showed impaired serial recall of spoken lists. In the case of William's syndrome, this was accompanied by commensurately slower performance on a verbal rehearsal speed task. In Down syndrome, this ordinary relationship disappeared. Moreover, children with Down syndrome did not appear to plan one long word while pronouncing another, and therefore produced peculiarly long pauses between long words. The conclusion was that there was a general slowing in William's syndrome, but instead a trouble with speech planning and articulation in Down syndrome. Thus, in terms of any working-memory-related remediation, one size does not fit all.

Training of Working Memory?

Clinicians and educators doubtlessly hope that, as soon as possible, our understanding of working memory can be parlayed into improvements in educational practices that benefit children with disabilities and maximize education for other children. There has been a lot of effort recently devoted to the possibility of training working memory. For example, Klingberg et al. (2005) claimed that adaptive training in working memory tasks not only improved working memory (i.e., near transfer) but also improved performance on complex reasoning (i.e., far transfer). However, there is currently quite a heated debate regarding many methodological details of working memory training studies, especially as applied to the concept of far transfer (for reviews, see Chein & Morrison, 2010; Melby-Lervåg & Hulme, 2012; Shipstead, Redick, & Engle, in press).

If it turns out that working memory training is not helpful, it will still be important to understand working memory so as to adjust the levels of task difficulty to match the skills of children at particular ages, to better diagnose disabilities, and to provide an ontological understanding of the human mind.

Conclusion

It has been rewarding to be the “working memory guy” with a developmental bent within a psychology department. New incoming faculty members from all areas of psychology (clinical, social, developmental, and so on) stand a good chance of being interested in working memory, as it has been related to many other processes in recent work. For example, as children grow to become more aware of stereotypes, with increasing frequency they become prey to stereotype threats, such as the notion that girls are not good at math; and such stereotype threats cause preoccupation, interfering with working memory capacity and thereby degrading academic test performance (McKown & Strambler, 2009).

At the same time, working memory is a frustrating topic because of its breadth. So many cognitive processes interrelate to working memory that investigators struggle to understand what it really means, how it is defined, and how it operates. It is my belief that working memory is closely related to consciousness and the contents of the conscious mind, and therefore is fundamental to understanding many of the most fundamental aspects of human experience. Child development provides a window to that experience, much as history provides a window to current events.

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Table 1

Number of one- or two-item word chunks recalled according to a scoring method that does not consider the serial order of responses.

	Singletons in List				Learned Pairs in List	
	4	6	8	12	4	6
No Articulatory Suppression	3.88	4.00	5.00	3.69	3.17	3.81
	(.06)	(.24)	(.33)	(.40)	(.15)	(.24)
Articulatory Suppression	3.06	2.72	2.85	3.06	2.83	2.98
	(.16)	(.21)	(.24)	(.30)	(.13)	(.22)

Note. The data are from Chen and Cowan (2009). The data reflect one-item chunks for lists of singletons and two-item chunks for lists of learned pairs. Standard errors are in parentheses.

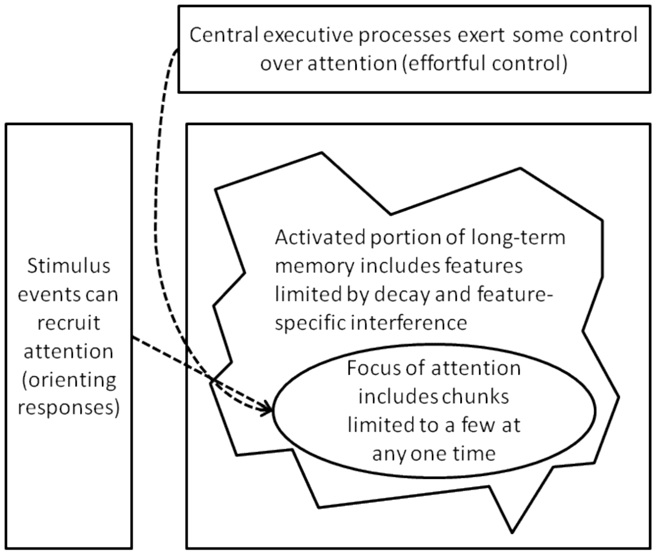
Figure Captions

Figure 1. A depiction of the theoretical model of Cowan (1988, 1999) as it pertains to short-term and working memory. Short-term memory refers here to information in the activated portion of long-term memory. Working memory here includes short-term memory plus central executive control processes that allow the focus of attention (a subset of the activated portion of long-term memory) to maintain some information especially well.

Figure 2. A depiction of the methods (top panel) and results (bottom panel) of Saults and Cowan (2007, Experiment 5) on capacity limitations across domains. The model for items in working memory used by Saults and Cowan was not exactly appropriate for this test situation (Rouder, Morey, Morey, & Cowan, 2011) and the results have therefore been re-analyzed here according to the method of Pashler (1988), but the basic findings have not changed.

Figure 3. Results of Vergauwe, Barrouillet, and Camos (2010) on effects of cognitive load across domains. The results are redrawn here, without the error bars for simplicity.

Figure 4. Results of Cowan, Nugent, Elliott, and Saults (2000) on developmental change in the loss over time of unattended digit lists. Top panel, all serial positions; bottom panel, last serial position only.



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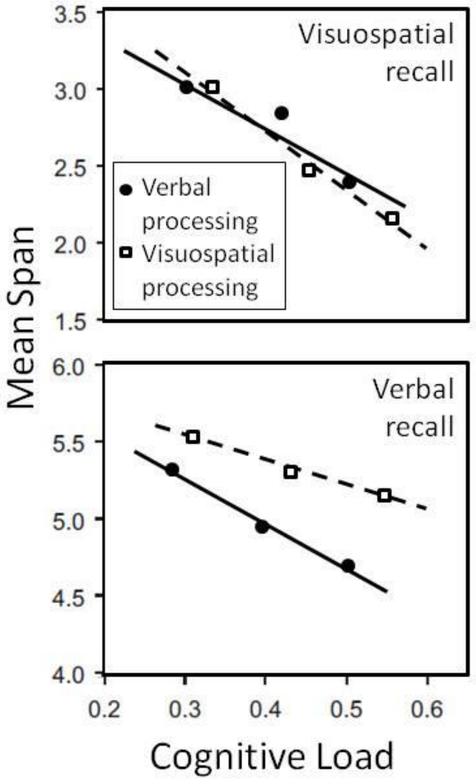

Figure 3. Results of Vergauwe, Barrouillet, and Camos (2010, Figure 1, p. 388) on effects of cognitive load across domains. The results are redrawn here, without the error bars for simplicity.

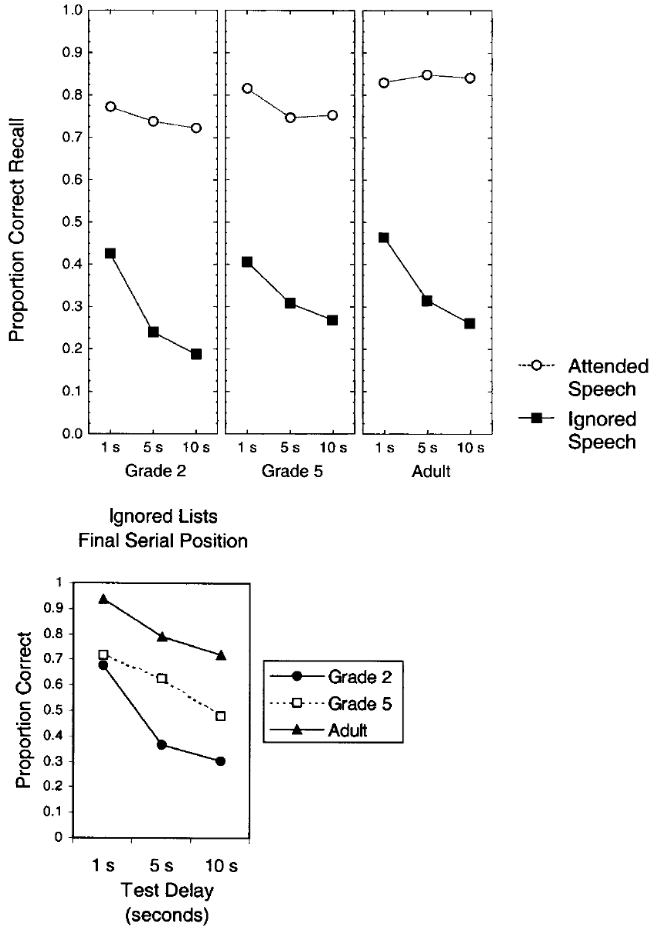

Figure 4. Results of Cowan, Nugent, Elliott, and Saults (2000) on developmental change in the loss over time of unattended digit lists. Top panel (Cowan et al., Figure 2, p. 163), all serial positions; bottom panel (excerpted from Cowan et al., Figure 3, p. 164), last serial position only.