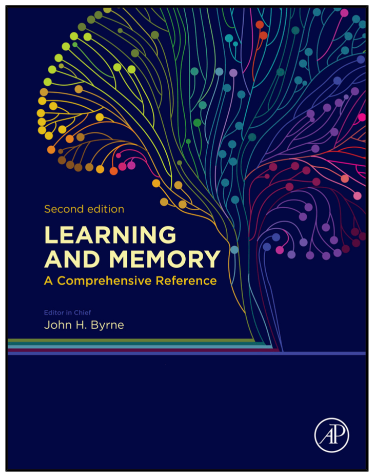

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2.09 Working Memory: The Information You Are Now Thinking of

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2.09.1 Introduction: Working Memory as a Quest and a Question

2.09.1.1 Philosophical Bookends We Will Need

William James (1890) beautifully summarized for the English-speaking public the research emanating from some of the earliest experimental psychological laboratories, in Germany and elsewhere. He suggested that the human experience depends on a trailing edge of the conscious present comprising our fleeting thoughts, which he termed primary memory. What could be more important as a quest for human understanding than to turn our attention inward toward that foundation of our experience? Robert Crowder (1993), however, memorably reacted against that way of thinking, concluding (p. 145): "I share these intuitions with James, but I do not trust them for a moment: What seems to be part of the conscious present and what seems to have passed into an earlier time must have more to do with the perception of time itself than it does with forms of memory, the more so as we learn that many manifestations of learning and memory never enter into consciousness at all, either as part of the present or as part of the past…Our intuitive observations about how our memories work must resemble people's intuitive observations, in earlier times, of how astronomy worked. Those intuitions are the same ones that led to a firm belief in a geocentric universe and a flat earth."

These two deep thinkers' comments are like bookends for a whole virtual library of research that has been conducted, and theories that have been recorded, about the human mind and how it operates, how we solve problems and process language, and how the conscious mind is served by unconscious processes.

2.09.1.2 Use of the Term Working Memory

The ideas go by many names: immediate memory and short-term storage to name a couple; but the most common term in the literature for this kind of idea has been *working memory*. It could be defined most generally as the holding mechanism for information that must be temporarily available to anyone engaging in thought or action, to carry out the necessary cognitive processes (i.e., mental work).

The term working memory was used in the 1950s by computer scientists (e.g., Newell and Simon, 1956) when they showed that computers could simulate complex cognitive operations such as solving a geometry proof. In the computer context, the temporary nature of the information in special storage was emphasized, but the availability of memory was for all practical purposes unlimited. In a psychological context that was closely related, Miller et al. (1960) used the term working memory to refer to any mechanism that could hold the various levels of plans one needs to proceed in life: the high-level goals such as career and social goals, the subgoals such as passing a test or impressing someone, and the various levels of sub-subgoals such as brushing one's teeth as one step to be ready to leave for work, which is in turn one step toward making a good living. Here, the available memory must be more limited inasmuch as people make frequent mistakes in planning. The term working memory reemerged and became much more popular among psychologists after Baddeley and Hitch (1974) used it to refer to a whole multicomponent system of mechanisms that they proposed to contribute to temporary memory used in thinking, as opposed to the all-in-one temporary storage that was included in many theoretical articles and chapters of the time. Baddeley and Hitch lumped those many approaches together as "the modal model" (probably best exemplified by Atkinson and Shiffrin, 1968), in contrast to their multicomponent model.

So here we have the question. Is there only one kind of functional memory, as Crowder (1993) implied? If so, the task is just to understand the rules of that memory and how they vary in tasks using a short versus a longer retention interval. Are there separate temporary and permanent memories, as others have implied? (These would include Atkinson and Shiffrin, 1968, but before that Broadbent, 1958.) Then the issue is to determine when each store is used, and how it is used. Is there a whole multicomponent

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system as Baddeley and Hitch (1974) suggested? Then an additional issue becomes what the components are and what their signatures are in psychological and neuroscientific research. This background sets the stage for what has become quite an engaging and productive field, though with many of the most basic questions still hotly debated. Thus, the *quest* is to understand the human mind and the *question* is whether it requires a separate kind of memory for the information in mind and, if so, what kind of memory mechanisms are involved.

2.09.1.3 Everyday Importance of Working Memory

Regardless of the answers to the question, nobody can deny that what the human mind holds in a ready form is essential for human though. Without some kind of mental mechanism to serve the need for working memory, we would forget the early part of a sentence before it is over; we would not be able to carry the partial sum in arithmetic. Working memory tasks are some of the best predictors of intelligence (Cowan et al., 2005; Daneman and Merikle, 1996; Engle et al., 1999; Kane et al., 2004; Kyllonen and Christal, 1990) and many human information processing disabilities are accompanied by working memory problems (e.g., language disorders: Archibald and Gathercole, 2006; Gathercole and Baddeley, 1990; Schuchardt et al., 2013; dyslexia: Berninger et al., 2008; attention deficit disorders: Klingberg et al., 2002; Holmes et al., 2014; Martinussen et al., 2005; and a variety of educational needs: Pickering and Gathercole, 2004) and in adults with various neural conditions (e.g., normal aging: Gazzaley et al., 2007; Alzheimer-type dementia: Morris, 1994; frontotemporal dementia: Stopford et al., 2012; stroke: Westerberg et al., 2007; and traumatic brain injury: Slovarp et al., 2012).

Sufficient working memory is essential for combining elements to form new concepts (Halford et al., 2007). In one of my favorite examples of that, to understand the concept of a *tiger*, a young child must realize that it is essentially a large cat with stripes. Forget that it must have stripes, and the term *lion* comes to mind; forget that it is a cat, and the term *zebra* comes to mind; and forget that it is large and one has a house cat. To understand cognitive growth and conceptual development, one must understand what working memory is available to support it at each stage (Cowan, 2014).

2.09.1.4 Organization of the Article

In what follows I will address (1) the early history of working memory research up to and including the seminal article by Baddley and Hitch (1974). This section also includes a synopsis of methodologies and theoretical frameworks that have been developed to help understand working memory. Following this first main section, I will explain several remaining, key controversies about working memory, regarding (2) the limits that have been proposed for working memory in terms of the number of items it can hold, (3) the limits in working memory that have been proposed in terms of the time period in which it can persist without rehearsal or refreshment, and (4) the effects of distributing attention across different sets of materials and the involvement of interference between sets. Finally, I will examine (5) practical applications of working memory. I hope that the historical section can explain something about how we got to where we are, so that the other sections can be devoted describing to the current status of each idea.

2.09.2 History of Working Memory Research

An important step in the early history of research into experimental psychology was probably for humans to learn what is real and what is hallucinatory. At least since fire was discovered, it seems likely that people have amused themselves at night by holding a burning ember with two sticks and rotating it to make a circle against the dark sky. But doing so leaves open the interpretation. Perhaps, primitive people may have thought, the fire leaves a burning residue in the air that we can see until it burns out. Against that interpretation, though, we can still see the afterimage of the glowing ember with our eyes closed, so a little thought indicates that the circle in the air may well be illusory, the construction of a residue not in the air but in the mind. A Hungarian physician and mathematician working at the University of Göttingen in Germany, Johann Segner, made use of that phenomenon in 1740 (from the Web sources I have gathered; I cannot check the Hungarian) to measure the persistence of information in the mind. He attached a burning ember to a wagon wheel and rotated it at various rates, observing what the stream of light looked like. Based on the rate of rotation that allowed the observer to see a full circle, it was calculated that the stream of light outlasted the actual ember's presence at any one point by several hundred milliseconds, an estimate that holds up well even today.

The theme that more depends on the mind than we typically realize continued in the other earliest psychological study, carried out by a famous astronomer from Königsberg, Friedrich Bessel (Boring, 1957). He read in 1820 that 24 years earlier, an astronomer in England fired his assistants because two of them disagreed in their timings of stellar transits by a large amount, about 0.8 s. The measurement involved comparing the visual phenomenon through the telescope with a ticking metronome. On touring Europe, Bessel found that various astronomers' measurements differed from each other, even though each astronomer generally was reliable between measurements. Bessel's solution was a "personal equation" adjustment to make the astronomers' measurements line up. The human was part of the measurement apparatus, apparently. In retrospect, their differences were probably a matter of how they used low-level working memory, in which the aggregation of telescopic view and metronome beats into a coherent event probably depended on the distribution of attention between vision and hearing.

A real explosion of interest in cognitive processes occurred in the middle of the 1800s. There are many examples of informal experiments that are close precursors to modern ones. One of the fun aspects of experimental psychology is that meaningful and thought-provoking experiments often can be constructed using ordinary household objects, even though computers are usually needed in actual experiments for precision of measurement. (In this day of far-reaching computer magic, students seem to be more impressed by stunts that can be carried out without computers.) Some of the early studies show this, though there also was an explosion of relevant gadgetry that helped to make measurements precise.

Baxt (1871/1982 translation) showed that when we are presented with a visual object briefly, the processing of that object continues after the object disappears. By presenting the object in a controlled, brief flash using a tachistoscope, and succeeding it with a flash of white light, he showed that the recognition process was impaired if there was not enough time between the object and the light flash. At the beginning of the field of cognitive psychology, other experimenters replicated and expanded on this finding (e.g., Averbach and Coriell, 1961). Sperling (1960) later changed the nature of measurement, presenting an array of characters (e.g., letters) followed by a cue indicating which ones would have to be recalled. For example, in one experiment there were three rows of four letters and the cue was a tone indicating that the top, middle, or bottom row had to be recalled. The evidence strongly suggested that there are two types of temporary memory. First, there is a vivid memory of the entire array, which is very short-lived; if the cue is delayed by a quarter of a second, most of this information disappears. We now call this kind of memory sensory or iconic storage. Second, even with the tone cue much delayed or with no cue, participants could recall about four items from the entire array. The limit seems to indicate that information was transmitted from sensory storage to a more processed kind, which was limited somehow. Because it was unclear how the memory was limited, the take-home message from Sperling's research has been more about the sensory memory aspect.

Subsequent research helps to clarify how the second kind of memory, which was termed short-term storage, was limited. It could be limited because the sensory memory fades so quickly that there is not enough time for more than about four items to be transferred to short-term storage. Against that interpretation, Darwin et al. (1972) carried out an analogue using speech sounds presented to different spatial locations using headphones and found a similar limit of about four items but, in this case, the loss of sensory memory was extended over several seconds rather than just a fraction of a second. This finding suggests that short-term storage is limited not primarily because of the fleeting nature of sensory memory that has to be transferred to a short-term store, but because there is a limit in how many items can be retained at once in short-term storage.

Cowan (1988) suggested that every sensory modality has two phases of sensory storage: a sensory afterimage lasting up to several hundred milliseconds as a stimulus is encoded, and a second phase that preserves the way an item was perceived for several seconds (cf. Massaro, 1975). Each sensory modality has its own coding properties. Visual sensory memory preserves more acute spatial information than audition, whereas auditory sensory memory preserves more temporal information than vision. This coding difference can explain, for example, the advantage for memory for the most recent items within lists of spoken words as opposed to lists of printed words (Penney, 1989). The difference between sensory and phonological memory for verbal lists is well illustrated in a study by Balota and Duchek (1986). When a spoken list to be recalled was immediately followed by a word that was not to be recalled (termed a suffix item) that was presented in the same voice as the list items, there was considerable interference with memory for the end of the list; when the suffix item was presented in a different voice, there was less interference; and when a tone suffix was presented, there was still less interference. Presumably, a suffix can interfere both with sensory information (hence the same- vs. different-voice suffix effect size difference) and with phonological information (hence the tone vs. different-voice suffix effect size difference). Moreover, when the suffix was delayed by 20 s before recall was allowed, the difference between the tone and the voice suffixes remained, but the difference between the same- and different-voice suffix effects disappeared. It appears that the sensory information faded across 20 s, but that the phonological information remained and was still vulnerable to speech interference, which would not depend on the similarity of voices between the list and suffix.

2.09.2.1 Growth of Methodology

As you can begin to see, one important outcome of a number of early studies was an invention of different methods that can be used to examine what we now call working memory. This is as good a time as any to introduce Fig. 1, which summarizes and illustrates the main methods whereby working memory has been examined. The remainder of the historical section will be devoted to explaining what was learned in the early days using these procedures, culminating in the landmark paper by Baddeley and Hitch (1974).

Subitizing. The first row of Fig. 1 shows a procedure to evoke a mental process called subitizing, the ability to enumerate rapidly a small number of objects without counting them. The earliest example I know is that of Jevons (1871), who tested himself by throwing a small handful of beans on the table and trying to guess the exact number without counting. Although the self-testing method leaves a lot to be desired, some early researchers found it to be the only way to obtain a subject willing to commit a long time to carrying out a procedure that, on the surface, may have seemed silly or pointless. In over 1000 trials, Jevons enumerated three and four beans without error, whereas increasingly more errors occurred for higher numbers. This seems to reflect the ability to assess only three or four objects as a collection of attended items at once.

Memory span. The second row of Fig. 1 shows a method called memory span, in which a series of items are presented and the participant is to repeat them back; the largest number that can be repeated in order without error about half the time is the typical measure of span. The origin of this method is not quite clear to me but something like it was done in what is considered the first experimental psychology laboratory, that of Wilhelm Wundt in Leipzig, Germany. Carpenter (2005) does a wonderful job of explaining some of Wundt's early work related to memory and why it is not well-known even today. She explains (p. 64) his interest in the "scope of attention, scope of consciousness, or temporal ideas." I wish I knew of this before using the term "scope of attention" without citing Wundt (Cowan et al., 2005).

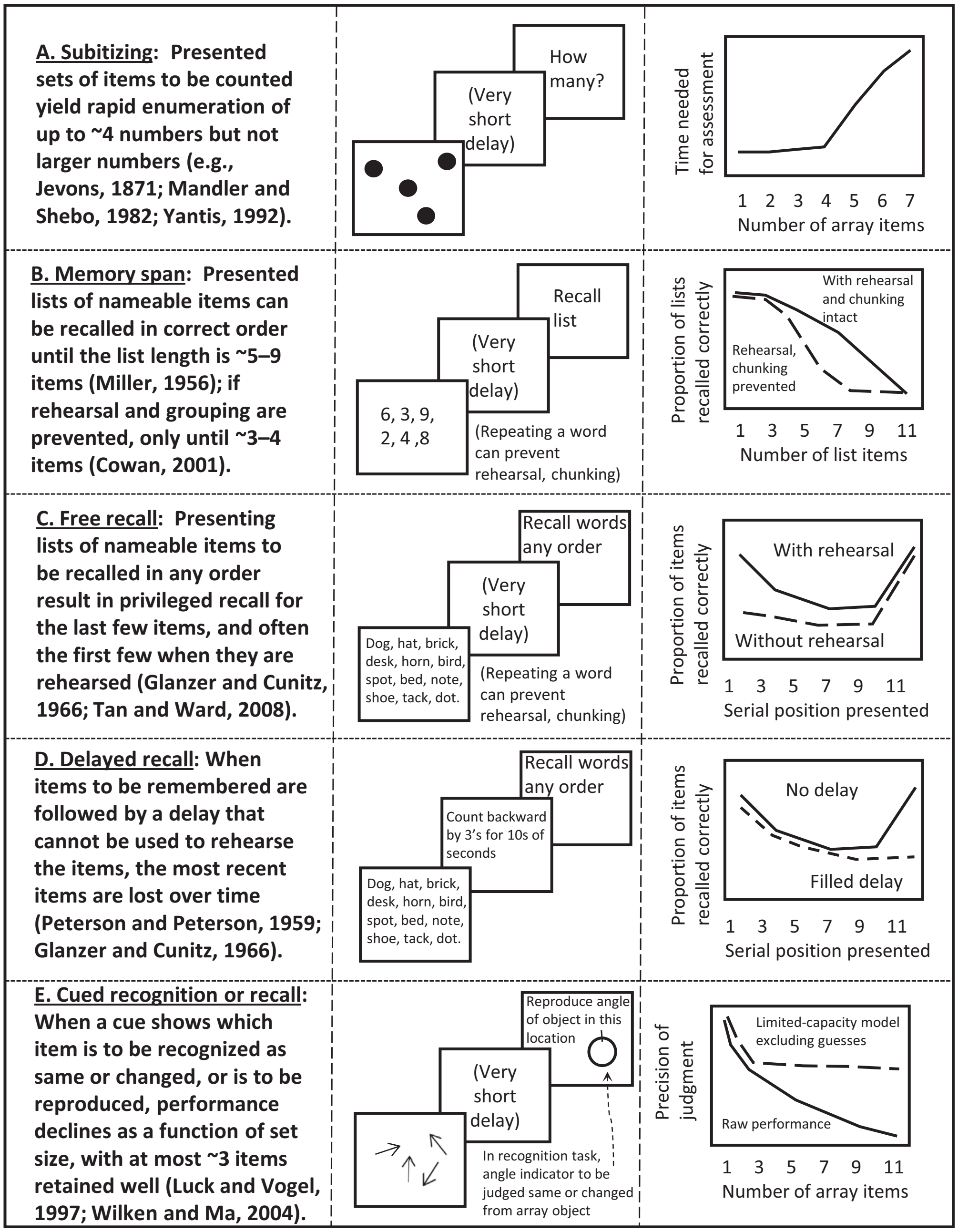

Figure 1 Five common procedures used to examine working memory ability. Left column, descriptions; middle column, illustration of procedure; right column, prototypical results.

Carpenter goes on (p. 66) to explain that "Wundt's entire definition of memory consisted of successive associations among ideas currently in consciousness. In this way, Wundt's definition bears some resemblance to modern concepts of short-term or working memory. This conceptualization is quite different from that of Ebbinghaus, who viewed memory as a measure of retention." Wundt's concept did not win out compared to Ebbinghaus, but is vitally important for our understanding of working memory. Wundt was misrepresented as an introspectionist but actually believed strongly in the need for experiments and carried out some resembling memory span.

Why has Wundt's experimental, pioneering work on working memory-related issues been underappreciated? It is not because of his theoretical position. I once visited the space where Wundt's laboratory existed and was told that most of it was translated into Russian and Hungarian, but not into English. One limiting factor was that Wundt was embittered because of the unfortunate fate of his country that was imposed after World War I and, after he died in 1920, his works were sold to a Japanese professor and have remained in Japan.

Ebbinghaus (1885/1913 translation) is best known for pioneering the research on long-term memory, using a method in which he tested himself repeatedly over time on the serial recall of lists of nonword syllables of different lengths. These kinds of materials were used not to approximate the conditions of learning that we engage in during real life, ecological validity; but rather to remove most factors that usually enter into learning to test the capability of the learning mechanism apart from any real-world knowledge. (This attempt occurs for much the same reason that physicists accelerate particles to 9/10th the speed of light even though they know that people will rarely if ever need to travel that fast.) This is an important point inasmuch as working memory research has largely proceeded in this vein, valuing procedures that would allow us analytical insight into the basic mechanisms of human cognition rather than trying to simulate real-world examples of the use of working memory.

Despite an emphasis on long-term learning processes, a close reading of the work of Ebbinghaus (1885/1913) shows the mechanism of working memory peeking through. He noticed (p. 33) that he sometimes had a "first fleeting grasp…of the series in moments of special concentration." This first fleeting grasp, however, did not ensure that the series had been memorized in a way that would allow its recall later on. Moreover, a single learning trial was typically enough for repetition of a 7-item list, but the next larger list that he tried, 12 items, required many repetitions to be learned. There was evidence of a limited-capacity mechanism similar to that of interest to Wundt.

Another early researcher, Francis Nipher of St. Louis, Missouri, did quite meaningful research with serial recall, reporting on the serial position effect and other aspects of recall in two short publications, in 1876 and 1878, several years before Ebbinghaus began his research (Stigler, 1978). Few knew about this research until Stigler brought our attention to it.

Whether inspired directly by Wundt or perhaps by Ebbinghaus, it was not very long before memory span was used in practical circumstances to examine individual and developmental differences (e.g., Bolton, 1892) and, in the early 1900s, it was incorporated into some tests of intelligence, such as Wechsler's well-known test. The theoretical interest in span as a possible indicator of limits of human thinking was amplified by Miller (1956) in what is perhaps the most-often-cited article in psychology. Miller was working at a time when the computer revolution was under way. Computers store information in terms of magnetic locations that are either on or off, and the rate of transmission can be measured in binary decisions or bits. For example, if a signal must distinguish between 8 choices, there are 2^3 choices so there are 3 binary choices or bits. From that perspective, if humans were similar to computers, it would be expected that they should have a much higher memory span for lists of digits—for which there are only 10 choices (0–9) for each item—than for, say, lists of words, for which there are thousands of choices. Yet, Miller found spans of approximately seven items in both cases. It was the number of meaningful units, which he called chunks, rather than binary choices that limited human working memory. A chunk could be a composite of several related elements so that there are nine chunks in the series of letters *ICLQRBSXN*, but only three chunks in the series *IBM, CIA, FBI* for a person who knows these acronyms and recognizes them in the stream of letters.

Cowan (2001) used Miller's (1956) principle of chunking to reexamine the magical number 7 in many tasks. As the second row of **Fig. 1** illustrates, the span that is obtained shrinks from about seven to about three when participants are prevented from making the task easier by mentally combining items through rehearsal and chunking. Recently published communications with Miller show that he did not disagree (Cowan, 2015). These strategies of rehearsal and chunking can be prevented through a dual task such as articulatory suppression (as in the figure illustration) or by presenting items that are nonverbal or are presented in a brief, concurrent array that does not lend itself to rehearsal.

Free recall. The third row of **Fig. 1** illustrates a method in which longer lists generally were used because the participant is not responsible for the order of items. I do not know when this procedure was developed but it was clearly in vogue already in the 1950s when the emphasis was on the number of repetitions that it would take to learn the list, similar to the emphasis of Ebbinghaus. Waugh (1961) compared serial and free recall and showed that when the amount presented for free recall was too much to be learned, one participant tellingly indicated that on each trial, he would "grab a mindful" of new items to learn. In the context of working memory, typically the emphasis has been more on this mindful or first fleeting grasp from the first presentation of a list. Typically, it leads to good performance on items at both ends of the list. The memory for the beginning of the list seems to depend on attentive processing, such as mentally repeating or rehearsing the early list items while receiving more items (e.g., Tan and Ward, 2008). In contrast, the most recent items are fresh in mind and, unlike the primacy effect, the recency effect is somewhat automatic and does not depend on rehearsal. Both of them, however, might rely heavily on working memory, primacy through an active process and recency through a more automatic process.

Delayed recall. Assuming that there is a working memory mechanism that is separate from the rest of memory, unlike what Crowder (1993) suspected, there are only a few ways in which the two types of memory could fundamentally differ. First, it could differ in that working memory could be limited to a small number of items, as Miller (1956) suggested. Alternatively, it might not be the number of items per se that is the limit, but rather the time during which each item can stay in working memory without being mentally refreshed, repeated, or somehow renewed. In order to test this idea, researchers have imposed a delay between the items to be remembered and the memory test. Typically, the recall delay or "retention interval" has been filled with a distracting task to prevent rehearsal.

Peterson and Peterson (1959) studied delayed recall and were best known for it (other relevant sources being Broadbent, 1958; Brown, 1958). According to the generally accepted principles of verbal learning, it was expected that interference with memory for an item depends on presentation of other, similar items. Peterson and Peterson, however, presented triads of letters and followed this with a variable-duration period of counting backward by 3's or 4's. This is quite a demanding task, but it was considered that the letters and numbers are very dissimilar and should not interfere with one another. In violation of that expectation, the triad of letters was forgotten markedly as the period of counting backward was extended up to 18 s.

The issue of the reason for an effect of delay has, unfortunately, not been settled to everyone's satisfaction; it is a hot topic to which we will return. Peterson and Peterson (1959) implied that their results occurred because there is a temporal limit to information in a working memory, i.e., that the information decays over time. In this early period, Keppel and Underwood (1962) tested an alternative hypothesis that the time of counting backward did not result in decay, but rather in a loss of temporal distinctiveness for the letter triad on a given trial. Given the passage of time, that letter triad could be confused with those from previous trials. In support of that hypothesis, they found little loss of information during counting backward examined in the very first trial across individuals.

There are, however, two interpretations of this finding of Keppel and Underwood (1962). There could be no short-term working memory involvement in the Peterson and Peterson study, as Keppel and Underwood seem to imply. Alternatively, on the first few trials, it may be possible to memorize the stimuli. With repeated trials, long-term memorization may become less feasible because of precisely the kind of proactive interference that Keppel and Underwood describe; but it may be precisely when long-term memorization becomes infeasible that the contribution of a working memory system kicks in. Baddeley and Scott (1971) tested hundreds of people for only one trial each on lists of three, five, or seven items and found that when the list was long enough to avoid ceiling effects, forgetting did occur across the first 5 s of the retention interval. They suggested that both decay and interference are needed to explain the full pattern of results in experiments with multiple trials.

The fourth row of **Fig. 1** depicts a free recall experiment in which the list is followed by a variable delay filled with counting backward (Glanzer and Cunitz, 1966). What is found is that the longer the delay, the poorer the performance on the recency portion of the list. This is in striking contrast to the effect of distraction during rather than after the list presentation, which hurts recall of the primacy portion of the list (as in the third row of **Fig. 1**). In each case, it appears that performance is impeded for the items for which neither strategic maintenance nor immediate recall are possible (cf. the negative recency effect in final free recall of all lists in the experiment: Craik et al., 1970).

In the free recall domain, as well, the interpretation is in question. Tzeng (1973) and Bjork and Whitten (1974) brought up a temporal distinctiveness interpretation similar to Keppel and Underwood (1962), this time based on procedures in which the items are separated by distracting tasks, making them temporally more distinct and allowing a recency effect even in the presence of a postlist final distracting task. In turn, there have been rebuttals of this line of reasoning by Cowan (1995) and by Davelaar et al. (2005), on the grounds of important discrepancies between the patterns of recall and the recency effect in ordinary list recall versus the recall of lists with items separated by distractors. The take-home message is once more that although single-memory theorists deny the existence of memory decay and put stock only in types of interference, the theorists who believe in a decaying working memory representation do not deny that there are also likely to be effects of interference.

Cued memory procedures. The fifth and final row of **Fig. 1** shows procedures in which a cue indicates which part of an array or list to recall. We have already discussed one procedure of that sort, the one of Sperling (1960) (also Averbach and Coriell, 1961). The advantage of such a procedure is that it is a more sensitive way to see what people retain from a set of items as opposed to what they can recall. It is not the same thing inasmuch as the very act of recall can result in severe output interference, that is, the loss of some information while you are busy recalling other information (Cowan et al., 2002). The figure's last row shows a modern sequel to Sperling's type of experiment in which certain items from an array are followed by a cue so that the participant only has to decide on the details of one item from the array.

The types of procedure that we have considered to this point involve accuracy as a measure. There also have been important studies using response time as a measure. Sternberg's (1966) procedure is the most notable one. On the surface, it addresses issues regarding how information is searched in working memory. A list is followed by a single probe item and the task is to indicate, as quickly as possible, whether the probe item was present in the list. The response times for correct answers are linear as a function of the number of list items, and comparable for probe items that were and were not in the list. This led to a theory in which items are searched in series, with the rapid search exhausting the list rather than terminating when the target is found; the search speed was about 40 ms/item, presumably faster than the process one would need to stop searching. Indirectly, the results also provide evidence regarding the limits in working memory capacity. Burrows and Okada (1975) showed that the apparently linear search rate breaks down when the list length reaches six or seven items, suggesting a natural break when the search is from short-term working memory versus long-term memory. Subsequent work (Wickens et al., 1981) also suggested that retrieval from long- and short-term memory can be additive, with a certain amount of time needed to retrieve a memorized list from long-term memory, which does not depend on its length, and additional time needed to search through the list, which is very much dependent on the list length.

Effects of dual tasks. One of the pivotal questions in the field has been whether working memory is a single mechanism, or a set of mechanisms that work together. If there is a set of mechanisms, a multicomponent system, then one way to show that this is the case is to capitalize on the differences between the components. A key way to do that is to present a dual task and show that there are certain kinds of working memory information that do not interfere with one another because they are processed by working memory components that have different properties. For example, the third row of **Fig. 1** shows that there is a large effect of introducing an articulatory suppression task in which a word is repeated over and over during the presentation of a verbal list. In contrast, other research shows that there is much less interference from articulatory suppression if the material to be retained is visual and spatial rather than verbal in nature. Conversely, there is interference from a task that requires repetition of a visual–spatial pattern when the material to be remembered is spatial in nature, but not interference from articulatory suppression. These dual-task effects with dissociations between modalities have been at the center of the prominent and seminal research leading to the notion of working memory as a multicomponent system (Baddeley and Hitch, 1974; Baddeley, 1986), which will be examined shortly.

2.09.2.2 Statements of Working Memory Theory

Graphical models. Fig. 2 shows three different basic models of working memory that have been often cited in the literature and that deal with the dual-task effects in different ways. The model of Atkinson and Shiffrin (1968) is shown in its basic form, modeled after Broadbent (1958); Atkinson and Shiffrin elaborated on it to account for strategic processes that shuttle information from one step of processing to another. It can account for the distinction between memory stores apparent in Sperling (1960) and other early works, but it is not really designed to provide an understanding of dissociations that occur within the set of dual-task effects.

The model of Baddeley and Hitch (1974) was stated in a verbal form and spoke most explicitly of a phonological verbal store and also a central store that could balance storage against processing, whereas the phonological store was immune to processing efforts. In the more extensive review of Baddeley (1986), another special store, the visuospatial store, was made more explicit than it was in 1974. At the same time, Baddeley eliminated the central store, suggesting that all storage was domain specific. Baddeley (2000) reconsidered, inasmuch as the phonological and visuospatial stores had no way to preserve information about the association or binding between different kinds of information in working memory, such as which name goes with which face, or to preserve semantic information in working memory. The central store might be expected to handle this, and it was reinstated with more explicit indications of these functions under the name of the episodic buffer in 2000.

Finally, Cowan (1988) acknowledged the dissociations but hesitated to attribute them to different stores. An alternative explanation is that there are not a few main modules but, rather, a large number of different but overlapping processes for different features of different types, such as semantic, phonological, visual, spatial, orthographic, acoustic, tactile, etc. Stimuli that share many of the same kinds of features may interfere with each other more than stimuli that share fewer or no features. Also, stimuli from two sources or streams that share verbal features may make it impossible to rehearse one of these stimulus streams while

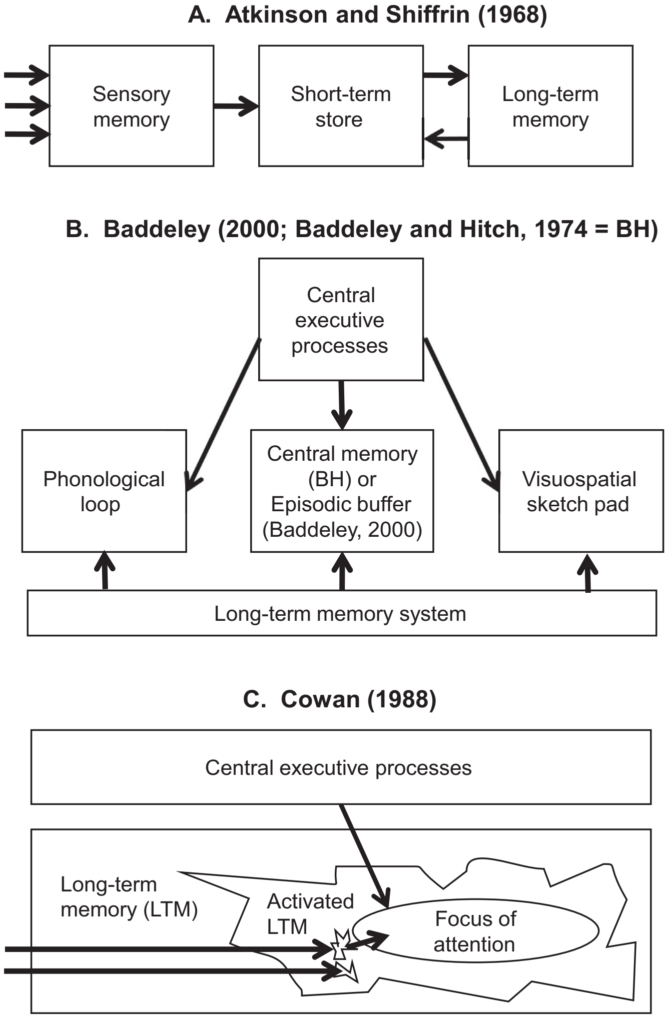

Figure 2 Illustration of three models of working memory. In Cowan's model, the direction of the focus of attention is controlled dually by incoming stimulation that is discrepant with the current neural model of the environment in some analyzed aspect of that stimulation, on one hand, and voluntary central executive processes on the other hand.

processing the other. This principle could account for the dual-process dissociations mentioned earlier. Cowan viewed working memory as a composite of the currently activated portions of long-term memory, which include various types of features for a short while and, embedded within this activated portion of memory, the focus of attention, a subset of several items held in a more integrated, processed, meaningful form.

Baddeley's episodic buffer was intended to account for aspects of working memory left out of the earlier model including, most importantly, semantic information and associations between different kinds of features (e.g., visual–verbal association or binding). However, key aspects of that system were left open pending further testing. Baddeley (2001) suggested that the episodic buffer might be limited to several items in focus, like Cowan (2001). Subsequent work suggested that this might not be the case inasmuch as dividing attention affected color and shape item information as much as it affected color-shape binding (Allen et al., 2006). Another way to understand that finding, though, is that because binding performance is lower overall, it loses a larger proportion of its capacity when attention is divided. Recent work by Baddeley with colleagues (Hu et al., 2016) has suggested that information can be prioritized using the focus of attention, and this prioritization was related to the episodic buffer so that it is now again seems similar to Cowan's focus of attention.

All of the graphical models share some notion of executive function to carry out processing. The notion there is that the ability to plan and carry out actions such as moving information from one kind of storage to another, reorganizing it, or planning or carrying out an action based on this information is an important part of human cognition. A great deal of neural evidence (e.g., D'Esposito and Postle, 2015; Cowan, 1995) suggests that the frontal lobes are heavily involved in central executive processing, though the processing may have several separable parts (e.g., Vandierendonck, 2016), whereas more posterior areas are involved in the focus of attention (Cowan, 2011) and the storage of information. Baddeley (1986) classified central executive processes as part of working memory even beyond any storage function, and this view is now predominant in the field though Cowan (1988) considers it separate as a matter of principle; that is a semantic issue of not much fundamental importance, but the difference in definitions has perhaps led to confusion.

Oberauer (2002, 2005) supported a model of processing that was derived from Cowan's embedded-process model shown in **Fig. 2**, but with an additional tier of embedded activity. In his model a single item resided in the active focus of attention and the rest of Cowan's focus of attention was considered to be a capacity-limited region outside of the focus. Cowan acknowledged that different items in the focus of attention are at different levels of strength or priority but conceived of the focus as necessarily a multiitem venture, allowing different elements of content to be directly compared to one another and interassociated (cf. Cowan et al., 2013). Rather than two discrete tiers (single-item focus and capacity-limited region), therefore, Cowan's model includes a unitary focus of attention with functionally up to three or four tiers, one for each element held at a different level of priority. The existence of different levels of priority for working memory was brought up to explain why some items can be retrieved faster than others in a probe recognition procedure (see for example Cowan, 2011).

Computational models. The graphical models might be considered just modeling frameworks, in that they help to guide research but do not really specify every aspect of the model necessary to make concrete predictions. An alternative approach that has been popular in the field is to add assumptions that are tentative but that allow more specific quantitative predictions to be made. For a summary of some often-discussed models see Lewandowsky and Farrell (2000, 2011), and for a sampling of diverse types of models see Anderson and Matessa (1997), Burgess and Hitch (1999), Cowan et al. (2012), Lisman and Idiart (1995), Oberauer and Lewandowsky (2011), O'Reilly et al. (1999), Schutte and Spencer (2009), and Simmering (2016).

In the remaining sections I will describe some of the main, current controversies about working memory, and will go into some of its practical consequences, which are still also controversial in some important ways. The exciting aspect of this situation is that experimenters are finding new methods to examine questions that have remained unanswered for at least 50–100 years, through the advancement not only of technology but of experimental design and quantitative analysis.

2.09.3 The Controversy Regarding Item Limits of Working Memory

There is a conflict between an old tradition in which participants are seen as knowing some items in discrete terms and guessing on others or omitting them (Miller, 1956; Waugh and Norman, 1965) and another, perhaps equally old tradition in which information comes in through the senses and is all processed to some degree, the tradition of signal-detection theory (Green and Swets, 1966). According to the discrete-items tradition, there is a fixed number of slots in working memory (Cowan, 2001; Luck and Vogel, 1997; Miller, 1956; Sperling, 1960; Zhang and Luck, 2008). If the items can be combined using knowledge, multiple items fill a single slot (Miller, 1956), like the trigrams representing US governmental agencies in the series, *IRS, CIA, FBI*. On the other hand, if the items are complex, more than one slot per item may be required. For example, a single Chinese character may be remembered by an individual as two subsets of the squiggles that suggest meaningful forms to the individual.

The discrete view seems appropriate at least when the items are well-known and simple, such as colors fitting known categories or letters. Then, simple formulas describe what happens in recognition tasks. If there are k slots in working memory holding k items, and there are N items in a list, then the chance that a queried item is in working memory is k/N. If it is in working memory, the match of that item to a probe can be recognized but, if it is not in working memory, the participant must guess. This kind of study yields estimates of k that increase with N and flatten out at three to four items in adults, and less in children (e.g., Cowan et al., 2006). When the assumptions of one slot per item break down, of course, it can be tricky to determine whether the fixed capacity theory still applies. There have been successful demonstrations that adults can hold three to four items when these items are complex, though the representations are not very detailed in that case (Awh et al., 2007; but see Brady and Alvarez, 2015). Such a theory needs a proviso that the precision of the representation (such as the exact color and orientation) is higher when there are fewer than three items (Zhang and Luck, 2008).

There are demonstrations that adults can learn new chunks and that the capacity is three to four chunks, though the capacity is estimated without regard for serial order and only applies when articulatory rehearsal is suppressed (Chen and Cowan, 2009). That capacity limit, though, can be overcome when the situation allows long-term memory to contribute meaningful information that differs from trial to trial (e.g., Cowan et al., 2012; Endress and Potter, 2014). There also is some kind of memory for the ensemble of items (Chong and Treisman, 2003; Brady and Alvarez, 2011) and it is unclear if that occurs at the expense of memory for individual items.

An opposing view, the continuous resource view, is that attention can be spread to take into working memory any number of items, albeit with very limited precision of some items when there are many (e.g., Ma et al., 2014). This theory seems elegant in its own way; often, information processing does appear to occur on a continuous basis, though good empirically based arguments can be made that this is not the case for working memory (Rouder et al., 2008). Against the continuous resource theory, though, Nosofsky and Donkin (2016) recently showed that the continuous viewpoint is awkward for situations in which difficult changes are recognized better than chance but easy changes still are not at ceiling.

The controversy between slots and resources seems a lot like the controversy between whether to accept a particle or wave theory of light. The analogy is that two mechanisms, such as a wave or a particle, both seem useful in certain contexts, but that it is not clear how to integrate them into a coherent, understandable view. For slots versus resources, it is possible that one system in the brain sharpens the stimulus field to result in a small number of separate objects categorically perceived, whereas other brain systems allow continuous information to be appreciated (but with practical limits). If so, this system would be analogous to the dual system that has been proposed for acoustic perception (the categorical and continuous codes of Braida et al., 1984 in acoustics and Pisoni, 1973 in speech perception) and number perception (the subitizing and continuous quantity perception mechanisms, e.g., Xu et al., 2005; Mou and vanMarle, 2014).

Cowan et al. (2016) developed a response mode that could be useful to investigate the question of continuous resources. An array of colored squares was presented and then, after a short retention interval, anywhere from 0 to 1 to 2…to all of the items in the array changed to a categorically different color. The task was to indicate how many items changed. The results suggested that only a few color changes could be noticed. However, suppose the task were simply to indicate whether there was any change in the array. If the continuous resources theory is correct, it might be possible to detect a change when it consists of all of a large number of array items each changing only slightly, in a case in which one to three such changes would not be noticed. On the other hand, this controversy is not easily resolved. Slot theorists could object on the basis of ensemble properties that if, say, one object changed 2 degrees toward blue on the color wheel and another object changed 2 degrees in the opposite direction, then the contrast between these adjacent colors has increased by 4 degrees, which might be a more salient change in its own right. This is a very difficult issue and it is fascinating how many different paths toward resolving it have been established recently.

2.09.4 The Controversy Regarding Attention Limits and Interference Across Sets

Whether one accepts that there is a capacity limit in terms of the number of slots or in terms of a fluid resource, a remaining unresolved controversy is whether the limit applies separately for different modules, as in the model of Baddeley and Logie (1999), or whether there is a central capacity limit as in the model of Cowan (1988, 1999). Saults and Cowan (2007) favored the central theory on the basis of experiments in which arrays of spoken digits and colored squares were presented at different times, to avoid encoding problems, but in the same trial nevertheless. Arrays of sounds were presented through four loudspeakers in different voices. The results favored a central theory but the low capacity for arrays of sounds was problematic. In the best-controlled experiments, specifically those with a bimodal mask to prevent the use of lingering sensory memory, participants could remember about two items from acoustic arrays attended alone, about four items from visual arrays attended alone, or about four items total when both modalities were to be attended on the same trial. This made it seem as if the amount that could be stored in working memory was fixed at four. It was problematic, though, that acoustic memory was so limited, inasmuch as the general rule could not be tested in a situation in which both modalities approached the suspected limit.

Cowan et al. (2014) repeated the same kind of experiment, but with series of spoken items instead of spatial arrays, to eliminate any perceptual encoding problems. The trials included articulatory suppression to prevent rehearsal, with a mask in both modalities to eliminate sensory memory. Another innovation of that study was to use capacity from four conditions together to estimate how many items were kept in a verbal form regardless of whether the visual information also had to be retained, how many items were kept in a visual form regardless of whether verbal information also had to be retained, and how many items were kept in a kind of memory that could be devoted either to visual or to verbal items, depending on the circumstances. For each modality, the difference between unimodal and bimodal trial performance on that modality indicated the amount of working memory resource that was reallocated to the other modality when both modalities were to be attended. Consistently visual information accounted for about two items, consistently verbal information accounted for about two items, and central information that could be allocated to verbal or visual material depending on the task accounted for about one item. Cowan et al. suggested a theoretical interpretation that involved a multiitem focus of attention, but also a process in which items from the first-presented modality are encoded using the focus of attention (up to a limit of about three items) and are then off-loaded to the activated portion of long-term memory to allow the other modality to be encoded. It can be assumed that items from the second modality are similarly encoded in the focus of attention up to the limit of about three and are then off-loaded to the activated portion of long-term memory. The reason why there is a slight cost of retaining two modalities specifically (a sum of about five items retained as opposed to the six that would be expected by separate verbal and visual modalities) may be because attention must tend to the representations in activated long-term memory to refresh them (Barrouillet et al., 2011) or improve them, with some competition between the two separate representations for the two modalities presented.

Some claim that there is no such fundamental interference between information in modalities that share no features (Fougnie et al., 2015), and others claim contrariwise that information held concurrently always demonstrates mutual interference, regardless of the similarity of the items (Morey and Bieler, 2013). There are memory theories based primarily on the notion of interference between concurrently held items (Oberauer et al., 2012).

Recent research using functional magnetic resonance imaging provides a good case for the idea that some portion of the retention of information cuts across modalities. Todd and Marois (2004) found that the intraparietal sulcus (IPS) not only shows more activity when more visual items from an array are to be retained in working memory, but also plateaus when the number of array items reaches about four, similar to where the measure of capacity itself (k) plateaus. Cowan et al. (2011) found that the left IPS responds not only to visual memory loads, but also to acoustic verbal memory loads. Li et al. (2014) showed that this left IPS area is functionally connected to the areas involved in encoding the information: basically temporal areas for spoken information and occipital areas for nonverbal visual information. Lewis-Peacock et al. (2012) used multivariate pattern analysis techniques to show that the areas that process the visual information (primarily occipital) also represent that information as a pattern that can be observed; when information is needed, the representation is active. For example, if the participant is to remember a couple of bar orientations along with a word, at first the patterns representing both of them are active. If a cue is given indicating that, say, the first test will be on the bars, the pattern for the word will decline to baseline. If, however, a second cue indicates that now a second test will be on the word, the pattern for the bars is seen to decline and the pattern for the word revives. These results were taken to suggest that information currently in use is held in the focus of attention, whereas other information is held in an activated portion of long-term memory (not necessarily activated in terms of neural activity, but with the information somehow preserved for later in the trial). Majerus et al. (2016) used multivariate pattern analysis in a different way, showing that the IPS represents not the types of items, but the number of items in the focus of attention regardless of the visual or verbal nature of those items. Thus, the IPS seems to serve as a focus-of-attention hub with pointers to other posterior areas that hold information in the focus. The selection of information for the focus seems to depend on the interaction of the parietal areas with frontal areas such as the dorsolateral prefrontal cortex (cf. Kane and Engle, 2002). There is convergent evidence (Unsworth and Robison, 2015) that pupil diameter increases until the capacity limit and then levels off, indicating an attention-related source of capacity.

2.09.5 The Controversy Regarding Time Limits of Working Memory

If short-term or working memory is to be a mechanism distinct from the rest of memory, then it must be limited either in the number of items that can hold concurrently, or the time period for which the information can be held. Like the capacity-limit debate, the debate about time limits has remained controversial for many years. At the beginning of the field of cognitive psychology, the work of Miller (1956) was timely in representing the capacity-limit idea; soon after, the idea of a time limit was represented as noted earlier, by Peterson and Peterson (1959) and Brown (1958), and opposed by Keppel and Underwood (1962) and Waugh and Norman (1965). (Neither idea excludes the other but in the early days, it seems, item and time limits were rarely considered together.)

Some theories of working memory depend on the existence of time-based loss of information. In the theory of Baddeley et al. (1975), phonological information was said to be lost over about 2 s in the absence of rehearsal. This idea was used to explain why participants could recall about as much information as they could recite in 2 s; the rate of overt recitation was assumed to approximate the rate of covert verbal rehearsal (and for support of that equivalence see Landauer, 1962). This rate varied by individual and was slower for lists of words that took longer to pronounce. The theory was that information is lost unless it is rehearsed in a repeating loop at a rate fast enough to prevent the items from decaying out of working memory. That view seems consistent with Peterson and Peterson (1959). The large difference in estimation of the useful duration in memory, 18 s for the Petersons versus 2 s for Baddeley et al., in principle could be explained away on the grounds that the much shorter memory set of Peterson and Peterson could have allowed some covert rehearsals despite the distracting task of counting backward by threes. In fact, evidence by Melton (1963) repeating the Peterson and Peterson procedure with longer lists to be remembered did indicate faster decay rates.

Later, the data underlying this interpretation was called into question (Jalbert et al., 2011; Lewandowsky and Oberauer, 2008).

Barrouillet et al. (2011) have a similar theory but based on refreshing of the items using attention rather than covert, verbal rehearsal, and it was shown that refreshing and rehearsal trade off depending on the task demands that can obstruct rehearsal or attention (Camos et al., 2011).

The existence of time-based loss of information has been just as central to the theory based on refreshing as it was to the theory based on rehearsal, and for similar reasons. The decay-and-refreshing idea, too, has been opposed (e.g., Lewandowsky and Oberauer, 2015). The most important basis of the opposition is that when attention and rehearsal are both prevented during the response period, it nevertheless makes very little difference whether the items are repeated slow or fast. Not all results have corresponded to that finding, though. Cowan and AuBuchon (2008) presented digits for recall at an irregular pace and either did or did not require that the digits be recalled in the exact timing in which they were presented. The theory was that when irregularly paced responses had to be made, remembering the timing of the list would require that the participant forego the usual rehearsal. In that circumstance, there was evidence of the loss of information when the items to be recalled first had to be recalled at a slow rate (see also Cowan et al., 1994, 1997a, 2000). There are probably objections to these findings on the grounds that the recall of irregular timing could be more effortful at a slow rate. Conversely, though, most or perhaps all of the studies showing no loss of memory as a function of time during the response may have involved responding at a participant-determined rate (which would allow sneaky refreshing) rather than the experimenter-determined rate that Barrouillet and colleagues have used.

Time-based loss appears better-established when participants do not have the opportunity to do extended encoding of the stimuli to the point at which a matching template is found in long-term memory, or to the point at which there is a clearly-established, unambiguous new representation. Under these circumstances, distraction is not needed to prevent rehearsal because memory loss over time is found even without such distraction, inasmuch as the stimuli seem unrehearsable. Supporting this point, Ricker and Cowan (2014) found that the rate of loss of memory from sets of three unfamiliar characters across an unfilled interval depended on the amount of time available to consolidate each character in working memory before having to move to another character, and equating the time available equated the rates of loss. Ricker et al. (2014) further examined whether the loss that does occur could be a matter of temporal distinctiveness being lost. Varying the time before each trial should raise its distinctiveness (Keppel and Underwood, 1962) but, at least for unfamiliar characters, that did not matter, provided that the time was long enough to parse the stimulus stream into separate trial events. There do, however, appear to be experimental designs that result in an effect of temporal distinctiveness as well (Shipstead and Engle, 2013; Souza and Oberauer, 2015; Unsworth et al., 2008).

Nevertheless, there does seem to be evidence of actual decay, whether or not it is pervasive enough to validate the theories of Baddeley et al. (1975) and/or Barrouillet et al. (2011). Other studies suggest that the nature of decay of working memory may be sudden, based on collapse of the representation after some seconds on particular trials, rather than steady decline (Cowan et al., 1997b; Winkler et al., 2001; Zhang and Luck, 2009).

2.09.6 Practical Applications of Working Memory

The currently most popular practical application of our knowledge about working memory is to attempt to improve behavior through extensive training (e.g., Jaeggi et al., 2011). This endeavor differs dramatically from what one would hope to achieve via long-term memory training. There, it is pretty clear that one would be trying to reinforce the mechanisms of encoding and/or retrieval to make sure that the trainee makes the most of memory. In working memory training, in contrast, there is a greater hope that stems from the strong correlation between working memory tasks and various measures of intelligence and cognitive aptitudes (e.g., Conway et al., 2002; Cowan et al., 2005; Daneman and Carpenter, 1980; Engle et al., 1999; Kane et al., 2004; Kyllonen and Christal, 1990; Oberauer et al., 2002). The hope has been that by training working memory, the "brain power" of the individual can be improved, that is, the ability to control attention. However, meta-analyses of these attempts have primarily come up negative (e.g., in adults, Shipstead et al., 2012; in children, Melby-Lervåg and Hulme, 2013). Working memory training seems to improve working memory skills but there is apparently not much effect on other aptitudes.

Attempts to train attention directly have been fewer in number but may be more successful, at least in children (Diamond, 2012; Rueda et al., 2005). Taken together, these studies suggest that the training that works best is direct training on the skill itself, so that training executive function and attention may work by improving the strategies that children apply to the task.

Aside from direct remediation of working memory, there are many practical reasons why we would want to know about individuals' working memory limits. One reason is to optimize educational materials (Cowan, 2014). Gathercole et al. (2006) found that children perceived by teachers as disobedient often act that way because they fail to remember instructions. Successful instruction almost certainly depends on adjusting the difficulty of the material to match the student's capability, and doing so requires understanding working memory limits that vary among individuals and across ages. Halford et al. (2007) have argued that working memory capacity limits what concepts a person can understand, presumably because items that are in the central, attention-dependent part of working memory at the same time can be linked together to form new concepts (Cowan, 1988). This suggestion has been supported by the finding that items concurrently in focus are associated in long-term memory even unintentionally (Cowan et al., 2013) but that concepts become very difficult even for adults when they involve the joint influence of three interacting factors (e.g., Halford et al., 2005). As computers make it more feasible to adjust educational materials individually, it may well be that a computer assessment of working memory may help in that adjustment, and teachers also can be on the lookout for working memory overload. Above, it was noted that many developmental disorders involve decreased working memory capacity and teachers must keep that in mind when planning materials.

More broadly, keeping in mind working memory constraints of readers is important not only for teaching, but also for clear and effective writing (Pinker, 2014). Granted, in fiction it is sometimes desirable to create ambiguity for effect, but that is rarely the case in nonfiction writing aimed at imparting specific information or ideas. Many sentences fail the test of clarity by front-loading ideas that impose a working memory load until late in the sentence, when disambiguating information finally arrives. Consider the following poorly planned, front-loaded sentence, for example: *The observation that it is unknown whether and how training on tasks using commonly applied working memory procedures, such as n-back tasks and other updating tasks, positively affects intelligence is unfortunate*. It could be replaced by something much easier on working memory at little cost in words, e.g., *it is unfortunate that we do not know* *whether training on working memory tasks improves intelligence and, if so, how it works. This observation applies to n-back tasks and other updating tasks among others.*

Many concepts of keen clinical interest may have a contribution of working memory. A good example is the theory of mind, i.e., the ability to reason about what other people think. More complex types of theory of mind logically must depend on working memory, such as the ability to keep in mind that one person in the room knows something that another person does not know (e.g., see Dennis et al., 2009). Yet, there is controversy because an opposing view is that there is a social module that controls theory of mind independent of working memory capacity generally; but that view is controversial (see Geary, 2004; Mitchell, 2007).

There is also controversy about the role of working memory in other social phenomena, in particular in stereotype threat. An example is that women taking a math test do much worse when they are told that women are not expected to do as well as men, or if that stereotype is somehow made salient. The theory involving working memory is that the threat itself is distracting during test taking, but according to competing theories it is the expected behavior that plays a role rather than distraction from the threat itself (Jamieson and Harkins, 2007).

Working memory has a pervasive effect on our everyday cognition that has yet to be fully recognized. Goldinger et al. (2003) carried out an interesting study showing that when working memory is tied up, reasoning can be faulty without people realizing the faultiness, and therefore without correcting it. Participants were asked to act as if on a jury to decide how much money an individual should receive for an injury acquired at a baseball game because part of the ceiling fell on that individual, either while the individual was sitting in his assigned seat or after he had moved to a different seat. When a participant's working memory was both low to begin with and tied up with a secondary task, the participant assigned a lot less money for the individual who had wandered from the assigned seat. Such a participant probably thought that he or she was doing well to have considered the logically provided argument that the injury would not have happened if the victim had remained in the assigned seat; but given a shortage of working memory, they overlooked the legal irrelevance of that point.

The most practical benefit of studying the operation of working memory may be related to its theoretical ramifications. Part of working memory, in my terms the focus of attention (Cowan, 1988), may relate to the information that we are conscious of holding in mind (Baars and Franklin, 2003; James, 1890). Another part, related to what I have termed the activated portion of long-term memory, still affects behavior and may therefore relate to how others perceive us. We sometimes overestimate the amount of information that we hold in working memory (Cowan et al., 2016) and therefore are overconfident of the excellence of our own thought processes. A little more awareness of these points by all of us could increase the extent that we are willing to consider the ideas of others who disagree with us.

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