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Chapter 7

Working-Memory Capacity Limits in a Theoretical Context

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After a brief definition and description of working memory (WM), several theoretical views will be discussed. The view most emphasized is based on the idea that attention is critically important for WM. However, there are several ways in which attention can be used. The present suggestion is that all of the functions of attention are relevant to WM.

A number of specific experimental tasks developed from different theoretical points of view will be examined. This will be done to make the case that the types of tasks that have been used most often to look at individual differences in WM are not as special as has typically been assumed. These tasks correlate well with scholastic abilities but so do other tasks that are suggested as possible alternatives. Correlations from various data sets between different WM measures and various measures of scholastic ability exemplify this point. Finally, conclusions will be reached about the value of various measures of WM.

DEFINITION AND DESCRIPTION OF WM (Working Memory)

Definitions of WM differ (Miyake & Shah, 1999). However, one useful, broad definition is the retention of information in a temporarily accessible form, through all available mental processing mechanisms (Cowan, 1999). That definition has some boundaries. For some theorists, but not others, WM includes the ability to manipulate the information being held in mind.

The importance of WM is that it must be used to complete many intellectual tasks. When we perceive the outside world, WM is needed to extend the perception. For example, imagine that you are walking along the street and reading a sign off to your right. While you are doing so, your WM is retaining a conception of what the world is like to the left, where you are not looking. It retains information about where the street is, how busy the traffic is, and what buildings are found along the opposite side of the street. To take another example, in comprehending speech, it is necessary to remember some of the words that are spoken, or at least the ideas behind those words, long enough for the entire idea to be constructed. WM is similarly important, to hold in mind the assumptions and partial results in calculations, in problem-solving generally, and in various sorts of logical reasoning.

THEORETICAL VIEWS OF WM

Several different views of WM have served as the basis of different kinds of experimentation and tests: a psychometric or modal view, a multicomponent view, a storage-plus-processing view, and an attentional view. According to the traditional, psychometric point of view, it is useful to measure peoples' ability to repeat simple lists of digits or words in the presented order. For example, digit span is a regular part of standardized intelligence tests. It is useful because serial recall of lists of items has much in common with the use of memory in other intellectual tasks. It reflects the storage of needed data in a temporary form and correlates with aptitude.

Baddeley (1986) challenged this approach by adopting what he saw as a multicomponent view. This view holds that there are different types of storage media in the brain, such as phonological storage of speech information on one hand and visual or spatial information on the other hand, and that one must also consider the quality of executive processes that maintain and transform the information. Daneman and Carpenter (1980) and others did not exactly challenge this view, but they concentrated on what kinds of memory task might be best if the goal is to measure WM in a way that reveals its quality in an individual. In order to measure the capacity of WM in a meaningful way, they suggested to tie up both its ability to store information and to carry out a processing task.

Although many researchers who accept the multicomponent point of view acknowledge that the type of task that Daneman and Carpenter (1980) pioneered works well in predicting scholastic abilities, not everyone agrees with the explanation involving tying up storage and processing together. For example, Engle, Kane, and Tuholski (1999, and various other articles by Engle and colleagues) suggest the alternative possibility that what is most important about WM tasks developed by Daneman and Carpenter is that they require the intensive use of controlled attention to carry out the task. It may be the control of attention that distinguishes between people with better or poorer WM spans.

In brief, here is what has happened to the different views of WM. The traditional psychometric or modal view is considered disconfirmed because Baddeley (1986 and elsewhere) showed that a multicomponent view is needed. Different types of brain damage, for example, produce different types of WM deficit that can be interpreted as resulting from damage to different parts of his multicomponent system. The multicomponent view is still viable. However, the methods developed from that point of view are generally not designed to study individual differences in the ability to carry out complex cognitive tasks. The storage - plus - processing view (Daneman & Carpenter, 1980) has produced the testing procedures that have become dominant in an examination of individual differences, used in hundreds of studies. Finally, though, the attentional view (Engle et al., 1999) has provided what is now probably the most generally accepted interpretation of how these storage-plus-processing tasks actually work. According to that reinterpretation, their success does not depend on storage plus processing per se, after all. It depends on controlled attention.

This chapter focuses on the attentional view, but within that view, notes several subtypes. Hasher and Zacks (1988) proposed that the ability to inhibit irrelevant information is what is critical and distinguishes between people with good versus poor WM and intellectual abilities. For example, when you recall a list of names you may think of a word that you already said and you must inhibit any inclination to say the same word again. Engle et al. (1999) and others have suggested that this view is too restricted and that any kind of executive function requiring attention is critical to WM. The relevant executive functions can include inhibition but also other functions (Miyake, Friedman, Emerson, Witzki, & Howerter, 2000), such as updating (e.g., during a baseball game if one is trying to keep track of how many balls and strikes there are, which is difficult because it keeps changing) and coordination (e.g., at a restaurant when a waiter tries to keep in mind which diner gets which meal while writing them down). Even keeping in mind the goal of a task that one is doing is a WM function (e.g., Kane & Engle, 2003).

The present approach is not very different from these other investigators. However, it suggests that attention always is critical for WM. In particular, attention can zoom in to processes as little as a single item or zoom out to apprehend up to about 4 independent items (chunks), though not much more than that (Cowan, 2001). However, whereas Engle and his associates have preferred to measure the capability of attention when it is zoomed in, the present view is that it is useful to try to measure performance when it is zoomed out because that may provide a meaningful measure of WM capacity. The emphasis on measuring how many chunks can be held in the focus of attention at one time can be associated with several investigators (Broadbent, 1975; Cowan, 2001; Miller, 1956). Also, the recent concept of the episodic buffer (Baddeley, 2000, 2001) may serve the same purpose as holding items in the focus of attention.

It is worthwhile to illustrate what a wide variety of functions the focus of attention is assumed to carry out. WM measures may be based on any of these functions, or at least may relate to them. The first function is filtering; for example, when one listens intently to one speaker at a party, at the expense of tuning out others. Fig. 7.1 shows that within the memory system, some items are in an activated state (represented by the jagged line), but that only some of the activated information is sufficiently active to be the focus of attention (represented by the large circle). The information in the focus of attention receives much more complete information processing. Each small dot represents an activated element of the memory system. Incoming sensory information activates representations in the memory system automatically, and any number of sensory stimuli can do this simultaneously. However, most of this information cannot make it into the focus of attention, which has limited capacity. This figure shows the ability of attention to focus on one stream of stimulation (horizontal, solid line) and to effectively filter out other streams (horizontal, dotted lines) on the basis of their differences in physical characteristics such as voice quality, or color if they are visual stimuli. As shown here (rising dashed lines), pertinent information in the memory system is used rather automatically to help interpret the incoming information in the focus of attention.

Another point that should be added is that this view is not as different as it seems from Baddeley's (1986) WM model. Any function that Baddeley would attribute to the phonological buffer or the visuo-spatial buffer could be attributed here to properties of the activated memory outside of the focus of attention. The differences between models have to do with assumptions about how specialized or general the storage devices are (Cowan, 1999).

Fig. 7.2 illustrates how the focus of attention may be involved in the process of comparing incoming stimulation to representations already in memory. This may occur, for example, when one is checking to make sure that a series of numbers is written down correctly. Fig. 7.3 shows the retention function of attention. For example, in watching a busy, urban street in Tokyo you can examine what a few people are doing at any one time but you cannot observe what, say, 10 people are doing all at the same time. There is a limit to how much independent information can be held at one time. Finally, Fig. 7.4 shows the chunking function of attention, in the spirit of Miller (1956). Information that resides in the focus of attention at the same time tends to be linked together or associated to form a larger chunk. For example, if you attend to the telephone number 7 5 7 8 0 3 2 you may soon focus on 7-5-7 as one chunk, 8-0 as a second chunk, and 3-2 as a third chunk. Then you are able to focus attention on the three chunks together; 757-80-32 and, before long, you have memorized the telephone number. A great deal of learning takes place through chunking.

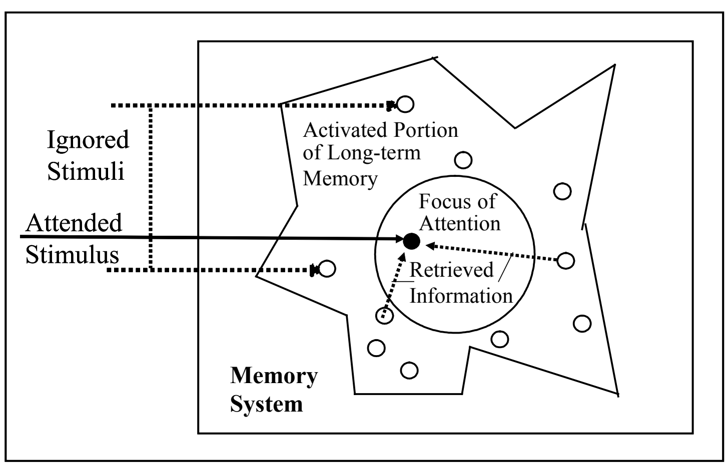

FIG. 7.1. Filtering and interpretation functions of attention (see text for details).

One can use these principles to distinguish between *compound* and *pure* estimates of WM capacity (Cowan, 2001). A compound estimate, exemplified by Miller's estimate of 7 $\pm$ 2 items in memory, comes from situations in which one item is presented at a time. The 7 items recalled presumably do not result from 7 separate chunks in memory. As discussed above, 7 items can be combined to form a smaller number of chunks. In contrast, a pure estimate presumably comes from situations in which familiar items are used but they cannot be grouped to form larger, fewer chunks of information. This can occur when information is presented too quickly or with too many items all at once, making chunking difficult. Under these circumstances, it turns out that adult participants recall about 4 items. The convergence of results from many procedures tends to lend support to the theoretical analysis of the tasks. Presumably, each item is a separate chunk in WM in these tasks, which is why they yield similar estimates of capacity.

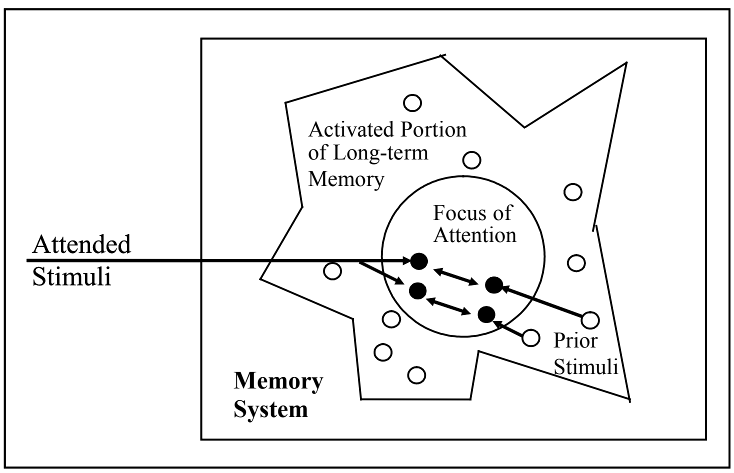

FIG. 7.2. Comparison and updating functions of attention (see text for details).

Cowan (2001) suggested that the focus of attention may be the *only* basis of true capacity limits, conceived as limits in how many chunks of information can be held in WM. Other faculties of WM, such as Baddeley's (1986) "slave systems" or Cowan's (1988, 1995) activated memory, would be limited by other factors such as decay, interference, and temporal distinctiveness but would not have chunk limits per se. Baddeley's (2001) newer, episodic buffer component may be an alternative conception of the chunk limit; it holds information that does not neatly fit into phonological or spatial stores. Yet, an episodic buffer might encounter attention limits at least in information acquisition, if not in its maintenance.

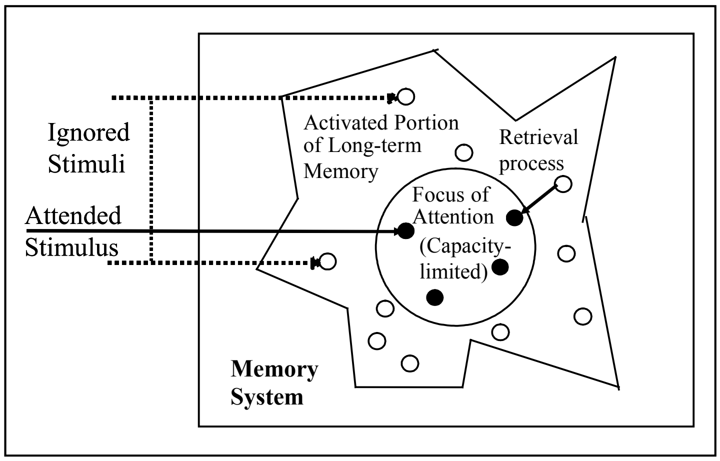

FIG. 7.3. Encoding and maintenance functions of attention (see text for details).

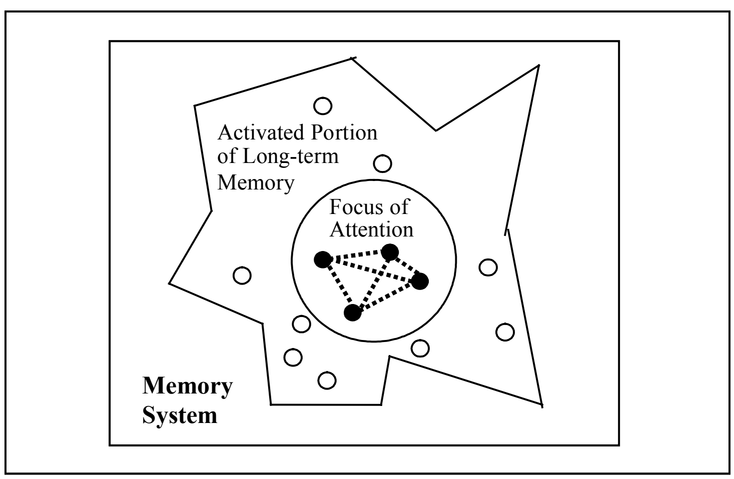

FIG. 7.4. Chunking and learning functions of attention (see text for details).

What is advocated here is that we now need to do more research in which the WM task itself is based on how much information the focus of attention can hold. The actual capacity or retention function of the focus of attention is important to study, for at least three reasons. The first is the validity of the WM concept as a memory concept as opposed to just an attention concept. Only items that are held in attention at the same time can be combined into one new chunk of information, and chunking is the main mechanism of new learning. A second, related reason is psychometric. Only the retention function of the focus of attention may lead to a meaningful numerical estimate of the capacity of WM. The third reason is philosophical. Limits on the contents of consciousness (as discussed by William James, 1890) can be estimated by the number of chunks in the focus of attention.

MEASURES OF THE CAPACITY OF WM

This section will review briefly the common methods of measuring WM span and suggest some alternative measures, which are taken as measures of the capacity of the focus of attention.

Measures Often Used

The types of measures that are used to examine WM from the traditional, psychometric approach and from the storage-plus-processing approach are well known (for a review see Daneman & Merikle, 1996). In the psychometric approach, on each trial, a list of items is presented and must be repeated back in the presented order. The list length grows until a point at which the participant can no longer repeat the lists correctly and span is defined in various ways with reference to the list length (e.g., as the list length at which 50% of the lists can be recalled correctly).

According to the storage-plus-processing approach, there are processing episodes interweaved with items to be recalled, in order, after the last processing episode. For example, in a counting-span task, the participant must count the number of dots on each screen and then recall the sums. In a sentence span task, spoken sentences are presented, whereas in a reading span task, written sentences are presented. Each sentence is evaluated in some way and then the final word of each sentence is recalled or, in another version, a separate word following each sentence is recalled.

In an arithmetic operation span task, an arithmetic operation is carried out and the result is retained in memory for later recall or a separate word is retained for recall. It is the number of presentations of the processing task (displays of dots, sentences, or arithmetic problems) that can be carried out along with correct recall of the task-final memoranda, that defines the WM span. This WM span correlates with complex cognitive task performance better than simple span (Daneman & Merikle, 1996).

Some Possible Measures of the Focus of Attention

In contrast, it is unclear how to measure WM from the theoretical standpoint in which it reflects attentional capacity. One might examine the effects of attention when zoomed in to focus on a goal (e.g., see Engle et al., 1999; Kane & Engle, 2003). However, this does not yield a task-independent estimate of some theoretical quantity. Perhaps, in the future, it will be possible to do so (e.g., to obtain an estimate of the number of seconds for which an individual can keep in mind a goal in the face of, say, a constantly-present competing task). What is proposed here, though, is that we can measure the capacity of WM in terms of the number of chunks that can be held in mind when attention is zoomed out to apprehend as many unconnected items as possible in a currently-relevant array. Methods by which one can do so were suggested by Cowan (2001).

According to the logic of Cowan (2001), there is a reason why it is difficult to obtain a theoretically-pure estimate of WM capacity. When an experimental participant is presented with a stimulus set, one typically does not know how the participant groups the stimulus set into a smaller number of chunks. Therefore, it is not possible to estimate the number of chunks held in WM in a manner that can be compared across stimulus situations. To overcome this problem, Cowan suggested examining situations in which there is good reason to suspect that grouping processes cannot be carried out (e.g., when the participant is engaged in a rehearsal-suppression task during the encoding of a verbal stimulus set). One also must restrict the examination to sets of stimuli that are familiar so that each item is represented in memory initially as an integrated chunk (e.g., studies using words in the participant's native language, but not foreign or nonsense words, would qualify). A wide variety of situations taken to fit these constraints provide estimates of WM capacity of about 4 chunks, with young-adult means in various experimental conditions ranging from about 3 to 5 chunks and individual scores ranging from about 2 to 6 chunks. By implication, these same limits might apply to all WM situations although that assumption cannot be verified in situations in which the chunking processes are unclear.

The striking convergence in the capacity observed in many different procedures was taken by Cowan (2001) to suggest that the analysis of these procedures was correct; that, in these procedures, to a close approximation, each item is retained as a separate chunk in WM, allowing an estimate of the number of chunks in WM. When other mechanisms are allowed to operate (rehearsal, chunking, sensory memory, and automatic forms of storage) the result is presumably a larger number of items retained, as in the ordinary memory span of about 7 items (Miller, 1956).

Cowan (2001) proposed four types of situation that lead to estimates of WM capacity in chunks: (1) when information overload limits chunks to individual stimulus items, (2) when other steps are taken specifically to block the recoding of stimulus items into larger chunks, (3) in performance discontinuities caused by the capacity limit, and (4) in various indirect effects of the capacity limit. Here, however, we focus on measures for which evidence exists, relating them to cognitive aptitude. These include memory for visual arrays, multi-object tracking, running memory span, memory for ignored speech, and conceptual span.

Before describing these measures it is important to note that the capacity limit of about 4 items cannot easily be attributed to the rate of sensory forgetting or the rate of transfer of information from sensory memory once attention is focused on it. Similar limits are obtained no matter whether the items come from briefly presented visual arrays, as in the seminal research with character arrays by Sperling (1960) and the more recent work with color arrays by Luck and Vogel (1997), or auditory arrays, as in the research of Darwin, Turvey, and Crowder (1972). That is true even though sensory memory seems to be useful for a much longer period in the auditory arrays. The present explanation is that the common result reflects a limit in how many independent pieces of information can be held in the focus of attention (or perhaps in an episodic buffer).

Visual-array Measure

The first measure is memory for visual arrays (Luck & Vogel, 1997). An array of randomly arranged colored squares is presented for a half-second or less and a second array is presented shortly afterward, at the same location that the first array was presented. The second array is identical to the first or differs in the color of one square. A cued (encircled) square is the one that may have changed and the required response is to indicate whether it has changed or not. Young adults can carry out the task very well with up to 4 squares per array, then performance levels begin to decline markedly across set sizes. Even at the larger array sizes, a simple formula to correct for guessing shows that people can retain about 4 colors in mind from the first array, to be compared to the second array. A formula that works well is $k = N * [h + c - 1]$, where k is the capacity of WM, N is the set size in the array, and h and c are the probabilities of hits and correct rejections (Cowan, 2001). This formula was calculated by assuming that k items are apprehended from the first array and that, if the cued item is one of those k items, the participant will know whether it has changed color or not; if the cued item is not among the k items, the participant will guess "different" with some fixed rate g (which drops out of the final equation). The formula works well in that the calculated k remains relatively constant across set sizes higher than 4, more so than a slightly different formula (Pashler, 1988).

The present interpretation of the visual array task is that items from the first array cannot be retained in an automatically-held form of memory activation that is not limited in capacity per se, such as visual sensory memory. The reason is that the second array presumably overwrites the visual memory of the first array. Luck and Vogel (1997) also showed that a memory load to suppress articulation during the trial has no effect. It is apparently necessary to hold items from the first array in an interference-resistant form, at least momentarily when that array is seen (presumably, in the focus of attention). It is possible that the k items that are apprehended in the focus of attention can be transferred to a form that does not require attention for maintenance; perhaps a form of activated memory such as Baddeley's (1986) visuo-spatial sketchpad.

Multi-Object Tracking

In this procedure (Pylyshyn & Storm, 1988), several dots flash and it is those dots that are to be tracked. When they stop flashing, all of the dots move around randomly but the participant must keep track of which dots had been flashing initially. People can track up to 3 or 4 dots simultaneously. The limit in tracking dots is presumably a limit in how many can be held in the focus of attention at once.

Running-Memory Span

In this task (Pollack, Johnson, & Knaff, 1959), typically using digit stimuli, spoken digits are presented rather quickly and continue until an unpredictable point. At that point, the list ends and the participant must recall a certain number of items from the end of the list. Under these circumstances, it is difficult or impossible to rehearse and group the items. Participants may adopt a passive attitude. Then, when the list ends, they presumably use auditory sensory memory or phonological memory to retrieve some items from the end of the list. This retrieval is limited by the amount that the focus of attention can apprehend from sensory memory. Young adults can remember about 4 items in the correct serial position relative to the end of the list. If the usable phonological memory is assumed to last about 2 s (Baddeley, 1986), it is clear that only about half that amount can be transferred to the focus of attention in the running span task.

Memory for Ignored Speech

In this procedure (Cowan, Lichty, & Grove, 1990; Cowan, Nugent, Elliott, Ponomarev, & Saults, 1999), more direct means are used to prevent rehearsal and grouping of items. Lists of spoken items are presented through headphones, one after another. Meanwhile, participants engage in a task designed to distract attention from the spoken items. Cowan et al. (1999) used spoken digits and a primary visual task in which rhymes are to be formed among the names of pictures that are presented, but without speaking. This task strongly discourages both rehearsal and attention to the spoken digits. Just occasionally, the rhyming game is interrupted and a display is presented on the computer screen, indicating that it is time to try to recall a spoken list that just ended. This can only be accomplished by suddenly shifting attention to a sensory memory trace of the spoken list and transferring as many items as possible into the focus of attention. Young adults recall an average of about 4 digits in their correct serial positions in this ignored-speech task, whereas children recalled fewer. Presumably, there is plenty of sensory memory but the attentional focus is limited. Therefore, regardless of the list length, which ranged from a maximum equal to the longest list the participant recalled in an ordinary span task to a minimum of 3 less than that, the number of digits recalled correctly stayed constant.

It is clear from the results of the ignored-speech task, including various safeguards that were taken, that it powerfully manipulates attention. First, no tradeoffs are found between visual and auditory task performance levels. For example, the rhyming game is carried out no more quickly when it is carried out alone than when there are digits to be ignored, suggesting that attention is not deflected to the digits. Second, the digits that are more frequent in the language, the low digits 1 - 3, are not recalled any better than the high digits 7 - 9, by children or adults. Third, the patterns of performance in memory for attended versus ignored lists of digits look very different from one another. Whereas the number of ignored digits recalled stays roughly constant across list lengths, the number of attended digits recalled climbs steadily across the same lists lengths. Fourth, the age and individual differences in memory for ignored lists of digits cannot be attributed to less forgetting of sensory memory over time in more capable subjects; those at different developmental levels forget the list at roughly the same rate, except for the final digit (Cowan, Nugent, Elliott, & Saults, 2000). It seems to occur instead because more information is transferred from sensory memory to the focus of attention in more capable subjects. These points are explained in more depth by Cowan, Elliott, and Saults (2002).

Some people comment that it is odd to use an ignored-speech task to measure the capacity of the focus of attention. An explanation might help. The point is to restrict the use of attention so that, hopefully, it is only used after the list is presented, to extract information from auditory sensory memory. The logic is similar to that of Sperling's (1960) study of visual sensory memory. It is presumably not possible in these procedures to use attention to group items when they are presented, only to extract information from sensory memory afterward. Sperling obtained a whole-report limit of about 4 items, similar to the tasks highlighted here.

It is worth pointing out that, in the attention-related WM tasks that have been described, what is meant by an "item" in WM is actually a binding between features. In the visual array task, it is a binding between the location of an object and the color, given that a particular color can occur more than once in an array. In the multi-object tracking task, similarly, it is a binding between an object and a present location. In the running span and ignored-speech procedures, it is the binding between a digit and a serial position in the list (in running span, at least, counted from the end of the list). It is assumed here that there is no limit on how many objects, colors, or digits can be in an activated state at one time (Cowan, 1988, 1995, 1999), but that there is a limit in how many feature bindings can be retained. (For a direct demonstration of the latter see Wheeler & Treisman, 2002.)

Conceptual Span

One more potential measure of the capacity of the focus of attention is a conceptual span task developed by Haarmann, Davelaar, and Usher (2003). A list of 9 words from 3 semantic categories is presented randomly and is followed by a cue to recall all of the words from one category (e.g., "*lamp, pear, tiger, apple, grape, elephant, horse, fax, phone,* FRUIT*?* Correct answer*: apple, pear, grape*"). Words are drawn repeatedly from a limited pool and are presented at a rapid rate of one word per second, minimizing the contribution of long-term memorization of the lists. People recalled an average of about 2 to 3 items in the cued category in this task. It is not known exactly how this task is carried out but the results differ in various ways from an ordinary word span; it seems likely that a conceptual structure is held in mind. If participants do not rehearse the phonological sequence as they often appear to do when serial recall is required (Baddeley, 1986), the alternative would be to retain concepts in an active form and to maximize the amount of activation of these concepts by recycling them through the focus of attention.

CORRELATIONS BETWEEN WM MEASURES AND COMPLEX COGNITIVE TASKS

Although it is clear that storage-plus-processing measures correlate with intellectual and scholastic types of aptitude better than do simple spans (Daneman & Merikle, 1996), it is not clear why this difference occurs.

Daneman and Carpenter (1980) proposed that it is because only the storage-plus-processing tasks explicitly tie up both storage and processing components of WM. However, another possibility is that the storage-plus-processing tasks represent just one situation in which items cannot be retained through an uninterrupted phonological rehearsal of the memoranda. With rehearsal processes out of the picture, the WM tests may reflect individual differences in how much can be held in the focus of attention or how well the attention processes can function when there is a need to shift from one task to another. If this is the case, it seems worth checking whether the tasks that have been reviewed above, as possible indicators of the capacity of the focus of attention, also will correlate well with aptitudes.

One set of correlations comes from an often-ignored meta-analysis of past research conducted by Mukunda and Hall (1992). The analysis included studies with children and adults, using within-age correlations between spans and various achievement and aptitude tests. The measures that they looked at included measures of conventional span, measures requiring both storage and processing, and one measure that may simply index the capacity of the focus of attention, running memory span. Whereas digit span (based on 53 independent tests) correlated with aptitude tests at a combined R = .22, word span did much better, (9 tests, R = .43). An often-used type of storage-plus-processing span, reading span, produced the expected high correlation (11 tests, R = .43). However, running memory span produced an almost equally good outcome (11 tests, R = .40). In contrast, correlations were lower for two other storage-plus-processing measures, operation span (6 tests, R = .23) and counting span (3 tests, R = .28). Inasmuch as running memory span does not require the verbal or mathematical ability that various storage-plus-processing spans require, but still produces hefty correlations with aptitude, it may be a purer measure of WM capacity.

In two unpublished studies of our own with elementary-school children and college students (with collaborators J. Scott Saults, Emily M. Elliott, Candice C. Morey, & Anna Hismjatullina), we found comparably high correlations between aptitude and achievement measures, on one hand, and measures of the capacity of the focus of attention, on the other hand. The aptitude and achievement measures include the American College Test and high school grades in college students; the Cognitive Abilities Test in children; and in all of the age groups, Stanford-Binet vocabulary and pattern recognition scores, Ravens Progressive Matrices, and the Peabody Picture Vocabulary Test. The latter include in all of the age groups, memory for ignored speech, running memory span, the visual array task, and an auditory analogue of that task. Although storage-plus-processing tasks that require verbal proficiency (specifically, listening and reading span, but not counting span) seem to contribute something extra that is not present within the focus-of-attention measures, it is likely that this part of the correlation is inappropriate and does not truly tap WM processes.

Oberauer, Süß, Schulze, Wilhelm, and Wittmann (2000) carried out a large-scale study of different types of WM tasks and included one task that was suggested as a possible measure of the capacity of the focus of attention, the multi-object tracking task. That task is rather special in measuring the capacity of the focus of attention directly, rather than measuring its mnemonic aftermath. Oberauer et al. did not show the correlations between this task and the scholastic tasks separately, but it was a valid predictor that was combined with other tasks in latent variable analyses. Its correlation with other WM tasks was highest for the spatial WM tasks, ranging from $r = .30$ to $r = .42$. This is a promising task for future correlative work on WM.

Haarmann et al. (2003) compared conceptual span to word span and reading span in terms of their correlations with text comprehension and spoken sentence comprehension. In both cases, conceptual span did at least as well as those types of other WM tasks. Once more, this result questions how essential the storage-plus-processing view really is in accounting for individual differences in complex cognitive activity.

There is one more relevant theoretical question. The storage-plus-processing tasks were developed originally as a type of span task that would improve the correlation between span and scholastic abilities measures, as compared to the simple digit span test that is used within tests of intelligence. The storage-plus-processing tests are successful in that regard, at least in adults; but why? From the point of view in which it is the quality of attentional processes that is important for WM, the critical difference between simple span and WM tasks may be the benefit of rehearsal in simple span tasks only. In storage-plus-processing tasks, the processing component may prevent covert rehearsal, perhaps just inadvertently. In the tasks that have been suggested to reflect the capacity of the attentional focus, the blocking of rehearsal is completely deliberate.

If this task analysis is correct, there is an interesting developmental prediction. It is well established that young children do not use rehearsal well. For them, we should find little difference in the way that simple span tasks and WM tasks correlate with measures of scholastic ability. When we look at developmental results, is that the case? Tentatively, the answer appears to be "yes." At least in some studies, digit span does just as well as storage-plus-processing tasks in predicting scholastic success in elementary-school children (Cowan et al., 2003; Hutton & Towse, 2001).

In conclusion, there is no reason to remain obsessed with storage-plus-processing tasks as a means to measure WM capacity. Measures designed to estimate how much information can be brought into the focus of attention at once are conceptually simpler. They may be less likely to confound WM with special knowledge such as linguistic knowledge, as the reading and listening span tests are likely to do, for example.

As the commentaries following Cowan (2001) attest, there are still open controversies regarding WM capacity and the focus of attention. For example, there could be separate capacity limits for various types of features, outside of the focus of attention (Wheeler & Treisman, 2002), or just a limit that emerges when attention is turned to any one feature field. A metric of complexity that takes into account the number of dimensions that must be considered to identify a stimulus correctly (Halford, Phillips, & Wilson, 2001; Phillips & Niki, 2002) might be unrelated to a chunk storage limit or might have to be combined with it to form a single, comprehensive theory.

SUMMARY

Although the concept of WM is at a forefront of research in cognitive psychology and cognitive neuroscience, there is little agreement on the definition of WM (Miyake & Shah, 1999) or how it should be measured. An apparent truism in the field has been that, in order to measure WM capacity, one must tie up both storage and processing mechanisms within WM (Daneman & Carpenter, 1980). However, an alternative conception of WM holds that it relies on the ability to use the focus of attention in processing (Engle et al., 1999). The present chapter is consonant with that view. Yet, numerical estimates of capacity, in terms of chunks held in the focus of attention, can be obtained in situations where the focus is zoomed out to apprehend multiple items in a set (that cannot be combined into a fewer number of chunks; Cowan, 2001), rather than zoomed in to keep a goal in mind notwithstanding competing interference. Several WM measures were described as potential measures of the capacity of the focus of attention. They correlate with scholastic and intellectual aptitude measures just about as well as storage-plus-processing types of WM measures. In children too young to use sophisticated means of verbal rehearsal and grouping, simple digit span also serves as a good correlate of aptitude. To investigate individual and developmental differences, this research advocates vigorous attempts to find WM measures that are as simple as possible and are designed to index the capacity of the focus of attention without relying on verbal knowledge that inadvertently contributes to more complicated WM performance. Note that this approach is compatible with efforts to determine individual and developmental differences in faculties other than the focus of attention, such as the persistence of activation in memory (Cowan et al., 2000; Towse, Hitch, & Hutton, 2000), the speed of processing of information (Kail & Salthouse, 1994), or changes in the use of strategies (Cowan et al., 2003; Hitch, Towse, & Hutton, 2001).

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