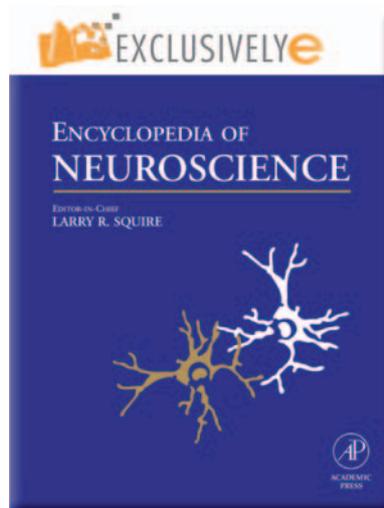


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Working Memory: Capacity Limitations

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Working Memory System

Working memory (WM) has been proposed to be a cognitive system that temporarily holds a limited amount of information in an active state so that it may be quickly accessed, integrated with other information, or otherwise manipulated. This type of memory is thought to underlie our ability to perform a wide range of basic tasks such as assigning meanings and syntactic roles to the interdependent words of a complex sentence, understanding the relationships among the ideas within a complex argument, performing mental rotation, and tracking the trajectory of a moving object when the visual input to the brain is continually disrupted by eyeblinks and saccades. Many cognitive processes that require information to be held in an online state are thought to use the WM system as a form of mental workspace to perform their requisite operations. As a result of its central position within cognition, the limited capacity of the WM system reflects one of the more significant processing limitations for human cognition.

Capacity Limits: Central or Modality-Specific?

One of the most notable characteristics of WM is that its storage capacity is highly limited. Most of the early models of short-term memory implicitly or explicitly assumed that it was a unitary memory store, irrespective of modality. In the 1970s, however, Baddeley and his colleagues proposed a multi-modal model of WM in which the memories for visual and verbal information are stored separately with independent capacity limits, both controlled by a central executive process. Early support for this model came from dual-task experiments in which little or no interference was found when verbal memory tasks were performed concurrently with visual memory tasks but substantial interference was found for two concurrent verbal tasks or two concurrent visual tasks.

Nelson Cowan, on the other hand, proposed that the capacity limits of WM reflect a more central limit, irrespective of modality. Specifically, his model proposes that WM is not an entirely separate system but is a part of the long-term memory system. Consequently, representations of information in WM are

proposed to be the activated portions of long-term memory within two embedded levels. The first level consists of activated long-term memory representations, which are memory representations that have recently been accessed. Although a large number of these representations can be active simultaneously, the highly accurate retrieval of this information is fairly limited as a consequence of interference. By contrast, the second level consists of a small subset of these active long-term memory representations that are held within the focus of attention, which has a capacity limit of approximately four items, irrespective of modality. That is, although there may be independent passive maintenance of information in modality-specific stores, the true capacity limits arise from the central limitation of the focus of attention.

Overview and Approach

At present, the evidence is somewhat mixed with regard to whether WM capacity limits are modality-specific or a single central limitation. Therefore, in the following sections, we consider the capacity limitations of WM separately for the verbal and visual modalities. Where appropriate, however, we also describe how these results can be alternatively accounted for within the Cowan framework. After discussing the common behavioral approaches to measuring WM capacity, we then describe more recent attempts to use neurophysiological methods to measure these capacity limits. In the final section, we summarize work that examines individual differences in WM capacity and how these differences relate to broader cognitive constructs such as intelligence and attentional control.

Verbal Working Memory Capacity – Memory Span Tasks

For over a century, the most common approach to measuring WM capacity has been with variations of the digit span task. In the standard version of this task, subjects are given a randomized list of numbers that they must immediately repeat back in the order of presentation. Subjects are initially presented with lists of two or three digits and if they repeat a list of numbers without making a mistake, the size of the list is increased until they cannot accurately complete the list. On average, most individuals can accurately report approximately seven items, although this number varies substantially across individuals. Similar estimates are typically observed when letters and words are used as the to-be-remembered stimuli.

Although the results of span tasks are often interpreted as reflecting the capacity of WM for verbal material, there are two important constraints that shed light on the nature of storage capacity in this context.

Chunking of Information

Recently, *Psychological Review* named George Miller's 1956 article, "The magical number seven, plus or minus two: Some limits on our capacity for processing information," as its most influential paper. Although many agree that the author intended the title of the paper to be taken as a tongue-in-cheek statement, the meme of short-term memory being limited to "seven plus or minus two" items has permeated the popular literature in psychology for the last 50 years. However, one of the primary ideas expressed in Miller's paper is that the exact number of items that can be held in WM depends heavily on whether the items can be grouped into meaningful units, or chunks. That is, chunking exploits preexisting information about concepts already stored in long-term memory so that new information can be more efficiently held in WM. For example, consider the letter string:

FBICIAFDRJFK

Memory span for this series is generally fairly poor because the 12 letters exceed the typical seven-item limit. However, consider the same items when broken into the following clusters:

FBI CIA FDR JFK

Performance is greatly enhanced under this condition because the units for memory span are four meaningful and familiar concepts rather than 12 independent letters. Thus, the precise number of items that can be held in WM is strongly dependent on what type of information is to be held, whether those items can be clustered into a smaller number of meaningful units, and finally whether the subject attempts to strategically code the incoming information into clusters. Indeed, efficient chunking of information is thought to be a pervasive aspect of daily cognitive life, and it may greatly underlie our ability to perform complex tasks such as reading and playing chess.

Phonological Coding of Verbal Information

The remaining constraint on estimates of verbal WM capacity is derived from studies that have examined the nature of how information is coded in verbal WM. One of the more popular characterizations stems from Baddeley's model of WM. In particular, information maintained in verbal WM is thought

to be stored in a phonological loop. Essentially, information is thought to be stored as a phonological or sound-based code within a structure (e.g., a tape loop) that can hold a limited amount of information for a very short period of time. However, this information can be held for much longer durations when the subject subvocally rehearses the phonological information repeatedly to keep it from being lost. There are several pieces of evidence that support the notion of phonological storage in verbal WM. For instance, fewer phonologically similar words (e.g., cap, slap, trap, map) can be held in WM than phonologically dissimilar words. However, memory span is not affected if the words are similar in meaning (e.g., big, tall, huge, wide) or similar looking (e.g., bough, dough, cough, through), which indicates that the phonological properties of the to-be-remembered items are a primary factor for the storage limit. In addition, many studies have shown that memory span is considerably smaller for phonologically longer words (e.g., alimony, Mississippi, testosterone) than for phonologically short words (e.g., hat, boy, up), which indicates that storage capacity is determined by how long it takes to pronounce the information to be remembered. Moreover, an individual's rate of speech also has a direct impact on how many items he or she can hold in a span task, with fast-speaking individuals capable of holding more items than slower-speaking individuals. On the basis of results such as these, many researchers agree that the capacity of verbal WM is determined by how much the individual can say in approximately 2 s. Thus, it appears that the capacity limits of this system are much better understood in terms of time (i.e., 2 s of speech) rather than by numbers of items (e.g., seven plus or minus two). Interestingly, when subjects are prevented from engaging in rehearsal, individuals can accurately report only three or four items accurately. This could be explained by Cowan's central capacity limit theory, in that the phonological loop is a domain-specific storage mechanism and the true capacity limit of attention can be observed when rehearsal is prevented.

Visual Working Memory Capacity: Whole Report

The initial measurement of the capacity of WM for visual information is often credited to George Sperling. In this influential series of experiments, subjects were presented briefly (50 ms) with arrays of 12 random letters and were asked to immediately report as many letters as possible. Across several experiments, subjects could accurately report between four and five items, irrespective of how many total letters were in the array, how they were configured, or how

long the array was presented (ranging from 15 to 500 ms). The results of these and other similar experiments suggest that subjects' ability to apprehend information from a brief display is extremely limited and that they are capable of maintaining information about only a relatively few items in memory.

Sperling's estimate of visual WM capacity has two potential limitations as an estimate of visual WM capacity. The first is the possibility of output interference. Subjects were asked to name or write each of the letters they remembered. This may have underestimated WM capacity because the process of transforming the visual input into a reportable form may be too slow to capture the fleeting sensory information before memory capacity is fully exhausted. Furthermore, Sperling used alphanumeric characters as the memoranda, which calls into question whether the items were being held strictly in a visual memory store or whether both verbal WM and visual WM contributed to the capacity estimate. Indeed, because the subjects had to report the identity of the letters at the end of the trial, they must have transformed the visual image into verbal labels. Thus, although suggestive, results from whole report tasks such as these do not provide definitive estimates of the capacity of WM for visual information.

Visual Working Memory Capacity: Features and Objects

In an attempt to measure the capacity of visual WM more directly, we and others developed a variation of Phillips' sequential comparison paradigm that is commonly known as the change detection paradigm. In this task, subjects are shown a brief array of simple objects that they must remember (see [Figure 1](#)). The objects disappear for a short retention period and afterward reappear in the same locations as before. On half the trials, the first and second arrays of objects are identical; on the other trials, one of the objects changes its identity (e.g., shape or color). Subjects make a single button-press response regarding whether the two arrays are the same or different. To examine capacity limitations in this task, the number of items in each array is manipulated to find when performance starts to decline. Luck and Vogel used this task to examine the capacity of visual WM for simple single-featured objects. These objects were bright, suprathreshold colors that were chosen to be highly discriminable from one another so that the task would be limited primarily by memory storage capacity rather than by perceptual and decision factors. Performance was near-perfect for arrays containing one, two, or three items, but declined at higher set sizes. They estimated visual WM capacity to be approximately three to four items, and this

was unchanged even when subjects performed a concurrent articulatory suppression task to keep them from verbally labeling the visual items. They also tested whether visual WM capacity is determined by the number of features that must be remembered or whether it is determined by the number of objects that must be remembered. To do this, they asked subjects to remember arrays of objects that each possess two features (e.g., color and orientation) to determine whether the additional features consumed more memory capacity. Surprisingly, they found that subjects could remember the same number of multifeatured objects as they could single-featured objects. Indeed, in one experiment, they found that subjects could remember four four-featured objects (i.e., color, orientation, size, and a stripe) just as well as they could remember just four colors. That is, they could retain up to sixteen features as long as they were distributed across four separate objects. Although there are some limitations to the strength of this object advantage, these results have been taken as strong evidence in favor of visual WM capacity being determined by the number of objects to be remembered.

Units of Capacity: Objects or Information Load?

A recent challenge to the object-based visual WM capacity proposal was provided by Alvarez and Cavanagh, who tested whether visual WM capacity was also determined by the information load engendered by various complex object categories. To examine this, they measured visual WM capacity for several object categories of varying complexity (e.g., simple colors, Chinese characters, and three-dimensional shaded cubes) and found that, as the complexity of the remembered objects increased, the memory capacity likewise decreased (see [Figure 2](#)). That is, subjects could remember approximately 4.5 colored squares (the least complex items), but they could accurately remember only 1.6 shaded cubes (the most complex items). They described these results as indicating a direct trade-off between the required resolution of the items in memory and the number of items that may be maintained in visual WM; complex items that require a high resolution cause a decrease in how many objects can be held in memory.

Recently, Awh, Barton, and Vogel examined whether the lower capacity estimates for complex objects may have been due to an increase in similarity between items in the complex categories. That is, change detection performance depends not only on the number of representations that can be maintained in working memory but also on the observers' ability

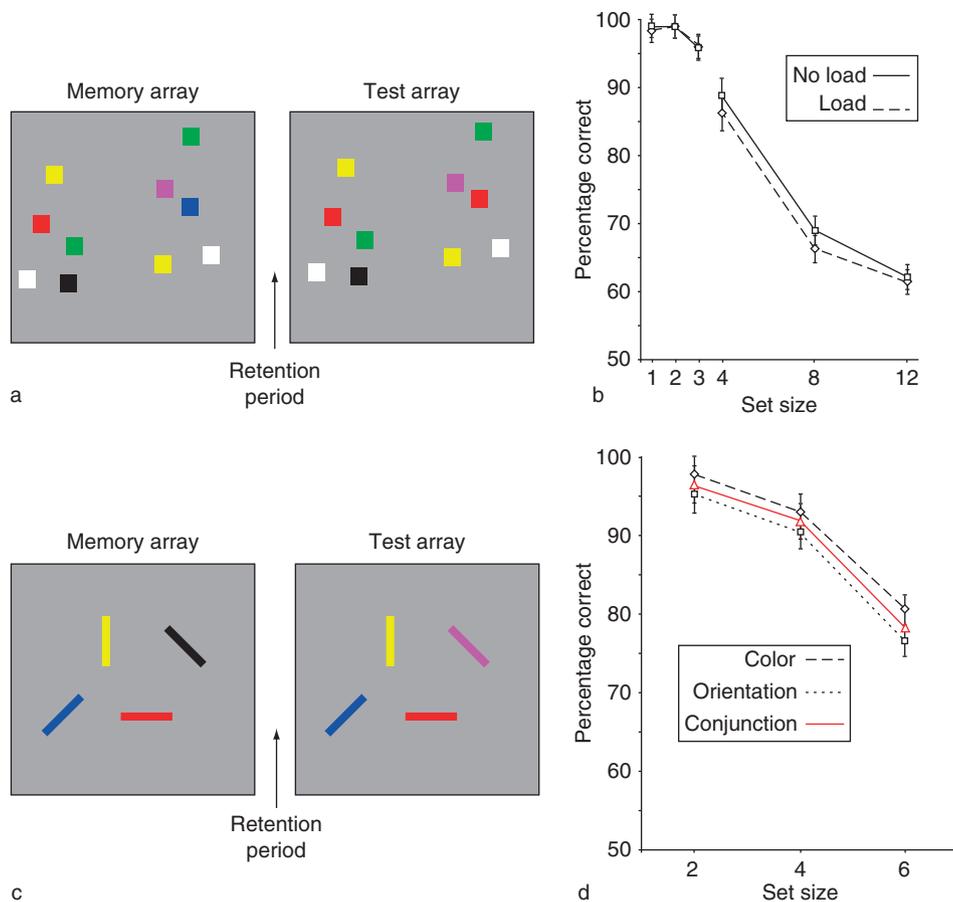


Figure 1 Estimating visual working memory capacity: (a) change detection paradigm using color; (b) memory performance in (a); (c) change detection paradigm using color and orientation; (d) memory performance in (c). In (a), subjects are asked to remember the colors in the memory array across the retention interval. At test, subjects judge the colors to be the same or different as the memory array. As shown in (b), performance in this task is near-perfect for 1, 2, or 3 items and quickly declines at higher set sizes. A concurrent articulatory suppression task has no effect on performance of the visual memory task. In (c), subjects are asked to remember both the color and orientation of the items. As shown in (d), memory performance is equivalent irrespective of the number of features. Adapted from Luck SJ and Vogel EK (1997) The capacity of visual working memory for features and conjunctions. *Nature* 390: 279–281.

to discriminate between these stored representations and the new items that are presented during change trials. If the similarity is high, then changes can be missed in this procedure even though the changed item was stored in memory. Along these lines, Awh and colleagues found that for the object categories used by Alvarez and Cavanagh there was a strong positive correlation between complexity and within-category similarity. Moreover, they found that when within-category similarity was decreased (by using cross-category changes) memory capacity estimates were equivalent for both simple and complex objects (i.e., three to four items). These data suggest that visual WM represents a fixed number of items, regardless of object complexity. These results do not contradict the important observation that change-detection performance is strongly influenced by object complexity. However, it may be that the

relationship between object complexity and change detection has more to do with the resolution for making discriminations than with the number of representations that can be maintained in memory.

Neural Measures of Working Memory Capacity

Neuroimaging Since the 1990s, numerous studies using neuroimaging in humans have found increased blood-oxygen level-dependent (BOLD) activation during the retention interval of various WM tasks. This activity is thought to be analogous to delay activity observed in monkey single-unit studies. The sustained BOLD activity is primarily observed in the prefrontal, posterior parietal, and inferotemporal cortices. Although there have been several demonstrations that the magnitude of the activity increases as memory load increases, it is often difficult to

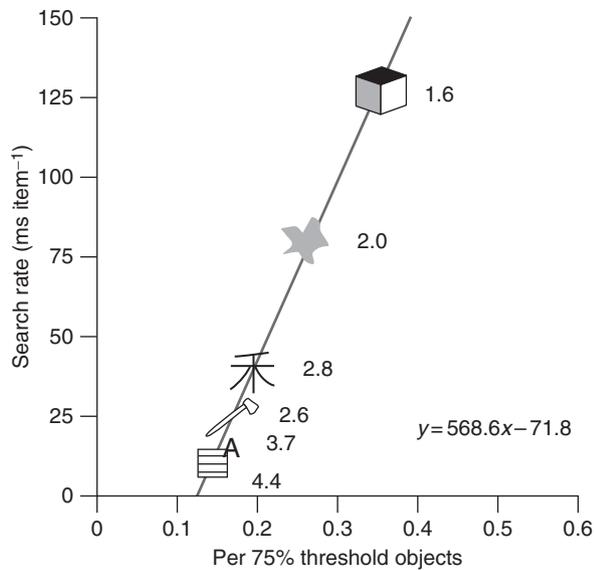


Figure 2 Information load and working memory capacity. As the information load for a type object increases, the estimated number of items that can be accurately remembered decreases from a high of 4.4 objects for color squares to a low of 1.6 for three-dimensional cubes. The search rate for each object type was found by asking subjects to perform a visual search for a specific object among other objects of that type. Search rate is a proxy for the amount of information load for a given object. Adapted from Alvarez GA and Cavanagh P (2004) The capacity of visual short-term memory is set by both the visual information load and by number of objects. *Psychological Science* 15(2): 106–111.

determine whether it necessarily reflects WM storage demands *per se* or whether other, more task-general activity is responsible for the load-related increase in activity. Consequently, it is often difficult to determine whether the increasing activation is due to more memory representations being held in WM or if it is simply the result of the increased difficulty in the high-load conditions.

Within the verbal WM domain, there is one notable functional magnetic resonance imaging (fMRI) study that appeared to distinguish between patterns of neural activity for subcapacity memory loads and supra-capacity loads. Specifically, Rypma and colleagues used a letter WM task and found increased activation in the left ventrolateral prefrontal cortex for loads of three items, compared to only one item. This region is in the vicinity of Broca's area, and it is plausible that the increased activity reflects the additional subvocal rehearsal demands for the additional items in verbal WM. Interestingly, when the load was increased from three items to six items, a wide range of prefrontal areas became active. These results suggest that when the verbal WM capacity was exceeded, many additional executive processes are recruited to assist in performing the task.

In the visual WM domain, there are two recent studies that suggested that activity in the posterior parietal cortex is sensitive to WM capacity limits. Todd and Marois used the change detection paradigm for colored items and found that retention period activity in the intraparietal sulcus (IPS) increased as a function of the number of items in memory, but this increasing activity reached asymptote at approximately four items (see Figure 3). These results suggest that the activity in the IPS reflects the number of item representations that can be successfully maintained in visual WM because it reaches a ceiling at the known storage-capacity limit of visual WM. Xu and Chun recently replicated and extended this finding by showing evidence that there are three primary areas that show this sensitivity to visual WM capacity limits: the superior IPS, the lateral occipital complex (LOC), and the inferior IPS. Interestingly, they found that the activity in the superior IPS and LOC reached asymptotic levels for smaller array sizes when the memory items were complex than when they were simple. However, the inferior IPS activity reached asymptote at arrays of four items, irrespective of whether the items were simple or complex. Together, these results suggest that a suite of posterior cortical areas underlie visual WM capacity limits and that distinct mechanisms may be sensitive to the necessary resolution and the number of items that can be held in visual WM.

Electrophysiological measures Our laboratory used event-related potentials (ERPs) to observe the storage and maintenance of object representations in visual WM. To do this, we used a modified version of the change detection paradigm in which we presented simple objects in both the left and right hemifields and asked subjects to remember the items in only a single hemifield using an arrow cue (see Figure 4(a)). This bilateral stimulus task design allowed us to isolate the ERP activity that is specific to the memory items by dividing electrodes in terms of whether they were contralateral or ipsilateral with respect to the side of the display the subjects were remembering on a given trial. Approximately 250 ms following the onset of the memory array, we observed a large negative wave at posterior electrode sites that were contralateral to the position of the memoranda for a given trial. This activity persisted throughout the retention period until the test array arrived, and we refer to it as the contralateral delay activity (CDA). An important property of the CDA is that its amplitude increases as a function of the number of items that are being held in visual WM. However, like the fMRI studies in the IPS, this amplitude increase reaches asymptote at approximately four items,

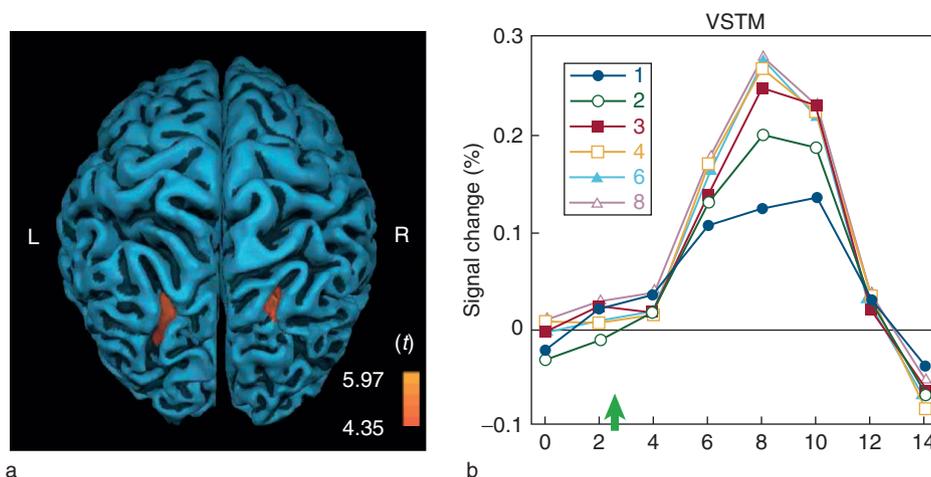


Figure 3 An fMRI measure of visual working memory capacity: (a) a statistical map of activation in the intraparietal sulcus (IPS) during the retention interval overlaid on a structural scan; (b) activation in the IPS as a function of number of memory items. The green arrow represents the time of presentation. Activation in this area increases until there are three items and then asymptotes for four to eight items. fMRI, functional magnetic resonance imaging; L, left; R, right; VSTM, visual short-term memory. Adapted from Todd JJ and Marois R (2004) Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature* 428(6984): 751–754.

indicating that this activity is sensitive to visual WM capacity limits and may reflect the active representations that can be held in memory. Indeed, the precise point at which it reaches asymptote is different for each subject depending on his or her specific memory capacity (see Figure 4(c)).

Individual Differences in Working Memory Capacity

Although the capacity of WM is known to be highly limited, these limitations have long been known to vary substantially across individuals. In fact, because WM is thought to play a central role in a wide range of cognitive processes, it is not surprising that an individual's WM capacity is positively correlated with performance on a wide range of cognitive and aptitude measures such as intelligence, reasoning, scholastic performance, math abilities, and ability to acquire a second language. Thus, WM capacity appears to be a core mental construct that underlies an individual's general cognitive ability in a variety of situations. Next, we review two primary correlates of WM capacity: intelligence and attentional control.

Intelligence and Working Memory Capacity

The relationship between WM capacity and intelligence has been well known and studied for over a century. For example, Binet and Simon observed that cognitively impaired children have sharply smaller digit spans than normal children, which prompted the view that WM capacity could provide a window to intelligence. Indeed, to this day, almost all intelligence battery tests include at least some form

of memory span component. In the last few decades, researchers began to move away from using digit span as an individual difference measure because it is highly susceptible to strategic performance differences, such as chunking, that often weaken the relationship to intelligence measures. Instead, many use WM measures of processing capacity rather than simple span as a predictor of cognitive performance. For example, Daneman and Carpenter demonstrated strong positive correlations between WM reading span tasks and cognitive aptitude. Their reading span task asked subjects to read sets of random sentences and to remember the last word of each sentence, which they were tested on at the end of the session. Performance on this task was strongly correlated with SAT verbal scores and reading comprehension scores. One currently popular method used to measure WM capacity is operation span (OSPAN). A subject's OSPAN is measured by asking the subject to read a simple mathematical equation, judge the accuracy of the equation, and then read a random word aloud. For example:

$$\text{Is } (3 \times 4) - 6 = 7? \text{ Dog}$$

After the task has been repeated several times, the subject is asked to recall as many of the words as possible. Both reading span and OSPAN show strong positive correlations with language comprehension and intelligence measures. However, the relationship between WM capacity and intelligence is not limited to measures of verbal WM, but can also be observed with visual WM measures as well. For example, Cowan and his colleagues recently found

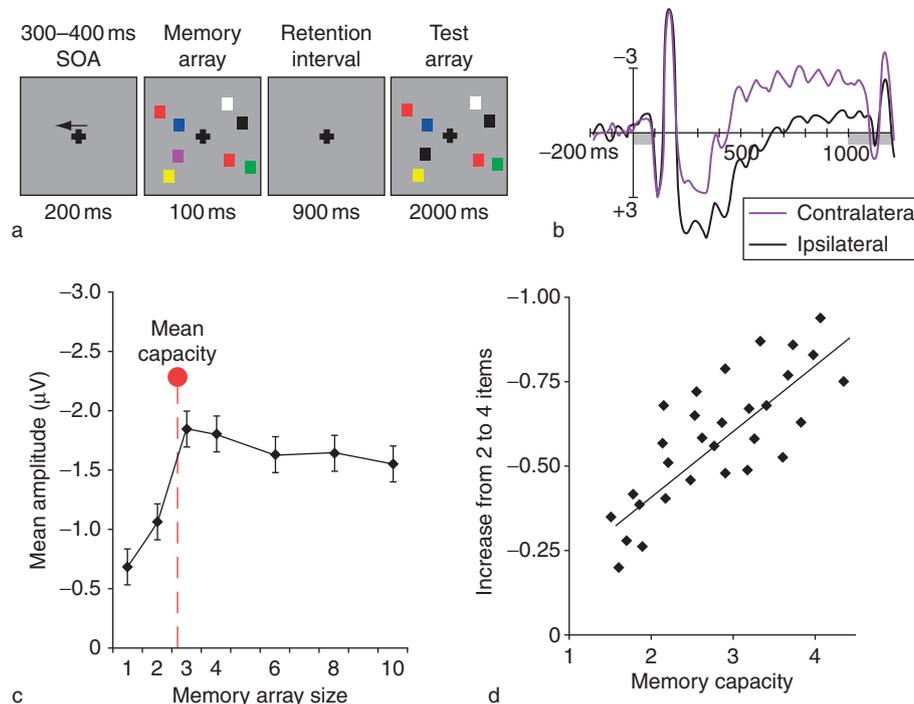


Figure 4 An event-related potential (ERP) measure of visual working memory capacity: (a) a bilateral change detection trial; (b) ERPs time-locked to the memory array; (c) mean amplitude of contralateral delay activity (CDA) during the retention interval; (d) correlation between an individual's memory capacity and the asymptote of the CDA ($r=0.78$). In (a), subjects are cued to remember the items in one hemifield. After a retention interval, subjects judge whether objects on the cued side of the test array are the same or different than objects in the memory array. In (b), note that negative voltage is plotted upward in the graphs, which show grand-average ERP waveforms time-locked to the memory array and averaged from occipital and posterior parietal electrodes. Ipsilateral and contralateral are defined with respect to the side of the screen that subjects are cued to attend. Gray rectangles represent the time of the memory and test array. As shown in (c), CDA amplitude increases up to approximately three items and then asymptotes at the point when the mean behavioral capacity (approximately three items) is exceeded. In (d), subjects with low memory capacity showed little increase from two to four items compared to high-capacity subjects. Adapted from Vogel EK and Machizawa MG (2004) Neural activity predicts individual differences in visual working memory capacity. *Nature* 428: 748–751.

that individual differences in capacity in change detection paradigms are also strongly predictive of intelligence and scholastic measures, including reading comprehension. This finding is consistent with Cowan's proposal that there is a single central WM capacity because measures that purport to quantify verbal and visual WM capacity are equally predictive of general cognitive ability, suggesting that the same central capacity limit underlies both visual and verbal WM tasks.

Attentional Control and Working Memory Capacity

More recently, researchers have begun to further examine the nature of the relationship between WM capacity and cognitive performance. However, rather than emphasizing the advantages of additional memory storage space, they have proposed that the benefits of a high WM capacity may actually be due to more efficient attentional control, that is, to how the WM system is used to determine the flow of information into WM and reduce the interference

from distracting information. To date, there have been many demonstrations of a strong relationship between performance on various attentional control tasks and WM capacity. For example, in the antisaccade task, subjects are asked to look away from the position of a target that abruptly appears on the screen. This task is thought to require attentional control to override the prepotent response to look directly at the new object location. Interestingly, low-capacity individuals are much worse at avoiding eye movements toward distractors than high-capacity subjects. Moreover, WM capacity has also been shown to predict cocktail party effects in which subjects sometimes notice their own names when they are embedded in an unattended auditory channel. Surprisingly, Conway and colleagues found that low-WM-capacity subjects were three times more likely to detect their name than high-capacity subjects. Results such as these question whether the differences between high- and low-capacity individuals are due strictly to storage or processing

abilities; it demonstrates that low-capacity subjects may often be processing more information than the high-capacity subjects but that this information may be detrimental to the task at hand. Along these lines, Vogel, McCollough, and Machizawa examined whether there are differences in the ability to voluntarily control what information is stored in visual WM. To do this, they presented subjects with arrays of objects that contained a mixture of relevant and irrelevant objects, and they measured the CDA

component to determine how many total objects (including distractors) were stored in visual WM. They found that high-memory-capacity subjects were extremely efficient at keeping the irrelevant distractors from being stored in memory, whereas the low-capacity subjects were highly inefficient at excluding the distractors from being stored and held in memory (see [Figure 5\(b\)](#)). Thus, the low-capacity subjects actually held more information in memory than the high-capacity subjects, but this ancillary

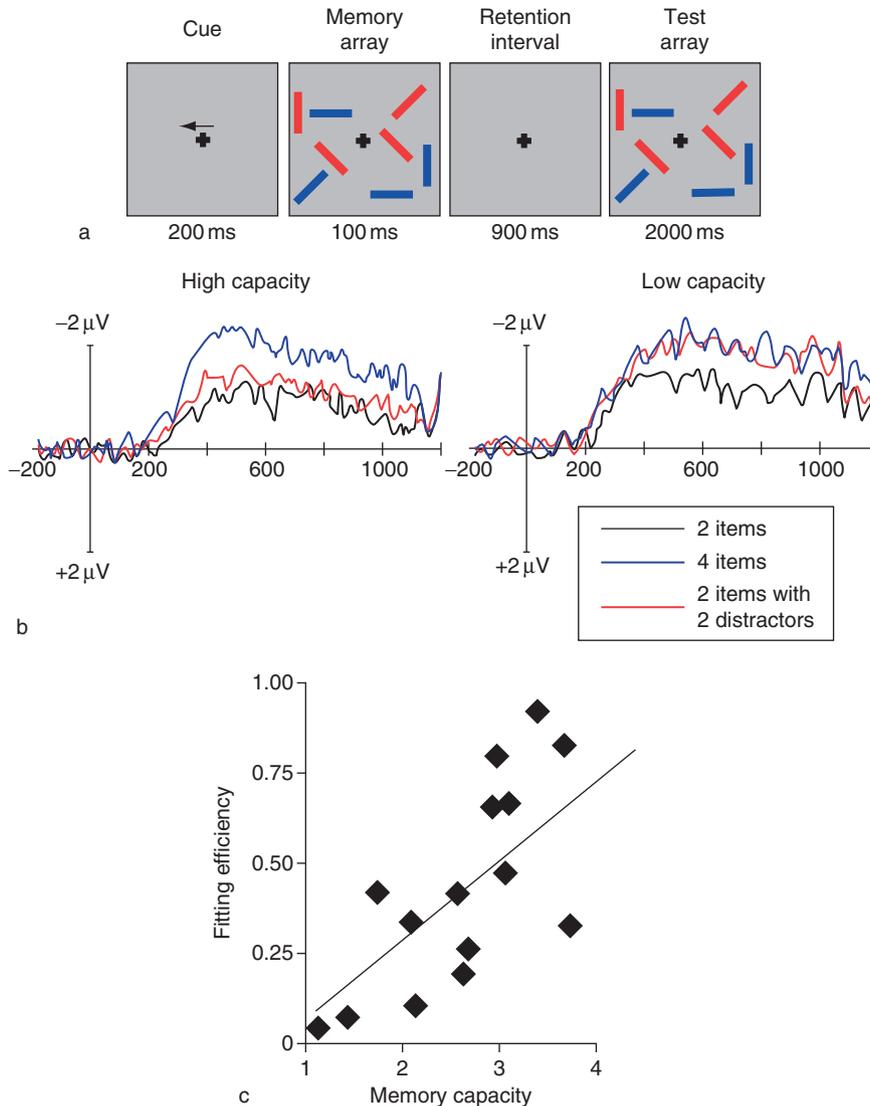


Figure 5 Attentional filtering and working memory: (a) attentional filtering test; (b) mean contralateral delay activity (CDA) amplitude waveforms split between high- and low-memory-capacity subjects; (c) correlation between filtering efficiency and working memory capacity. In (a), subjects were instructed to remember the orientations of only the red items and to ignore the blue items. There were three trial types: two red items alone, four red items alone, and two red items intermixed with two blue distractors. In (b), the CDA amplitude indicates that low-capacity subjects encoded the irrelevant items along with the red items, whereas high-capacity subjects encoded only the red items. In (c), the filtering efficiency measures how similar the CDA amplitude in the distractor condition is to the amplitude in the conditions without distractors. Perfectly efficient attentional filtering would result in equivalent amplitudes for the distractor condition and the two-item condition, resulting in an efficiency score of 1. As memory capacity increases, filtering efficiency also increases ($r=0.69$). Adapted from Vogel EK, McCollough AW, and Machizawa MG (2005) Neural measures reveal individual differences in controlling access to working memory. *Nature* 438: 500–503.

storage was for irrelevant information. Together, these results suggest that individual differences in WM capacity may actually be the consequence of the attentional control process that determines what information is stored in memory and whether distractions can be resisted rather than the consequence of how much information can be held at one time.

See also: Attentional Functions in Learning and Memory; Cognition: An Overview of Neuroimaging Techniques; Executive Function and Higher-Order Cognition: Neuroimaging; Multiple Memory Systems; Short Term and Working Memory; Spatial Cognition and Executive Function; Strategic Control of Memory; Visual Associative Memory.

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