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What ERPs can tell us about Visual Working Memory

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What is Working Memory?

Our ability to perform a broad range of everyday cognitive tasks is thought to depend heavily upon the operation of the Working Memory system, which allows us to temporarily store information “in mind” so that it may be manipulated or acted upon (e.g., Baddeley & Hitch, 1974; Cowan, 2001). Many cognitive processes that require information to be held in an “online” state are thought to utilize this memory system as a form of “mental workspace” to perform their requisite operations. A fundamental characteristic of working memory is that it is severely limited in its capacity to maintain information. In the visual working memory (VWM) domain, this capacity limit is thought to be approximately 3-4 objects simultaneously (Cowan, 2001; Luck & Vogel, 1997; Sperling, 1960; Vogel, Woodman, & Luck, 2001). Although, this capacity estimate actually varies substantially across individuals, ranging from as low as 1.5 objects up to about 6 objects (Vogel & Awh, in press; Vogel & Machizawa, 2004). This inter-subject variability in memory capacity appears to reflect an important and stable cognitive trait of the individual because it is strongly predictive of his or her performance on a host of high level aptitude measures. Individuals with high memory capacity tend to perform better on measures of fluid intelligence, abstract reasoning, reading comprehension, and tend to have higher grade point averages in school than individuals with low memory capacity (Cowan, Fristoe, Elliott, Brunner, & Saults, 2006; Daneman & Carpenter, 1980; Engle, Kane, & Tuholski, 1999; Kane, 2001; Kyllonen & Christal, 1990). Moreover, given the centrality of this memory system, it is not surprising that disruptions in working memory are often associated with pathological cognitive states, such as attention disorders, dementia, psychosis, and depression (Gold, Wilk,

McMahon, & Luck, 2003; Goldman-Rakic, 1999; Morris & Baddeley, 1988; Rinck & Becker, 2005; Sonuga-Barke, Dalen, Daley, & Remington, 2002).

Measuring Visual Working Memory

Over the years, researchers have developed a variety of tasks to measure working memory function. Many of these tasks are variations of the match-to-sample task, in which the subject is initially shown a sample item and must later decide whether a later item matched the original sample. One such task that we have used over the years to measure VWM capacity is the *change detection task* (Phillips, 1974). In this task, subjects are briefly shown an array of objects (e.g., colored squares) that they must attempt to remember. These objects disappear for about a second, after which they reappear and are either all identical to the original objects, or one of the objects was different. The subject's task is to report with a button press whether the items were the same or different. The real beauty of this task is that it is extremely flexible and simple manipulations of the task can be used to test a bevy of cognitive questions related to VWM and other related systems. For example, by varying the number of items in the memory array one can measure VWM storage capacity (it's about 4 items; Luck & Vogel, 1997); by varying the type of objects that need to be remembered, one can measure how information is represented in VWM (Alvarez & Cavanagh, 2004; Luck & Vogel, 1997); by varying the magnitude of the changed item, one can measure the resolution of the information that is held in VWM (Awh, Barton, & Vogel, 2007). Thus, because of the elegance and flexibility of this task, *change detection* has become a staple measure of VWM.

Neurophysiological Measures of Visual Working Memory

One important neural signature of VWM from single-unit studies in monkeys is referred to as *delay activity*, which is the increased and sustained firing rate of a neuron during the memory delay of a match-to-sample task (Fuster, 1973; Fuster & Alexander, 1971; Kubota & Niki, 1971). This delay activity appears to be necessary for accurate working memory performance because it is often reduced or absent on trials in which the incorrect response is made (Funahashi, Bruce, & Goldman-Rakic, 1989; Sakai, Rowe, & Passingham, 2002). Although many cortical regions have cells that show delay activity, there are three primary areas that have a large proportion of cells that show this property: the inferotemporal cortex, which often shows delay activity that is sensitive to the *identity* of the remembered stimulus (Chelazzi, Duncan, Miller, & Desimone, 1998; Miller, Li, & Desimone, 1993); the lateral intra-parietal (LIP) cortex, which often shows *location*-specific delay activity (Chafee & Goldman-Rakic, 1998; Colby & Goldberg, 1999); and the prefrontal cortex, which often shows delay activity that is sensitive to the *rules* of the current task (Miller & Cohen, 2001; Wallis & Miller, 2003). The fact that the delay activity from a given area is often differentially sensitive to the attributes of the remembered material indicates that this activity is contributing to the specific representations held in memory rather than being the result of task-general processes such as task difficulty or fluctuations within the individual such as arousal or expectation.

Functional magnetic resonance imaging (fMRI) in humans has also been used to observe delay activity during working memory tasks, and the same three cortical areas appear to play substantial roles during online maintenance. Moreover, the sustained BOLD responses in the inferior temporal cortex have been shown to be sensitive to the identity of the stimuli in memory (Druzgal & D'Esposito, 2001). Location-specific activity in the posterior parietal cortex has been shown to code for memory-driven maps of remembered locations (Sereno, Pitzalis, & Martinez,

2001). Additionally, Pessoa et al. (2002) demonstrated that sustained BOLD activity in fronto-parietal regions during a delayed response task was necessary for successful performance on a working memory task. In sum, this evidence demonstrates the crucial involvement of delay activity during the retention interval of VWM tasks.

Event-Related Potential Studies of Working Memory

Like single-unit recordings and fMRI, studies using event-related potentials (ERPs) have also provided useful measures of delay activity in VWM tasks. Importantly, the high temporal resolution of ERPs allows for the isolation of activity during the retention period of memory tasks, and can provide information about the timing of brain processes recruited in working memory. One ERP component that has been observed across many studies of working memory is the Negative Slow Wave (NSW), which is a broadly distributed sustained negative wave that persists during the memory retention period of a VWM task (Ruchkin, Johnson, Canoune, & Ritter, 1990). In at least one study, the amplitude of this component has been shown to increase as the memory load increased from one to two faces (Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992). Moreover, the scalp topography of the component has been shown to be different depending upon the type of information that is being held in VWM; with a more posterior distribution for spatial memory tasks and a more frontal distribution for object memory tasks (Mecklinger & Muller, 1996). Further, Rosler et al. (1997) found that in trials where a larger NSW amplitude was observed during the retention period, there was a stronger probability of successfully remembering the information at test, which suggests that this activity is important for performance on the task.

Although it seems quite plausible that the NSW reflects the operation of VWM maintenance processes, a significant challenge for the validation of any neurophysiological measure of a cognitive process is to demonstrate that it is specific to that particular process. That is, performing any complex task enlists the engagement of a wide variety of processes, some of which are specifically relevant to memory (e.g., VWM maintenance), some only partially relevant to memory (e.g., perceptual processing of stimuli), and some are task-general non-mnemonic processes such as arousal, effort, or the preparation of an upcoming response. Consequently, it is critical for any valid ERP measure of VWM maintenance to demonstrate that it is specifically related to VWM maintenance and not also to this set of non-mnemonic processes that are active during any task.

One useful approach to controlling for these types of task-general activity is referred to as the *Contralateral Control method* (Gratton, 1998). Essentially, the idea here is to exploit the fact that visual system is primarily organized in a contralateral fashion. In these task designs, the subject fixates centrally and is presented with a bilateral display with equal amounts of stimuli in each hemifield. The subject is asked to remember or attend or make a decision about the stimuli in only one of these hemifields, and the activity of the process of interest can be isolated by examining the contralaterally-specific activity with respect to the attended side of the display. The logic here is that most of the task-general activity (e.g., perceptual response, arousal, response preparation) will be equivalent for each hemisphere, and that the primary differences between the hemispheres will be the result of the process of interest. Klaver et al. (1999) used this approach in a VWM task by presenting a bilateral array of two polygons (one in each hemifield), and cued subjects to remember one or both items. Beginning at about 250ms after the onset of the memory array, they observed a sustained negative wave at posterior electrodes that

were contralateral to the attended hemifield. This memory item-specific activity was isolated by subtracting the *ipsilateral activity* (which contained mostly task general processes) from the *contralateral activity*. Thus, because the activity was contralaterally-specific to the remembered information, this sustained component appears to be a good candidate for a highly-specific measure of VWM maintenance.

Contralateral Delay Activity (CDA)

Using a similar contralateral control approach, we presented subjects with a bilateral display of colored squares and asked them to remember the items in a single hemifield over a 1 second retention interval (Vogel & Machizawa, 2004). After this interval, subjects were presented a test array that was either identical to the original array or one color had changed, and subjects reported whether the two arrays were the same or different (see Fig 13.1). Similar to Klaver et al (1999), we observed a large, sustained negative wave at posterior electrodes that were contralateral with respect to the side of the display that the subject was asked to remember on a given trial. This contralateral activity began approximately 275 ms following the onset of the memory array and persisted throughout the retention period until the test array appeared. Importantly, we found that the amplitude of this activity was significantly reduced when subjects performed the task incorrectly, which suggests that the wave reflects a process that is necessary for correct VWM performance. We refer to this wave as the contralateral delay activity (CDA), because of its apparent similarity to delay activity observed in monkey single-unit studies using delayed match-to-sample tasks.

CDA amplitude: memory load or other task factors?

The most exciting attribute of this component is that we found it to be acutely sensitive to the number of items that the subject was remembering on a particular trial. Specifically, CDA amplitude was smallest for memory loads of one item, and rose monotonically as the memory load increased to two, three, and four items (see Figure 13.1). The fact that this component is sensitive to the present memory load suggests that it is a good candidate for an ERP-based measure of VWM, and could possibly be used as an online measure of how much information is currently “in mind”. However, because several cognitive mechanisms in addition to VWM maintenance are likely involved in a task such as *change detection*, we see at least two potential alternative accounts of this amplitude increase. The first alternative is that as the number of memory items increases, the spatial scope of the memory array necessarily increases. Thus, the increase in amplitude may actually be the result of a broader spotlight of attention for larger arrays. We tested this in a later study by manipulating the spatial distance (close vs far) between the memory items and found that while CDA amplitude was not modulated by the distance between the items, it was again strongly modulated by the number of memory items (McCollough, Machizawa, & Vogel, 2007).

A second alternative for the CDA amplitude increase is that as the memory load increases, the task becomes more difficult, and it is this general increase in effort or arousal that is actually modulating the amplitude of the component. To test this, we also examined memory arrays that exceeded the known limits of VWM capacity (i.e., arrays of 6, 8, or 10 items; Vogel & Machizawa, 2004; McCollough et al, 2007). Our logic was that if the CDA was sensitive to the number of items that can be held in VWM, it should be constrained by the capacity limits of this system and reach a limit at approximately 4 items. Alternatively, if CDA amplitude was

driven by the amount of effort required to perform the task, we would expect it to continue to increase as the difficulty of the task continues to increase -particularly for arrays of 6, 8, and 10 items. However, we found that CDA amplitude reached an asymptotic limit for arrays around 4 items, showing no further increases for larger arrays. That is, despite continued increases in difficulty for supracapacity memory arrays, CDA amplitude did not increase, which indicates that task-general factors such as arousal and effort are insufficient to account for the rise in amplitude from 1 to 4 items.

CDA amplitude: sensitivity to individual differences in memory capacity

To further examine how sensitive this component is to memory capacity limitations, we tested whether the exact point at which the CDA reached a limit was different for each subject depending upon his or her specific memory capacity. We reasoned that if it was a highly specific measure of the number of items that can be actively held in VWM, then the CDA for high memory capacity individuals, who can presumably hold more information in VWM, should reach a limit at larger array sizes than that for low memory capacity individuals. To do this, we measured the rise in amplitude of the CDA from two items to four items and plotted this as a function of each subject's memory capacity which we estimated from their behavioral performance. Indeed, there was a strong correlation ($r=0.78$, see Fig 13.1) between an individual's memory capacity, and the point at which the CDA reached asymptote (Vogel & Machizawa, 2004). Low capacity individuals showed little rise in amplitude from two to four items, whereas high capacity individuals showed large increases in amplitude. Thus, beyond being highly sensitive to the number of items that are currently held in VWM, we found that the CDA is also finely sensitive to individual differences in working memory ability.

CDA amplitude: sensitive to identity of items in VWM?

While the *number of items* in memory appears to be a primary factor that modulates the amplitude of the CDA, it is still an unresolved issue whether this component is sensitive to *what* information is currently being held in memory. One piece of evidence that has suggested that it is at least somewhat sensitive to the identity of the information being held was recently provided in a study by Woodman & Vogel (2008). Here, we examined CDA amplitude for memory arrays in which subjects were presented colored, oriented rectangles and were asked to remember in separate blocks only the colors, only the orientations, or both the color and orientation of the items. Interestingly, we found that the overall amplitude of the CDA was significantly larger when the subject held the orientations in memory than when they held colors in memory, despite the fact that these two conditions used identical stimulus displays and only differed by the instructions to the subject. Thus, one implication of this result is that the amplitude of the CDA appears to be determined by what *task-relevant information* is being held in memory rather than by what was simply present on the screen. Moreover, a critical aspect of this effect was that the increase in amplitude for orientations did not interact with the number of items the subject was remembering. That is, the increase in amplitude was simply an additive effect with set size: the amount of rise in amplitude from two to four items was equivalent for both color and orientation. These results suggest that at least some aspect of the identity of the remembered items is reflected in the CDA. If it was completely insensitive to identity, we would expect no difference between conditions, particularly when the same physical stimuli (i.e., colored, oriented rectangles) are used in each condition. Precisely why orientation information generates larger CDA amplitudes is still somewhat a mystery. In subsequent unpublished studies in our

laboratory, we have observed that this increase in amplitude appears to occur for any stimulus with significant orientation information as part of its external contour (e.g., abstract line drawings). However, future work examining CDA amplitudes across a much broader range of stimulus types will be necessary to better characterize how much and what type of identity information is reflected in this component.

The time-course of the CDA

While most of the studies examining the CDA have focused on amplitude as the primary dependent measure, the time-course of the component also appears to provide useful information regarding the operation of VWM. Of course, as with any sustained component there are several temporal aspects of the wave that each may reflect different cognitive states. Here, we will discuss three aspects of CDA latency: onset, maximum, and duration. In terms of *onset*, the CDA generally begins at approximately 275 ms following the onset of the memory array. It is seen in the waveform as a large contralateral deflection that immediately follows the N2pc component. Interestingly, CDA onset is not at all affected by the number of items that are in the memory array, and this detail suggests to us that it may reflect the start of the process of storing the items in VWM. For example, Brisson & Jolicoeur (2007) observed that the onset of the CDA was delayed for targets that were presented during the psychological refractory period, suggesting that the encoding of items into VWM is delayed while attention is occupied with the first target.

While there is no clearly distinct peak, the CDA generally reaches maximum amplitude by approximately 450ms following the memory array. However, the latency at which it reaches maximum amplitude is strongly dependent upon the number of items that are to be stored in VWM. As can be seen in Figure 13.2, the latency to maximum amplitude (defined here by

fractional area latency, though peak latency is equivalent) increases linearly from one to four items; reaching an asymptotic limit for arrays exceeding capacity ($F(1,6) = 16.74$; $p < .01$). Several previous studies using psychophysical procedures have shown that the required time to consolidate items into VWM increases as the memory load increases up to capacity, and that the slope of this increase is approximately 49ms per object (Gegenfurtner & Sperling, 1993; Shibuya & Bundesen, 1988; Vogel, Woodman, & Luck, 2006). Consequently, the temporal sensitivity of the CDA suggests that it may reflect the point at which the memory items have reached a durable/stable state in VWM. Indeed, when we measure the slope of the CDA latency from one to four items, it is 42ms per object; which is remarkably similar to the estimates of VWM consolidation time derived from psychophysical masking procedures.

How long does the CDA last? Generally speaking, the CDA persists throughout the retention period of the VWM task. In the vast majority of experiments, we have used 900ms retention intervals, but in a few experiments we have observed it out to about 4.5 seconds. Of course, there are several obvious reasons for using a shorter rather than a longer retention interval during ERP recordings: it's difficult for subjects to not make an eyeblink; the tradeoff between very long recording sessions and too few trials. However, one additional reason that we have used shorter retention periods is that after approximately 1000ms, the CDA appears to decline in amplitude. Importantly, this apparent decline is not due to a decrease in the negative wave over contralateral electrodes, but is the consequence of an increase in the amplitude of the ipsilateral electrodes (McCollough et al, 2007). Thus, around 1000ms the contra-minus-ipsi difference wave appears to decline because the ipsilateral activity begins to rise. Precisely why this ipsilateral increase occurs is still presently a mystery and requires much further investigation. One plausible, but wholly unsubstantiated, explanation of this effect would be that

the memory representations initially begin as predominantly hemispheric-specific representations, but that after a period of time they become represented equally in each hemisphere. Perhaps, this could explain why many fMRI studies of WM, which generally use retention intervals of several seconds, often do not find lateralized BOLD activations even when subjects are remembering items from a single hemifield (Ikkai & Curtis, in press).

Scalp topography and possible neural sources of the CDA

The CDA is a broadly-distributed wave that is primarily centered over the posterior electrodes (see Fig 13.3). The maximum amplitude of the component is often observed over the posterior parietal electrodes. While the component is typically measured by collapsing the left and right hemispheric responses, in previous work we measured the negative wave separately for each hemisphere and found that there was no significant difference in amplitude between the left and right hemispheres (McCollough et al 2007). Moreover, in that study we found that the scalp distribution of the CDA was significantly more dorsal than the N2pc component (see Chapter 11), which is an earlier contralateral component with a more ventral focus.

Although a formal source localization of the CDA has not yet been attempted, one cortical region appears to be a potential candidate source of this wave: the intra-parietal sulcus (IPS). While the dorsal, posterior scalp topography of the CDA is generally consistent with such a locus, the strongest evidence in favor of an IPS source comes from neuroimaging experiments of VWM. In particular, several recent fMRI studies examining the BOLD response during VWM tasks have found that the IPS is strongly modulated by the number of items that are currently being held in memory, but reaches an asymptotic limit at approximately 4 items (Todd & Marois, 2004; Xu & Chun, 2006). Moreover, Todd & Marois (2005) found that this IPS

activity was also sensitive to individual differences in memory capacity. Together, this pattern of functional properties for the IPS appears highly similar to that of the CDA, and makes it a plausible candidate/contributor to the component. However, it seems fairly unlikely that such a large and sustained ERP component is generated by a single cortical source, and is more likely the result of several coordinated sources of which IPS may play a significant role.

Using the CDA to examine attentional control over working memory

The constructs of attention and working memory have historically been closely intertwined, and some theorists have even proposed that they are essentially the same mechanism (Cowan, 2001; Cowan et al., 2006). In recent work, we have begun to use the CDA as a powerful tool to examine how attention controls the flow of information into VWM (Vogel, McCollough, & Machizawa, 2005; Vogel, Woodman, & Luck, 2005). In particular, because the amplitude of the CDA is modulated by the number of items that are presently in VWM, we can use it as an online measure of how much information from a display was represented in memory. Moreover, because we have demonstrated that this component is acutely sensitive to individual variability in performance, it has potential to help us begin to understand the nature of these individual differences.

One long outstanding question about individual differences in memory capacity regards whether high capacity subjects can maintain more representations in memory than low capacity individuals, or whether this apparent difference is due to differences in the ability to control what is ultimately stored in VWM (Engle et al., 1999; Hasher & Zacks, 1988; Kane, 2001). That is, all individuals may be able to store roughly the same amount of information in VWM, but the high capacity individuals may simply be much better at restricting what gets into memory than the

low capacity individuals. We tested this question by giving subjects arrays of items in which they had to voluntarily control which items from a display would be stored in VWM (Vogel, McCollough & Machizawa, 2005). In one experiment, subjects were asked to remember only the red items. On some trials, they were shown only red items (either two or four red rectangles). On other trials, they were presented a mix of two red items and two blue items, which required them to selectively keep the blue items out of VWM. We measured the efficiency of keeping the blue items out of memory by examining the CDA amplitude in relation to the red items-only conditions. If a subject was perfectly efficient at keeping the blue items out, then we would expect that CDA amplitude would be equivalent to when they were presented only two red items. By contrast, if the subject was perfectly inefficient at keeping the blue items out, then CDA amplitude should be equivalent to when they remembered four red items. Our results showed that high capacity subjects were highly efficient at keeping the blue items out of memory, and that the low capacity subjects unnecessarily stored the blue items in memory (see Fig 13.4). Thus, the CDA proved to be a useful tool for testing specific cognitive questions regarding how attention and working memory interact and gave us some insight into the nature of individual differences in VWM capacity. Moreover, this study helped establish one more important detail regarding the CDA: the amplitude is not simply determined by how many items are present in the display, but by an interaction between how many task-relevant items are present and how efficiently the subject can select those items.

Using the CDA to examine the role of VWM during Multiple Object Tracking

One of the more dramatic demonstrations of divided attention is that of Multiple object tracking, in which a subject must attempt to attentionally track the positions of multiple targets as

they move amongst several identical distractors over the course of several seconds (Pylyshyn & Storm, 1988; Scholl, Pylyshyn, & Feldman, 2001). This task requires attention to dynamically update the positions of the moving targets and keep these representations segregated from the distractors. Several theorists have proposed that these target representations are held and updated in VWM (Cavanagh & Alvarez, 2005; Oksama & Hyönä, 2004). One piece of evidence in support of this proposal is that subjects can typically track up to a maximum of four targets, which is suspiciously similar to the capacity limit of VWM. Recently, we used the CDA as a means of further testing the role of VWM in MOT. In particular, because the CDA appears to be finely sensitive to the number of items that are currently being maintained in VWM, we reasoned that it should be present while the subject performs an MOT task and should be modulated by the current number of tracked targets. Indeed, in a bilateral variation of a typical MOT task, we observed a large and sustained CDA that was strongly modulated by the number of targets that were being tracked on a given trial (Drew & Vogel, in press). Moreover, we found that the rise in CDA amplitude between tracking one and tracking three targets was strongly predictive of an individual's specific tracking capacity ($r = 0.72$). While further research will be necessary to determine the degree of cognitive and neural overlap between the mechanisms facilitating the performance of MOT and VWM tasks, these results suggest that the same capacity-limited representational system may underlie both of them.

Future directions and Unresolved Issues

We are definitely optimistic about the future utility of the CDA as a tool to examine how VWM operates, as well as how various other cognitive mechanisms interact with this limited online memory system. Thus far, the property of the CDA that appears to have the most potential

to help answer cognitive questions about capacity-limits and representations is its sensitivity to the number of objects that are presently maintained in VWM. Of course, there are several remaining unanswered questions about this component that will need to be addressed before its full impact may be appreciated. Throughout this chapter, we have noted a few of these questions. For instance, what identity information about remembered objects is reflected in the CDA? We know it is modulated by the presence of orientation information, but we really have no idea why this is the case. What is necessary to understand this property is a careful examination of CDA amplitudes across a very broad range of stimulus classes. If it turns out to be reliably sensitive to stimulus identities held in memory, it could open a whole new set of questions about the nature of memory representations that could be addressed with this ERP component.

A second unanswered question about the CDA is its neural origin. While recent fMRI studies have helped to implicate the IPS as a plausible source, a formal attempt at localizing this component will help to determine whether there are multiple cortical sources contributing to this component which would in turn help us determine the network of cortical activity that underlies this capacity limited system. Of course, we understand that traditional source localization approaches can only go so far in establishing the neural sources of ERP components (Luck, 1999). Perhaps more traction could be made on this issue by adopting the approach recently developed by Woodman et al (2007) in which they measured scalp-recorded ERPs while simultaneously recording single-unit responses in awake, behaving monkeys.

One critical, but presently unexplored aspect of the CDA regards the oscillations at various frequencies that underlie this averaged ERP component (see e.g., Chapter 3). As of yet, we have not examined what frequency bands are at play throughout the sustained time-course of the CDA. However, at a theoretical level, we and others have proposed that synchronous firing

across populations of cells may be the mechanism for maintaining object representations in VWM (Lisman & Idiart, 1995; Tallon-Baudry, Bertrand, & Fischer, 2001; Vogel et al., 2001). Indeed, it is even possible that VWM capacity limits are the consequence of a limited ability to keep the oscillations for a given object separate and asynchronous from the oscillations representing other objects in memory (Raffone & Wolters, 2001). Consequently, understanding the oscillations that give rise to the CDA will likely be critical to answering one of the most fundamental questions about working memory: why is it capacity limited in the first place?

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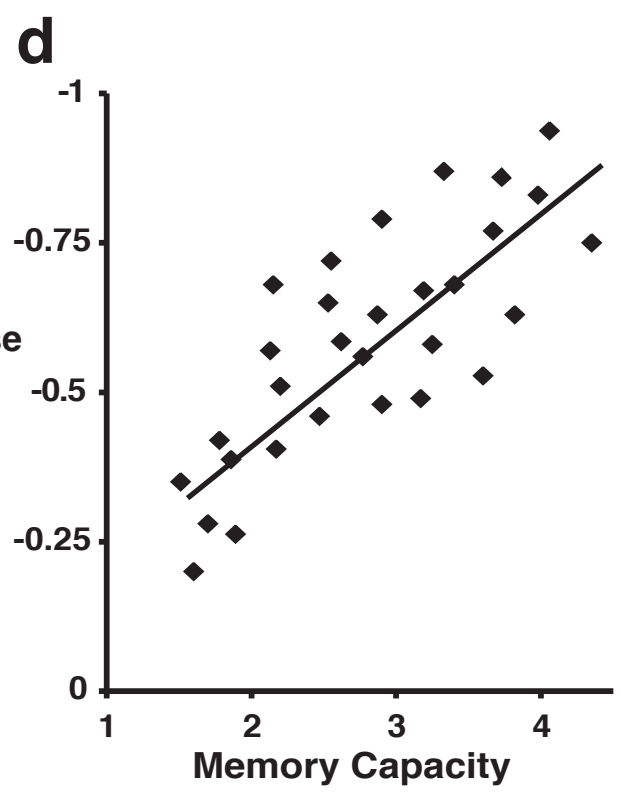
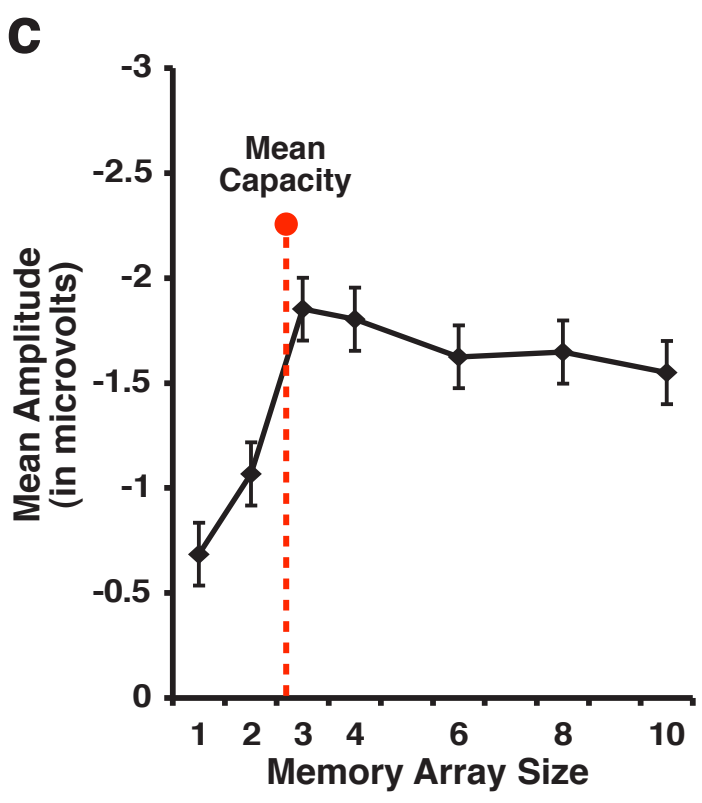
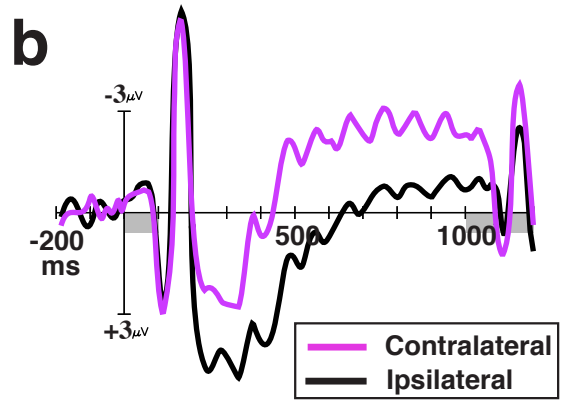
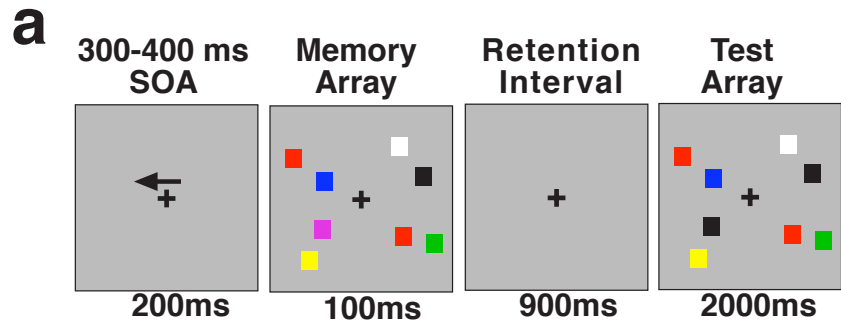
Figure Captions

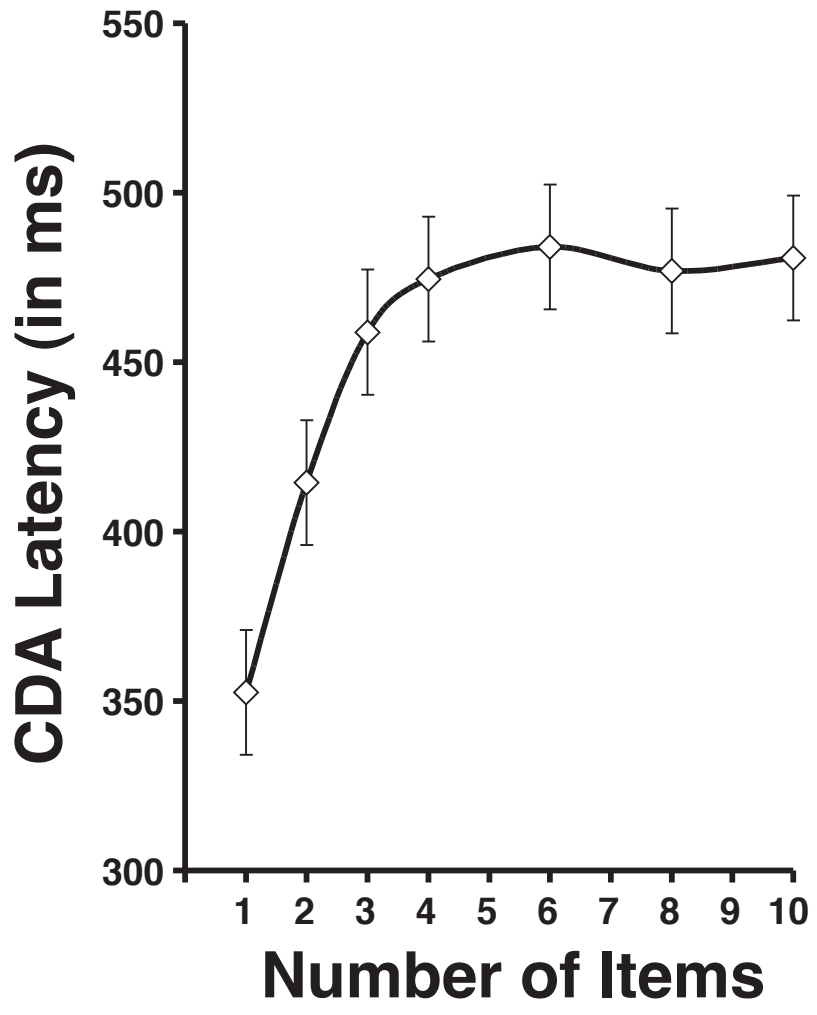
Figure 13.1. **a.** Example of the bilateral change detection paradigm, for a “remember-left” trial. **b.** Grand-averaged contralateral and ipsilateral waveforms time-locked to the memory array and averaged over posterior parietal, inferotemporal, and lateral occipital electrode sites. By convention, negative voltage is plotted upwards. **c.** Mean amplitude of CDA (300-900ms) as a function of the number of items in the memory array. Dotted line represents the mean behavioral visual memory capacity for the sample. **d.** Scatterplot of the rise in amplitude between 2-item arrays and 4-item arrays as a function of an individual’s memory capacity ($r = 0.78$).

Figure 13.2. CDA latency as a function the number of items in the memory array. Fractional area latency was measured as the time-point at which 75% of the CDA amplitude had been reached.

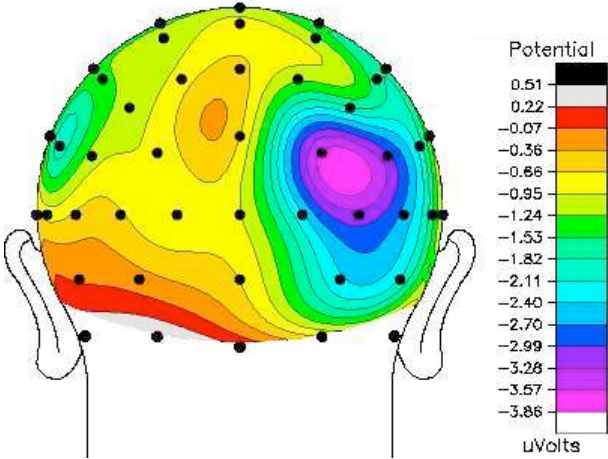
Figure 13.3. Isocontour voltage maps fit to the spherical spline method of Perrin et al. (1989). Blue and purple regions represent increased delay activity in posterior scalp distributions responsive to remember-left and remember-right trials. Mean amplitude voltage is measured 300-900ms after the onset of the sample array.

Figure 13.4. Grand averaged difference waveforms (ipsilateral delay activity subtracted from contralateral delay activity) divided across high and low memory capacity subjects from Vogel et al (2005). While high capacity individuals showed a distractor-present amplitude that was equivalent to 2-items only, the low capacity individuals showed a distractor-present amplitude that was equivalent to the 4-items only condition.





Remember Left



Remember Right

