Published in final edited form as:

Brain Res. 2009 February 13; 1254: 49–62. doi:10.1016/j.brainres.2008.11.063.

Stage and load effects on ERP topography during verbal and spatial working memory

Janet L. Shucard^{*}, Ayda Tekok-Kilic, Keri Shiels, and David W. Shucard

Division of Cognitive and Behavioral Neurosciences, Department of Neurology/Jacobs Neurological Institute, University at Buffalo, State University of New York School of Medicine and Biomedical Sciences, 100 High Street (D-6), Buffalo, New York 14203, USA

Abstract

Frontal-parietal neural networks play a significant role in the functional organization of visual working memory (WM). The relative contribution of material-specific information (e.g., verbal or spatial) on activation of WM circuitry is not fully understood. Process-specific models of WM propose that the activation of WM circuitry is more dependent on the stage of WM than on the type of information being processed. This study investigated the effects of WM information type (verbal, spatial), stage (encoding, maintenance), and load on both the anterior–posterior topography and lateralized scalp distributions of the event-related potential (ERP) P3 amplitude. Seventeen young adults performed verbal and spatial tasks that were equated for stimulus properties and response requirements. Both tasks were presented under 1- and 3-load conditions. The anterior–posterior topography of P3 amplitude at left hemisphere, midline, and right hemisphere scalp locations was affected by the stage of WM and the memory load, but not by the type of information. The encoding stage showed minimal load effects and was associated with a posterior-maximum P3 amplitude distribution. During the maintenance stage, probe letters were presented that were irrelevant to the previously encoded stimuli. Here, higher WM load produced relatively greater frontal and reduced parietal P3 amplitude compared to lower WM load. These anterior–posterior P3 amplitude patterns for encoding and maintenance were similar at left, midline, and right locations. Within the limitations of the study, our results tend to support a process-dependent activation of WM circuits in that P3 amplitude topography only differed as a result of WM stage and load, and not as a result of the type of information (verbal or spatial) presented.

Keywords

Encoding; Maintenance; P3; P300; Task-irrelevant stimuli; Parietal cortex; Frontal-parietal network

1. Introduction

Working memory (WM) has been defined as a multi-component, limited-capacity, short term memory system for temporarily holding and manipulating different types of information to guide goal-directed behavior (Baddeley and Hitch, 1974). It is a fundamental process underlying higher cognitive functions such as learning and language comprehension (Baddeley, 2003; Wagner, 1999). Various models have been offered to explain the

functional significance and organizational principles within WM (Shah and Miyake, 1999). For example, Postle (2006) has suggested that WM may be “a property that emerges from a nervous system that is capable of representing many different kinds of information, and that is endowed with flexibly deployable attention. That is, WM processes occur when attention is aimed at brain systems that have evolved to accomplish certain functions such as vision or movement.” Common to all models are the basic processing stages of WM, namely, encoding, maintenance (storage), and retrieval. Although it has been experimentally challenging to isolate the separate mechanisms associated with the individual stages of WM, Woodman and Vogel (2005) demonstrated that encoding and maintenance operate independently in visual WM.

Functional neuroanatomical studies of WM with animals and humans have revealed that visual WM depends on distributed neural activity of a number of cortical regions, involving mostly prefrontal cortex (PFC) and posterior association areas (Halgren et al., 2002; Honey et al., 2000; Postle, 2006; Sarnthein et al., 1998; Smith and Jonides, 1998). Research on the functional organization of WM within the PFC has generated debate in terms of the basic organizational principles of WM. On the one hand, according to the “material-specific” view, different PFC regions are involved in WM stages based on the *type of information* being processed (Courtney, 2004; Courtney et al., 1998; Sala et al., 2003). On the other hand, more “process-specific” models suggest that different PFC regions are activated by the different *processing stages* of WM, mostly independent of the type of information involved (D’Esposito et al., 1999; Owen et al., 1998; Postle et al., 2000). Recently, more integrated approaches have been offered suggesting both an information and process-related organization of WM functions within the PFC (Johnson et al., 2003; Sala and Courtney, 2007). In addition to the contribution of the PFC, studies have shown that the parietal lobes are also involved in WM processes, such as the storage of phonological and visual information (Baldo and Dronkers, 2006; Curtis, 2006; Honey et al., 2000; Jonides et al., 1998, 2005; McCollough et al., 2007; Ravizza et al., 2004; Todd et al., 2005; Todd and Marois, 2004). Studies of differential cerebral hemisphere involvement of WM circuitry have shown both information type (Smith and Jonides, 1997; Na et al., 2000) and process or stage-related lateralization (Smith et al., 1996; Talsma et al., 2001). Bilateral activation in both parietal and frontal cortices was also reported (Nystrom et al., 2000; Zurowski et al., 2002).

As noted, WM is a limited capacity system. Functional magnetic resonance imaging (fMRI) studies that examined the relationship between WM and brain activity by manipulating memory load have shown task demand effects on WM performance. Activation of areas within the PFC and parietal cortex has been found to increase or a decrease related to load and to the processing stages of WM (Prabhakaran et al., 2000; Ryma et al., 1999, 2002). Interestingly, some studies showed increased activation in the parietal areas during low memory load conditions and suppression of these areas with increased memory load (Honey et al., 2000; Löw et al., 1999; Todd et al., 2005; Ravizza et al., 2004; Tomasi et al., 2007). For example, Ravizza et al. (2004) showed functional differences between the dorsal and ventral aspects of the inferior parietal cortex. Effects of memory load and type of information were examined with fMRI during two WM tasks (*n*-back and item recognition). Manipulation of load in non-verbal WM tasks affected dorsal and ventral aspects of inferior parietal cortex differently. The ventral inferior parietal area showed attenuated activation with increased load. The authors interpreted their findings as inhibition of the ventral parietal inferior cortex by the central executive when the task demand is relatively high. Todd et al (2005), using fMRI in a series of experiments, reported that activity from the right temporo-parietal junction is suppressed as a function of increasing visual memory load. They also noted that this suppression was most notable during the maintenance phase of the task.

The functional localization of WM networks has been greatly enhanced by the research using high spatial resolution neuroimaging techniques such as fMRI. However, there is agreement that these techniques have less than perfect temporal resolution because of the delay between the hemodynamic response and neural activation (de Haan and Thomas, 2002). Event-related potentials (ERPs), on the other hand, have excellent temporal resolution which makes it possible to obtain time-locked brain activity related to task, process, and various parametric manipulations noted to be important during WM tasks.

Different electrophysiological approaches have been used to investigate the dynamics underlying WM networks. Synchronized activity between prefrontal and posterior association areas during WM tasks have been reported using coherence analyses of EEG (Sarnthein et al., 1998; Sauseng et al., 2005; Schack et al., 2005). Lw et al. (1999) studied ERP responses during a delayed matching to sample task in which memory load was also manipulated. The results showed posterior activation during the encoding and maintenance stages of spatial WM as well as a load-related scalp distribution of ERP responses. Specifically, source modeling indicated greater activity in anterior areas under high WM load and increased posterior activity under low WM load, similar to the load-related fMRI findings described above by Ravizza et al. (2004). Using dense electrode arrays, Gevins et al. (1996) investigated the spatio-temporal dynamics of WM in verbal and spatial WM tasks. In this study, although task demand influenced the ERP components and their scalp distributions, frontal-parietal topographical distributions elicited by the verbal and the spatial tasks were similar, supporting a process-specific organization of WM. Similar results regarding information type and memory load were also observed in a subsequent study (McEnvoy et al., 1998).

The amplitude of the P3 component of the ERP has been shown to be sensitive to the manipulation of task relevancy, and memory updating functions (Kok, 2001). Further, it has been demonstrated that the scalp topographical distribution of the P3 component is sensitive to stimulus context, evaluation processes, and learning (see for example Luu et al., 2007). Typically a parietal maximum scalp distribution is present for target detection, while a more fronto-central distribution occurs, for example, under stimulus conditions such as distraction, novelty, response inhibition, and increased task difficulty (Bekker et al., 2004; Polich and Comerchero, 2003). The fronto-central versus parietal maximum P3 amplitude distributions have been shown to be generated by distinct frontal and parietal neural structures. Therefore, the P3 response appears to be a good measure for the study of WM processes.

In summary, convergent findings have revealed at least one cortical network that underlies WM function and includes both anterior and posterior structures. To some extent, activation of this network is modulated by memory load, and possibly the type of information, although their effects on the different processing stages of WM are not yet clear. Lateralized and bilateral hemispheric activation patterns have also been reported during different WM stages.

In the present study we examined the effects of WM load and the type of WM information on the anterior–posterior topographical distribution of the P3 component of the ERP at left hemisphere, midline, and right hemisphere locations during the encoding and maintenance stages of WM. We manipulated memory load with 1 or 3 items during parallel versions of verbal and spatial WM tasks. By using the same stimuli in both tasks, we eliminated the effects of the physical properties of the stimuli on the ERP waveform, in order to investigate only the effects of type of information, load, and stage. In addition, we examined the lateralization of P3 amplitude during WM stages related to load and type of information. We hypothesized that the encoding and maintenance stages of WM would produce different

anterior/posterior P3 amplitude distributions, with load having a greater impact on the distributions during the maintenance rather than the encoding of information in WM. Consistent with the proposed function of frontal areas in demanding and effortful processing, we expected that memory load effects would be obtained at more anterior scalp sites, such that relatively greater P3 amplitudes would occur at frontal scalp sites for the higher load conditions compared to the lower load conditions. On the other hand, as suggested by previous literature, we also expected that P3 amplitude at the posterior scalp sites would decrease with increasing load. Again, these load effects were predicted to be the most prominent during the maintenance stage. We also hypothesized that anterior–posterior P3 amplitude distributions would not be affected by the type of information (verbal, spatial), thereby supporting a more process-dependent rather than information or material-dependent activation of WM circuits.

2. Results

2.1. Performance measures

All participants performed the tasks with high accuracy (see Table 1 for means and standard deviations of performance measures). Omission errors reflect the mean number of times participants did not respond to a correct match. Commission errors reflect the mean number of times that participants responded when they should not have to non-matches. There were significantly fewer commission errors for the verbal 1-load versus verbal 3-load task ($t = -3.4, p = .004$). No difference in commission errors was present between the spatial 1 and 3 load tasks (see Table 1). The average percentage of correct responses (for the 40 possible correct matches) was 94.5% for verbal 1-load, 90.6% for verbal 3-load, 94% for spatial 1-load, and 94.7% for spatial 3-load. Reaction time (RT) to correct matches was analyzed using Task (verbal, spatial) $\times$ Load (1-load, 3-load) within subjects repeated measures ANOVA. The results, as depicted in Fig. 1, revealed a significant Task $\times$ Load interaction [$F(1,16) = 19.42, p < .001$]. Further analyses conducted for simple effects showed significant RT differences between verbal and spatial tasks in the 3-load condition [$F(1,16) = 29.59, p < .001$] with longer RT for the verbal task than for the spatial task. Longer RTs were also found for the verbal 3-load compared to the verbal 1-load condition [$F(1,16) = 55.12, p < .001$]. Reaction times did not differ between 1- and 3-load conditions of the spatial task (Fig. 1). These analyses revealed that the RTs between the two tasks differed during higher memory load (verbal slower than spatial) and the increased load also produced slower RT during the verbal task but not during the spatial task.

2.2. ERP P3 analyses

Analyses were conducted to examine the effects of the type of WM information (verbal, spatial), the stage of WM (encoding, maintenance), and memory load (1 and 3 stimuli) on the anterior–posterior topographical distribution of P3 amplitude, and the left–right hemisphere P3 amplitude responses. First, an Information Type (verbal, spatial) $\times$ Location (left, midline, right) $\times$ Site (frontal, central, parietal) $\times$ Stage (encoding, maintenance) $\times$ Load (1- and 3-load) ANOVA was conducted. Neither the 5-way interaction nor any of the 4-way interactions were significant. Significant Location $\times$ Site $\times$ Stage [$F(4, 64) = 3.68, p = .022$], Site $\times$ Load [$F(2, 32) = 23.41, p < .001$], and Information Type $\times$ Stage [$F(1, 16) = 7.83, p = .013$] interactions were present. Thus, the type of information (verbal or spatial) did not affect P3 amplitude differentially at left hemisphere, midline, or right hemisphere locations, and did not interact with site or load. Therefore, the approach that was taken was first to probe both the Location $\times$ Site $\times$ Stage and Site $\times$ Load interactions within the midline (Fz, Cz, Pz), left hemisphere (F3, C3, P3), and right hemisphere (F4, C4, P4) locations, separately. This approach allowed for the examination of the effects of WM stage and load on the anterior–posterior topography (site) of P3 amplitude within each location.

Second, the interaction that included the effect of information type on WM stage, irrespective of site, is discussed below.

2.2.1. Anterior–posterior distribution of midline P3 amplitude—A Site (Fz, Cz, Pz) $\times$ Stage (encoding, maintenance), $\times$ Load (1,3) within-subjects repeated measures ANOVA was conducted. The results revealed a significant Site $\times$ Stage $\times$ Load [$F(2,32) = 6.3, p = .013$] interaction.

The significant Site $\times$ Stage $\times$ Load interaction for the midline sites is depicted in Fig. 2 (center). This interaction indicated that regardless of the type of information (verbal or spatial), both the stage of WM and the WM load affected the P3 amplitude at anterior, central, and posterior sites. This interaction was probed with a Site $\times$ Load ANOVA to examine the P3 amplitude scalp distribution for the encoding and maintenance stages of WM, separately (Fig. 2 Midline Encoding, and Midline Maintenance respectively). For the encoding stage, only a main effect for Site was present [$F(2, 32) = 90.20, p < .001$]. Regardless of information type or load, the encoding stage produced the greatest P3 amplitude at the parietal site (Pz), which was significantly greater than both central (Cz, $p < .001$) and frontal (Fz, $p < .001$) amplitudes. P3 amplitude at the central site (Cz) was also significantly greater than Fz amplitude ($p < .001$). For the maintenance stage, a significant Site $\times$ Load interaction was present [$F(2, 32) = 20.26, p < .001$], as seen in Fig. 2 (Midline Maintenance). To probe this interaction further, the anterior–posterior distribution of P3 amplitude was examined for each load, separately. For the 1-load condition, a Site effect [$F(2, 32) = 29.22, p < .001$] was present, with $Pz > Cz > Fz$ ($p < .001$, respectively). Thus, as in encoding, the greatest P3 amplitude occurred at Pz. For the 3-load condition, no significant differences in P3 amplitude were present among the sites. That is, P3 amplitude for Fz, Cz, and Pz were equivalent. Additional analyses were conducted to compare the effect of load (1-load vs 3-load) on P3 amplitude at each scalp site separately (Fz, Cz, and Pz, respectively). The results of these analyses revealed that at Fz, P3 amplitude differences between the 1-load vs 3-load conditions approached significance, with a trend toward greater P3 amplitude at the frontal site for the 3-load condition [$F(1,16) = 3.75, p = .07$]. Conversely, at Pz, the 3-load condition produced significantly lower P3 amplitude than the 1-load condition [$F(1, 16) = 9.24, p = .008$]. There was no significant effect of load at Cz.

In summary, P3 amplitude scalp topography at the midline sites was not affected by information type (verbal versus spatial). Rather, the anterior–posterior topography of P3 amplitude showed different patterns related to both the stage of WM (encoding versus maintenance) and the memory load (1- versus 3-load). During encoding, the posterior scalp site (Pz) produced the greatest P3 amplitude, with lowest amplitude at the frontal site, regardless of WM load. During maintenance, the topographic distribution of P3 amplitude was more dependent on load. Here, the higher WM load (3-load) produced relatively greater P3 amplitude at the frontal site and lower P3 amplitude at the Parietal site than lower WM load (1-load). Again, these findings were not dependent on the information type (verbal versus spatial).

2.2.2. Anterior–posterior distribution of left hemisphere P3 amplitude—In order to investigate the effects of stage and load on the topographical distribution of P3 amplitude in the left hemisphere, the same analysis reported above for the midline electrode sites was conducted for the left hemisphere sites. A Site (F3, C3, P3) $\times$ Stage (encoding, maintenance) $\times$ Load (1,3) repeated measures ANOVA showed significant Site $\times$ Stage [$F(2, 32) = 8.95, p = .004$], and Site $\times$ Load [$F(2, 32) = 21.46, p < .001$] interactions. Fig. 2 (Left Hemisphere) presents the findings for the left hemisphere sites during encoding and maintenance collapsed across verbal and spatial information types.

The Site $\times$ Stage interaction was probed by collapsing across load, and the P3 amplitude for encoding and maintenance was compared at each electrode site, separately. At F3 and C3, P3 amplitude did not differ between the two stages. At the left parietal scalp site (P3), however, P3 amplitude during the encoding stage was significantly greater than the P3 amplitude during the maintenance stage [$F(1,16) = 9.25, p < .01$].

The Site $\times$ Load interaction was probed by collapsing across stage to examine the P3 amplitude differences between the 1- and 3-load conditions at each electrode site, separately. Regardless of WM stage, the 3-load condition elicited significantly greater amplitude than the 1-load at the frontal site [$F(1,16) = 6.23; p = .024$]; whereas relatively smaller P3 amplitude was elicited at the parietal site for the 3-load condition, although this difference between the 1- and 3-load conditions at the parietal site when tested for simple effects was not significant [$F(1,16) = 3.49, p = .08$]. No difference was present between 1- and 3-loads at the C3 site.

In summary, the left hemisphere topographical effects revealed that, irrespective of load, the encoding stage produced greater P3 amplitude at the parietal site compared to the maintenance stage. Memory load effects on topography revealed that as load increased, relatively greater frontal and smaller parietal amplitude was present, regardless of the stage of WM. This effect of load was more apparent at the frontal than parietal site.

2.2.3. Anterior–posterior distribution of right hemisphere P3 amplitude—The same 3-way ANOVA was conducted for the right hemisphere scalp sites (F4, C4, P4) as for the midline and left hemisphere sites. Significant interactions were present for Site $\times$ Stage [$F(2,32) = 11.45, p < .001$] and Site $\times$ Load [$F(2,32) = 19.1, p < .001$]. Fig. 2 (Right Hemisphere) illustrates these results.

The Site $\times$ Stage interaction at the right parietal scalp site (P4) revealed the same effect as that seen for the left hemisphere. The P3 amplitude at P4 elicited during the encoding stage was significantly greater than the P3 amplitude at P4 elicited during the maintenance stage [$F(1,16) = 9.25, p < .01$], while P3 amplitude between the stages did not differ at the F4 or C4 sites.

The significant Site $\times$ Load interaction showed that regardless of WM stage, the 3-load condition produced relatively greater P3 amplitude at the frontal site (F4), and smaller P3 amplitude at the parietal site (P4) than did the 1-load condition. Examination of the simple effects between load at F4 revealed that the differences in amplitude were not significant [$F(1,16) = 3.16, p = .094$]; whereas, at the parietal site (P4), the 3-load condition produced significantly smaller P3 amplitude than the 1-load condition [$F(1,16) = 13.25; p = .002$]. Amplitude differences related to load were not present at the central site (C4).

In summary, the right hemisphere topographical effects revealed, again, as seen at the midline and left hemisphere locations, that irrespective of load, the encoding stage produced a greater parietal maximum P3 amplitude distribution than the maintenance stage. Examination of load effects, irrespective of stage, showed that as memory load increased, relatively greater frontal and lower parietal amplitudes were present, similar to the left hemisphere. For the right hemisphere, however, compared to the left, this effect of load was most apparent at the parietal rather than the frontal site.

2.2.4. Interaction involving the effect of Information Type on Stage—Although Information Type did not affect the topographic distribution of P3 amplitude within midline, left or right hemisphere locations, verbal versus spatial information did interact with stage of WM regardless of the location, electrode site, or load. The significant Information Type $\times$

Stage interaction is illustrated in Fig. 3. The interaction was probed by comparing verbal and spatial P3 amplitudes for the encoding and maintenance stages. The P3 amplitudes for verbal encoding, spatial encoding, and spatial maintenance did not differ (viz., verbal encoding = spatial encoding = spatial maintenance). The only difference that was present was that the P3 amplitude for verbal maintenance was significantly lower than the P3 amplitude for verbal encoding [$F(1,16) = 14.43, p = .002$]. Thus, the findings show that, in general, P3 amplitude is reduced during the maintenance stage when the WM task is verbal as opposed to spatial. This finding is most likely due to the greater difficulty of the verbal task than spatial task.

2.3. Anterior–posterior distribution of P3 to Cue versus Maintenance stimuli

In order to help interpret the effects of load on P3 amplitude observed during the maintenance stage, an additional analysis was conducted. During both the cue presentation and maintenance stage, the letter stimuli that occurred were irrelevant to the task. The suppression of irrelevant stimuli has been shown to produce reduced parietal P3 amplitude during WM (Postle, 2006). To test the hypothesis that the maintenance of information in WM may produce load-related P3 amplitude changes due to active suppression of the irrelevant stimuli, a Site (Fz, Cz, Pz) $\times$ Stage (Cue, Maintenance) $\times$ Load (1, 3) ANOVA, collapsed across verbal and spatial tasks, was conducted. A significant Site $\times$ Stage $\times$ Load [$F(2,32) = 10.97, p < .001$] interaction was present. See Fig. 4 for an illustration of this interaction.

The 3-way interaction revealed that both the stage (cue vs maintenance) and load affected the P3 amplitude topography. To probe this interaction, a Site $\times$ Load ANOVA was conducted to compare the topographical distribution of P3 amplitude to the cue with the maintenance stage topography. For the Cue, only a main effect for Site was present [$F(2,32) = 48.85, p < .001$]. Regardless of information type or load, the cue produced the greatest P3 amplitude at the parietal site (Pz), with $Pz > Cz > Fz$ (all comparisons $p < .001$). Thus, the cue produced a topographical distribution similar to that seen for the encoding stage. However, the maintenance stage, as described in the midline analysis above, showed a significant Site $\times$ Load interaction due to relatively greater frontal and reduced parietal P3 amplitude to the 3-load versus the 1-load condition.

To summarize the results of this study, the analyses showed that the organization of WM in the left and right hemispheres closely parallels the anterior–posterior WM organization at the midline sites, and that these findings were not dependent on the whether the type of WM information being presented was verbal or spatial. The effects of task difficulty (load) were dependent on stage only at the midline location. Higher load during maintenance produced a pattern of relatively greater frontal P3 amplitude and reduced parietal amplitude compared to lower load. The effects of the type of information on P3 amplitude appeared to be related more to the difficulty of the 3-load verbal task in comparison to the 3-load spatial task than to differences in verbal versus spatial WM circuitry within or between the hemispheres. The load effects during maintenance were further confirmed by comparing the topography associated with the cue and maintenance stimuli. Only maintenance was effected by WM load, even though the cue stimuli had the same task-irrelevant probe letters as those presented during maintenance.

3. Discussion

The purpose of this study was to examine the effects of information type (verbal vs. spatial material), stage (encoding and maintenance) and memory load on both the anterior–posterior and lateralized scalp distribution of P3 amplitude during verbal and spatial WM tasks. In general, our findings support a stage (process) and load rather than a material-specific

organization of visual WM in the brain. The type of the information did not change the anterior–posterior topographical distribution of P3 amplitude elicited during the encoding and the maintenance stages of WM at the left hemisphere, midline, or right hemisphere locations, nor were there any hemispheric asymmetries related to information type.

The WM tasks that were used in this study were unique in that the physical stimuli and response types were identical for both verbal and spatial tasks. Only the instructions differed between the two tasks. For the verbal task, participants were required to remember either one or three letters, irrespective of location; whereas for the spatial task, participants were required to remember the location of one or three letters, irrespective of the letters themselves. This standardization of stimulus properties across tasks enabled us to eliminate the possible effects of the physical aspects of the stimuli, and focus directly on the cognitive operations required by the tasks (maintaining the identity versus the location of the stimuli).

The performance data revealed similar RTs for the verbal and the spatial tasks during the 1-load condition. As expected with increased task difficulty, RT significantly increased during the 3-load condition, but only for the verbal task (Fig. 1). The mean number of commission errors also increased from the 1-load to the 3-load condition for the verbal task but commission errors did not differ between the spatial 1 and 3-load conditions (Table 1). The 3-load condition of the spatial task may not have been significantly more difficult than the 1-load condition because of the strategy participants used to remember the 3 locations. In a post-experiment strategy questionnaire, fifty-seven percent of the participants reported that they were able to “chunk” the spatial stimuli during the 3-load condition to form a pattern that made it easier to remember the location of the letters. This strategy is consistent with the findings about organizational principles of information in spatial domains (see Bor et al., 2003; De Lillo, 2004). Thus, simply increasing the number of stimuli to encode or remember for the spatial task may not have had as much of an effect, at least behaviorally, as increasing the number of stimuli for the verbal task.

As hypothesized, the anterior–posterior topography of P3 amplitude was affected by WM stage and by the amount of WM load. As illustrated in Fig. 2, a similar topographical pattern for P3 amplitude was present at midline, left, and right locations, although subtle differences occurred among locations. At the midline location, the encoding of information was associated with a posterior-maximum P3 amplitude distribution, regardless of load. The topographical distribution of P3 amplitude during the maintenance of this information, however, was affected by load. Under the low load condition (1-load), a parietal-maximum P3 amplitude distribution was present similar to that seen for the encoding stage; whereas increased WM load (3-load) was associated with a relatively greater frontal and reduced parietal P3 amplitude distribution compared to that seen for 1-load.

For both the left and right hemispheres, the topographical effect of load was not dependent on stage, but only on scalp site (site $\times$ load). A similar topography was present for both hemispheres regardless of stage, with relatively greater frontal and reduced parietal P3 amplitude with increased load. However, increased load resulted in significantly greater P3 amplitude only at the frontal site in the left hemisphere, and significantly reduced P3 amplitude only at the parietal site in the right hemisphere. The greater frontal P3 amplitude appears to be due mainly to the effect of load during maintenance, as was seen for the midline location. In addition, regardless of load, the effect of the stage of WM on the anterior–posterior topography of P3 was significant. For both hemispheres, only at the parietal sites, encoding produced greater amplitude than maintenance (site $\times$ stage).

The topographic effect for the encoding stage, which showed the greatest P3 amplitudes at the parietal scalp sites, irrespective of information type (verbal or spatial), is consistent with

previous neuroimaging and ERP data. Parietal cortical involvement in stimulus encoding has been demonstrated during various visual WM tasks (Löw et al., 1999; Habeck et al., 2005). Kiss et al. (2007) reported enhanced parietal ERP positivity during a verbal WM task in which storage (encoding) and rehearsal (maintenance) of verbal stimuli were required, simultaneously. In the present study, at the midline location, the topographical shift to a relatively greater frontal and reduced parietal pattern with increased memory load during maintenance compared to encoding, suggests the recruitment of resources from more anterior areas of the WM network, along with possible inhibition of resources at posterior locations.

Numerous studies have shown that areas of the PFC are critical in the maintenance of information during the delay period between encoding and responding (see for review Curtis and D'Esposito, 2003; Postle, 2006). According to the WM model of Jonides et al. (2005), visual information entering WM is processed by parietal structures (spatial information) and temporal structures (object identity or verbal information), and these structures continue to be activated after the visual stimulus is removed. During the maintenance of information, when rehearsal is required, frontal attentional systems are also activated, particularly so when interference is present. Our findings of a posterior-maximum P3 amplitude distribution during encoding for both the 1- and 3-load conditions, and a shift toward a relatively greater frontal and a reduced parietal P3 amplitude distribution during the maintenance of 3 stimuli (3-load) supports the model of Jonides et al. (2005).

The findings are also consistent with those of Todd et al. (2005), who suggested that suppression of temporo-parietal junction activity may prevent unexpected stimuli that are irrelevant to the task from interfering with the task. One hypothesized role of the prefrontal cortex in WM, according to a number of investigators, is to act as a gain controller of activity in “sensory processing areas of the posterior cortex” so that potentially distracting information would be less likely to interfere with the WM process at hand (see Postle, 2006 for review). In the present study, during the maintenance stage, task-irrelevant letters were presented and acted as probes for ERP recording. As noted, parietal P3 amplitude decreased as a function of WM load during maintenance with some increase in frontal P3 amplitude. (Only borderline statistical significance was present for the frontal amplitude increase when tested for load effects at the midline location).

As mentioned previously, the letter stimuli presented with the cue and during maintenance, were irrelevant to the task. Suppression of irrelevant stimuli has been shown to produce reduced parietal P3 amplitude (Postle, 2006). Thus, it is possible that if P3 amplitude was related only to the number of irrelevant stimuli, similar P3 amplitude distributions for the cue and during maintenance would be present for the 1 and 3 irrelevant letters. On the other hand, if P3 amplitude reflects an active process of maintaining information in WM, different P3 amplitude distributions would be expected between the cue presentation and maintenance stage as a function of load. That is, the irrelevant stimuli during the cue would produce no P3 amplitude topographical relationship based on their number (1 or 3). For maintenance, however, topography would be related to load. Greater WM load would produce a reduction in parietal P3 amplitude compared to lower load only during maintenance. The findings of a decrease in P3 amplitude at the parietal scalp site during maintenance and not during the cue presentation supports the notion of suppression of posterior cortex during the maintenance of information in WM. In addition, and importantly, the number of probe letters present during the cue stimulus did not affect the topography, lending further support to the notion that the effect of WM load was, indeed, measured by the P3 amplitude to irrelevant stimuli during maintenance (Fig. 4).

In the present study, the lack of significant interactions that included site and information type argues against domain specific segmentation of WM organization, at least within the scalp recording sites examined. However, we did not measure activity at temporal sites, which, for example, may be more sensitive to the encoding of verbal information. Our findings do suggest that both spatial and verbal information relevant to WM similarly activate anterior and posterior structures, at least during the encoding stage of WM. During maintenance, the effect of information type on the suppression of the irrelevant letters may be less clear, although no effects of information type were found.

The anterior–posterior scalp topography effects of memory load observed in our study are supported by neuroimaging studies. For example, studies using fMRI have shown that an increase in memory load augments activation of frontal areas (Linden et al., 2003; Rympa et al., 2002; Woodward et al., 2006). Interestingly, Rympa et al. (2002) used a WM task in which one to eight letters were required to be maintained over a short delay period. They reported that as the number of letters to be remembered increased, there was a decrease in ventrolateral PFC activation during encoding, and an increase in dorsolateral PFC activation during maintenance. Additionally, several studies (fMRI and ERP) have reported results that support our findings of greater posterior activation under lower memory load conditions compared to higher load conditions (Linden et al., 2003; Löw et al., 1999; Ravizza et al., 2004; Todd et al., 2005).

Activation due to memory load also has been shown to be related to WM stages (Rympa and D'Esposito, 1999; Habeck et al., 2005). Recently, using fMRI, Woodward et al. (2006) reported separate load-dependent encoding and maintenance systems during a visually presented verbal Sternberg task in which item load was parametrically manipulated. The load-dependent encoding system consisted of the occipital, superior parietal, dorsolateral PFC, and dorsal anterior cingulate regions activated bilaterally. With respect to maintenance, the results revealed two load-dependent systems; one subsystem showed increased activation with increasing load (left posterior parietal, left inferior prefrontal, left premotor and supplementary motor areas); whereas the other showed decreased activity related to increasing load (bilateral occipital, posterior cingulate, and rostral anterior cingulate/orbitofrontal regions). Our results are consistent with the general findings that higher load is associated with increased frontal and decreased parietal activation of WM systems, and lower load with increased parietal activation. As discussed, these findings for the present study were most robust during the maintenance stage of WM at the midline locations.

Aside from the anterior–posterior topographic findings, we also showed a relationship between information type and the stage of WM, which occurred irrespective of the location, scalp site, or load. The verbal task had reduced P3 amplitude compared to the spatial task, only during the maintenance stage (Fig. 3). A possible interpretation of this finding is that maintenance of verbal information was more difficult than maintenance of spatial information for the paradigm used in our study. P3 amplitude at posterior scalp sites has been shown to be inversely related to task difficulty (Kok, 2001). Although the significant interaction was not dependent on site, the parietal sites most likely had the greatest influence on the mean P3 amplitude (collapsed across sites) in this interaction. The post-experiment questionnaire, performance errors, and RT in our study also support the possibility that the verbal 3-load task was more difficult than the spatial 3-load task.

In summary, using parallel verbal and spatial WM tasks that allowed us to examine each stage of WM separately, we investigated the relationship between WM stage, information type, and memory load on ERP P3 amplitude topography. Although our design does not allow for detailed neuroanatomical analyses, the absence of any differences among the left,

midline, or right locations related to the processing of verbal and spatial information appears consistent with a process-dependent model more so than a material-specific segmentation of WM (for example see Courtney, 2004). Thus, this support for a stage (process)-dependent organization of frontal-parietal WM circuits reflects the interdependence of frontal and parietal sites with respect to available neuronal resources and possible suppression of posterior cortical activity during the maintenance of information, regardless of whether the WM information being processed is verbal or spatial. It should be noted, however, that although the verbal and spatial information used in our study may not have had great enough cognitive demand to produce location-related differences, the findings pertaining to the anterior-posterior WM circuit, WM stage, and load effects are compelling. Our primary finding was that as WM load increased there was a trend toward an increase in frontal P3 amplitude (significant in left hemisphere only); whereas parietal P3 amplitude decreased with increased load. This effect of load was present mainly during the maintenance of information in WM, and was measured indirectly via task-irrelevant probe stimuli. This finding can be explained either by active suppression of the parietal areas (Ravizza et al., 2004; Todd et al., 2005), or by a limited resource WM system that becomes apparent through manipulation of load. Ravizza et al. (2004) obtained load-related findings similar to ours. In their fMRI study, suppression of parietal activity by the frontal executive system was proposed to account for decreased parietal activation with increased WM load. Todd et al. (2005) also supported this model.

One shortcoming of our study is that the ERP methodology does not allow for the direct measurement of maintenance processes in a similar fashion as encoding. In the present study, during encoding, ERPs were recorded to the stimuli to be held in WM, whereas during maintenance, ERPs were recorded to irrelevant stimuli presented while information was held in WM. The comparison of P3 amplitude to irrelevant stimuli during the cue versus maintenance helped provide insight into P3 amplitude patterns observed during maintenance. Further studies with paradigms that isolate the stages of WM, along with the use of dense electrode arrays capable of examining more closely both anterior-posterior and left-right activity, as well as the sources of the scalp electrocortical activity, would help to clarify further the spatial dimensions of WM circuits. A better understanding of WM circuitry and the ability to measure reliably the various processes involved in WM, will have significant implications for improving the understanding of cognitive dysfunction in a variety of neurological and psychiatric disorders as well as our understanding of cognitive processes in general.

4. Experimental procedures

4.1. Participants

Twenty-two healthy undergraduate students, 10 men and 12 women were initially recruited for the study. Data for three women and one man were excluded due to excess artifact present during the electrophysiological recording. Data for one other female participant were excluded because ERP peaks were not identifiable for the lateral electrode sites.

The final sample consisted of 9 men and 8 women, with a mean age of 19.06 (SD = 1.8 years). All participants were native English speakers with no known medical, neurological or psychiatric problems. There were no hearing problems or history of learning disorders reported and vision was normal or corrected-to-normal. All participants were right handed as determined by the Handedness Inventory of Briggs and Nebes (1975). Participants signed an informed consent prior to testing. They were compensated through research credits for their participation and were treated in accordance with the “Ethical Principles of Psychologists” (APA, 1992).

4.2. The verbal and spatial WM tasks

All participants completed four separate visual WM tasks: Two verbal tasks (1- and 3-load) and two spatial tasks (1- and 3-load). Fig. 5 presents a schematic illustration of the 1- and 3-load conditions of the spatial tasks (the verbal tasks had the same stimuli but participants received different instructions as described below). All four of the tasks were continuous performance tasks, each consisting of a series of 337 letters presented either one at a time (1-load), or three at a time (3-load) on a 14 in. computer monitor. The duration of each task was 10.7 min. A plus sign was located in the center of the screen during each stimulus presentation, and participants were instructed to fixate on the plus sign throughout the task (see Fig. 5). The letters appeared in any of 48 possible locations on the screen based on a 10.5 in. square grid (7×7 locations excluding the location of the plus sign). For all of the tasks, each stimulus (1 letter or 3 letters) was presented for 400 ms, with a 1200 ms interstimulus interval (stimulus offset to stimulus onset). The stimuli were 25 capital letters (excluding the letter X) which were produced by a NeuroScan STIM system and presented in white on a black background. The computer monitor was at eye level at a distance of 60 cm from the bridge of the participant's nose.

For the 1-load verbal or 1-load spatial tasks, participants were instructed that letters would appear one at a time in different locations on the screen, and that they should keep their eyes fixated on the plus sign in the center of the screen while each letter was presented. Their task was to look for a small square around the fixation sign (*cue*) that would signal them to get ready for the next letter to be presented. For 80 of the letter presentations, the small square surrounded the plus sign, signaling the beginning of a trial. During the verbal WM task, participants were told to remember the identity of the letter (regardless of the location), and during the spatial WM task, they were told to remember the location of the letter (regardless of the letter identity) that appeared on the screen following the cue (encoding stage). During the presentation of the next screen (maintenance stage), participants were required to remember, or maintain, the information that was presented to them during encoding. Here, either 1 or 3 task-irrelevant probe letters were presented (see Fig. 5). Following the maintenance stage, participants had to determine whether the next stimulus matched the identity (verbal task) or the location (spatial task) of the encoded stimulus (response stage). If the stimuli matched, they were to respond by pressing two buttons on a response pad with their right and left thumbs, simultaneously. RTs were recorded for the fastest press for each response. If the stimuli did not match, participants were to withhold their response. In the 3-Load condition, for both the verbal and spatial WM tasks, 3 letters appeared simultaneously on the screen. As in the 1-load tasks, participants were to remember the identity of the three letters (verbal task), or the location (spatial task) of the three letters (encoding stage), maintain this information in memory during the next stimulus presentation (maintenance stage), and then determine if the information held in memory matched the next presentation, and make the appropriate response (response stage). A short practice trial was administered preceding each task to ensure that the participants understood the instructions, and that they were able to keep their eyes fixated on the plus sign. Eye movements were monitored online, and participants were given further instructions about keeping their eyes fixated, if necessary, before the tasks began.

For each task, there were 80 cue stimuli, 80 encoding stimuli, 80 maintenance stimuli, 40 target matches, 40 nonmatches, and 17 non-task-related presentations of letters (filler stimuli). The 17 filler letter presentations occurred randomly after the response letter so that the occurrence of the cue was less predictable and the task was viewed as continuous. The verbal and spatial tasks were designed so that the physical parameters of the stimuli were identical (always one or three letters) for each of the stimulus types (cue, encoding, maintenance, etc.) for both the verbal and spatial tasks. Thus, any differences in the ERP measures between the verbal and spatial tasks could be attributed to the instructional/

cognitive set of the task, and not to the physical parameters of the stimuli. A short break occurred after each task, and during this time, the participant's current level of alertness was assessed by the Stanford Sleepiness Scale (Hoddes et al., 1972). All participants scored in the alert range of the scale. The order of administration of the verbal and spatial tasks was counterbalanced across participants. Within the verbal and spatial tasks, the 1-load condition always preceded the 3-load condition so that the more difficult version of the task followed the easier version. The letter stimuli for the response stage during the verbal tasks could occur in the same location as the letters for the encoding stage (the task was only to remember the identity of the letters), and, alternatively, the identity of the letters during the spatial tasks could be identical to those in the encoding stage (the task was only to remember the location). Participants were instructed that for a correct match, all of the stimuli had to be the same letter identity (verbal), or in the same location (spatial) to be a match. When the response was a non-match, for the spatial 3-load task, the locations did not match for at least two of the three letters (one of the three letters could have a matched location with that of the encoding stage), and for the verbal 3-load task, the identity of at least two of the three letters did not match.

4.3. Electrophysiological recording and processing

All participants were tested in the Department of Neurology's Division of Cognitive and Behavioral Neurosciences Laboratories. Participants were seated on a reclining chair in an electrically shielded sound-attenuated chamber. Gold plated electrodes were placed at 16 scalp sites (F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, Oz) according to the 10–20 International System of Electrode Placement (Jasper, 1958), with linked ears as the reference and a forehead ground. Vertical and horizontal eye movements were monitored from bipolar electrodes at supra and infra-orbital sites of the left eye and the outer canthi of both eyes, respectively. Impedances were kept below 10 K Ω throughout the experiment.

The continuous EEG data were filtered during acquisition with a bandpass of 0.1 to 100 Hz using Grass 7P511 amplifiers, digitized at a sampling rate of 250 Hz, and stored on the NeuroScan system. During post-collection processing, the EEG was segmented into 1600 ms blocks, and digitally filtered with a 0.3 to 25 Hz bandpass at 24 dB octave roll off. Trials that exceeded $\pm 100 \mu\text{V}$ for horizontal eye movements were rejected. Trials contaminated by excessive artifact in the EEG channels were also rejected based on EEG exceeding $\pm 200 \mu\text{V}$ in any channel. Vertical eye movements from the filtered EEG were corrected with an eye movement correction algorithm (Semlitsch et al., 1986). Also, data from trials in which the participant responded incorrectly were discarded. ERPs were averaged separately for the encoding, maintenance, response match, and response non-match stimuli for each task (verbal and spatial) and each load condition (1- and 3-load). The 300 ms pre-stimulus recording prior to each stimulus type (e.g., encoding, maintenance) was used for baseline correction of the ERPs obtained for that stimulus type. Behavioral response data (RT, hits, omission, and commission errors) were collected for both tasks. As noted, the RT was recorded only from the fastest of the two thumb presses to each response. Participants were required to respond with both thumbs to eliminate a possible lateralized bias that may affect the ERPs.

In the present study, only data for the encoding and maintenance stages were examined to test the hypotheses related to these stages of working memory. Fig. 6 (a–d) presents the ERP grand averages for the 1- and 3-load verbal and spatial tasks during encoding and maintenance. The P3 component was identified as the maximum positive deflection that followed the P2 component, and occurred within a 250–550 ms post stimulus window based on the grand averages of verbal and spatial WM tasks (see Table 2 for P3 latency means and standard deviations).

4.4. Statistical analyses

Reaction times to the correct targets were analyzed using within subjects repeated measures Analyses of Variance (ANOVA) separately for verbal and spatial WM tasks. Anterior–posterior and lateralized P3 amplitude values were analyzed using within subjects repeated measures ANOVAs. Greenhouse–Geisser corrections for the degrees of freedom were used and the corrected probability values are reported. Analyses were performed with SPSS version 14.1.

Acknowledgments

This study was funded in part by NIH Grant #5R01NS49111.

REFERENCES

- American Psychological Association. Ethical principles of psychologist and code of conduct. *Am. Psychol* 1992;47:1597–1611.
- Baddeley AD. Working memory and language: an overview. *J. Communicative Disorders* 2003;36:189–208.
- Baddeley, AD.; Hitch, GJ. Working memory. In: Bower, GH., editor. *The Psychology of Learning and Motivation*. Vol. vol. 8. New York: Academic Publisher; 1974. p. 47-89.
- Baldo JV, Dronkers N. The role of inferior parietal and inferior frontal cortex in working memory. *Neuropsychology* 2006;20:529–538. [PubMed: 16938015]
- Bekker EM, Kenemans JL, Verbaten MN. Electrophysiological correlates of attention, inhibition, sensitivity and bias in a continuous performance task. *Clin. Neurophysiol* 2004;115:2001–2013. [PubMed: 15294202]
- Bor D, Duncan J, Wiseman RJ, Owen AM. Encoding strategies dissociate prefrontal activity from working memory demand. *Neuron* 2003;37:361–367. [PubMed: 12546829]
- Briggs GG, Nebes RD. Patterns of hand preference in a student population. *Cortex* 1975;11:230–238. [PubMed: 1204363]
- Courtney SM. Attention and cognitive control as emergent properties of information representation in working memory. *Cogn. Affec. Behav. Neurosci* 2004;4:501–516.
- Courtney SM, Petit L, Maisog J, Ungerleider LG, Haxby JV. An area specialized for working memory in human frontal cortex. *Science* 1998;279:1347–1348. [PubMed: 9478894]
- Curtis CE. Prefrontal and parietal contribution to spatial working memory. *NeuroImage* 2006;139:173–180.
- Curtis CE, D’Esposito M. Persistent activity in the prefrontal cortex during working memory. *Trends Cogn. Sci* 2003;7:415–423. [PubMed: 12963473]
- de Haan M, Thomas KM. Applications of ERP and fMRI techniques to developmental science. *Dev. Sci* 2002;5:335–343.
- D’Esposito M, Postle BR, Ballard D, Lease J. Maintenance versus manipulation of information held in working memory: an event-related fMRI study. *Brain Cogn* 1999;41:66–86. [PubMed: 10536086]
- De Lillo C. Imposing structure on a Corsi-type task: evidence for hierarchical organization based on spatial proximity in serial-spatial memory. *Brain Cogn* 2004;55:417–426.
- Gevens A, Smith ME, Le J, Leong H, Bennet J, Martin N, et al. High resolution evoked potential imaging of the cortical dynamics of human working memory. *Electroencephalography and Clin. Neurophysiol* 1996;98:327–348.
- Habeck C, Rakitin BC, Moeller J, Scarmeas N, Zarahn E, Brown T, Stern Y. An event-related fMRI study of the neural networks underlying the encoding, maintenance, and retrieval phase in a delayed-match-to-sample task. *Cogn. Brain Res* 2005;23:207–220.
- Halgren E, Boujon C, Clarke J, Wang C, Chauvel P. Rapid distributed fronto-parieto-occipital processing stages during working memory in humans. *Cereb. Cortex* 2002;12:710–728. [PubMed: 12050083]

- Hoddes E, Dement W, Zarcone V. The development and use of the Stanford Sleepiness Scale (SSS). *Psychophysiology* 1972;9:150–152.
- Honey GD, Bullmore ET, Sharma T. Prolonged reaction time to a verbal working memory task predicts increased power of posterior parietal cortical activation. *NeuroImage* 2000;12:495–503. [PubMed: 11034857]
- Jasper HH. The ten twenty electrode system of the International Federation. *Electroencephalogr. Clin. Neurophysiol* 1958;10:371–375.
- Johnson MK, Raye CL, Mitchell KJ, Greene EJ, Anderson AW. fMRI evidence for an organization of prefrontal cortex by both type of process and type of information. *Cereb. Cortex* 2003;13:265–273. [PubMed: 12571116]
- Jonides J, Schumacher EH, Smith EE, Koeppel RA, Awh E, Reuter-Lorenz PA, et al. The role of parietal cortex in verbal working memory. *J. Neurosci* 1998;18:5026–5034. [PubMed: 9634568]
- Jonides J, Lacey SC, Nee DE. Process of working memory in mind and brain. *Curr. Dir. Psychol. Sci* 2005;14:2–5.
- Kiss I, Watter S, Heisz JJ, Shedden JM. Control processes in verbal working memory: an event-related potential study. *Brain Res* 2007;1172:67–81. [PubMed: 17803980]
- Kok A. On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology* 2001;38:557–577. [PubMed: 11352145]
- Linden DEJ, Bittner RA, Muckli L, Waltz JA, Kriegeskorte N, Goebel R, et al. Cortical capacity constraints for visual working memory: dissociation of fMRI load effects in a fronto-parietal network. *NeuroImage* 2003;20:1518–1530. [PubMed: 14642464]
- Löw A, Rockstroth B, Cohen R, Hauk O, Berg P, Maier W. Determining working memory from ERP topography. *Brain Topogr* 1999;12:39–47. [PubMed: 10582564]
- Luu P, Tucker DM, Stripling RR. Neural mechanisms for learning actions in context. *Brain Res* 2007;1179:89–105. [PubMed: 17936726]
- McCollough AW, Mackizawa G, Vogel EK. Electrophysiological measures of maintaining representations in visual working memory. *Cortex* 2007;43:77–94. [PubMed: 17334209]
- McEnvoy LK, Smith ME, Gevins A. Dynamic cortical networks of verbal and spatial working memory: effects of memory load and task practice. *Cereb. Cortex* 1998;8:563–574. [PubMed: 9823478]
- Na DG, Ryu JW, Byun HS, Choi DS, Lee EJ, Chung WI, et al. Functional MR imaging of working memory in the human brain. *Korean J. Radiol* 2000;1:19–24. [PubMed: 11752924]
- Nystrom LE, Braver TS, Sabb FW, Delgado MR, Noll DC, Cohen JD. Working memory for letters, shapes, and locations: fMRI evidence against stimulus-based regional organization in human prefrontal cortex. *NeuroImage* 2000;11:424–446. [PubMed: 10806029]
- Owen AM, Stern CE, Looks RB, Tracey I, Rosen B, Petrides M. Functional organization of spatial and non-spatial working memory processing within the human lateral frontal cortex. *Proc. Natl. Acad. Sci. U. S. A* 1998;95:7721–7726. [PubMed: 9636217]
- Polich J, Comerchero MD. P3a from visual stimuli: typicality, task, and topography. *Brain Topography* 2003;15:141–152. [PubMed: 12705810]
- Postle BR. Working memory as an emergent property of the mind and brain. *Neuroscience* 2006;139:23–38. [PubMed: 16324795]
- Postle BR, Stern CE, Rosen BR, Corkin S. An fMRI investigation of cortical contributions to spatial and nonspatial visual working memory. *NeuroImage* 2000;11:409–423. [PubMed: 10806028]
- Prabhakaran V, Narayanan K, Zhao Z, Gabrieli JDE. Integration of diverse information in working memory within the frontal lobe. *Nat. Neurosci* 2000;3:85–90. [PubMed: 10607400]
- Ravizza SM, Delgado MR, Chein JM, Becker JT, Fiez JA. Functional Dissociations within the inferior parietal cortex in verbal working memory. *NeuroImage* 2004;22:562–573. [PubMed: 15193584]
- Ryma B, D'Esposito M. The roles of prefrontal brain regions in components of working memory: effects of memory load and individual differences. *Proc. Natl. Acad. Sci. U. S. A* 1999;96:6558–6563. [PubMed: 10339627]

- Rympa B, Prabhakaran V, Desmond JE, Glover GH, Gabrieli JDE. Load-dependent roles of frontal brain regions in the maintenance of working memory. *NeuroImage* 1999;9:216–226. [PubMed: 9927550]
- Rympa B, Berger JS, D'Esposito M. The influence of working-memory demand and subject performance on prefrontal cortical activity. *J. Cogn. Neurosc* 2002;14:721–731.
- Sala JB, Courtney SM. Binding of what and where during working memory maintenance. *Cortex* 2007;43:5–21. [PubMed: 17334204]
- Sala JB, Rama P, Courtney SM. Functional topography of a distributed neural system for spatial and nonspatial information maintenance in working memory. *Neuropsychologia* 2003;41:341–356. [PubMed: 12457759]
- Samthein J, Petsche H, Rappelsberger P, Shaw GL, von Stein A. Synchronization between prefrontal and posterior association cortex during human working memory. *Proc. Natl. Acad. Sci. U. S. A* 1998;95:7092–7096. [PubMed: 9618544]
- Sauseng P, Klimesch W, Schabus M, Doppelmayr M. Fronto-parietal coherence in theta and upper alpha reflect central executive functions of working memory. *Int. J. Psychophysiol* 2005;57:97–103. [PubMed: 15967528]
- Schack B, Klimesch W, Sauseng P. Phase synchronization between theta and upper alpha oscillations in a working memory task. *Int. J. Psychophysiol* 2005;57:105–115. [PubMed: 15949859]
- Semlitsch HV, Anderer P, Schuster P, Presslich O. A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology* 1986;23:695–703. [PubMed: 3823345]
- Shah, P.; Miyake, A. Models of working memory. In: Miyake, A.; Shah, P., editors. *Models of Working Memory: Mechanisms of Active Maintenance and Executive Control*. Cambridge: Cambridge University Press; 1999. p. 1-27.
- Smith EE, Jonides J. Working memory: a view from neuroimaging. *Cogn. Psychol* 1997;33:5–42. [PubMed: 9212720]
- Smith EE, Jonides J. Neuroimaging analyses of human working memory. *Proc. Natl. Acad. Sci. U. S. A* 1998;95:12061–12068. [PubMed: 9751790]
- Smith EE, Jonides J, Koeppel RA. Dissociating verbal and spatial working memory using PET. *Cereb. Cortex* 1996;6:11–20. [PubMed: 8670634]
- Talsma D, Wijers AA, Klaver P, Mulder G. Working memory processes show different degrees of lateralization: evidence from event-related potentials. *Psychophysiology* 2001;38:425–439. [PubMed: 11352131]
- Todd JJ, Marois R. Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature* 2004;428:751–754. [PubMed: 15085133]
- Todd JJ, Fougner D, Marois R. Visual short-term memory load suppresses temporo-parietal junction activity and induces inattention blindness. *Psychol. Sci* 2005;16:965–972. [PubMed: 16313661]
- Tomasi D, Chang L, Caparelli EC, Ernst T. Different activation patterns for working memory load and visual attention load. *Brain Res* 2007;1137:158–165. [PubMed: 17169343]
- Wagner AD. Working memory contributions to human learning and remembering. *Neuron* 1999;22:19–22. [PubMed: 10027285]
- Woodman GF, Vogel EK. Fractionating working memory: consolidation and maintenance are independent processes. *Psychol. Sci* 2005;16:106–113. [PubMed: 15686576]
- Woodward TS, Cairo TA, Ruff CC, Takane Y, Hunter MA, Ngan ETC. Functional connectivity reveals load dependent neural systems underlying encoding and maintenance in verbal working memory. *Neuroscience* 2006;139:317–325. [PubMed: 16324799]
- Zurowski B, Gostomzyk J, Gron G, Weller R, Schirrmeyer H, Neumeier B, et al. Dissociating a common working memory network from different neural substrates of phonological and spatial stimulus processing. *NeuroImage* 2002;15:45–57. [PubMed: 11771973]

Fig. 1.
Information Type (verbal, spatial) $\times$ Load (1, 3) interaction for RT.

Fig. 2.

Anterior-posterior scalp distribution of P3 amplitude for the left, midline, and right locations. Topographical distributions were analyzed separately for each location. P3 amplitude is represented for both the 1- and 3-load conditions during the encoding and maintenance stages of WM.

Information Type X Stage

Fig. 3.
The significant Information Type (verbal, spatial) × Stage interaction (collapsed across location, site, and load).

Fig. 4.

Comparison of the anterior-posterior scalp distribution of P3 amplitude to the cue versus the maintenance stimuli at the midline location for the 1- and 3-load conditions separately.

Fig. 5.

Schematic representations of the spatial 1-load and spatial 3-load WM tasks. The response is a correct match for the 1-load and the 3-load (all three locations match the encoding stage). Stimulus duration is 400 ms and ISI (offset to onset) is 1200 ms. The verbal 1- and 3-load stimuli were the same as the spatial stimuli, but the instructions were to match the letter identity rather than the location. Presentation of non-task-related (filler) stimuli occurred randomly following the response stage 17 times during each task.

Fig. 6. Grand averages of the ERP waveforms recorded for encoding and maintenance during (a) verbal 1-load (b) verbal 3-load (c) spatial 1-load and (d) spatial 3-load conditions.

Table 1

Means and (standard deviations) of performance measures (reaction time in ms, total omission and total commission errors) for verbal and spatial WM tasks

Performance variables	Verbal		Spatial	
	1-load	3-load	1-load	3-load
Reaction time	445.7 (103.5)	569.6 (125.2)	425.9 (120.2)	438.2 (123.0)
Omission errors	2.12 (1.76)	3.76 (3.17)	2.41 (2.37)	2.12 (3.18)
Commission errors	0.71 (0.77)	2.35 (2.02)	2.18 (2.65)	2.18 (1.38)

Table 2

P3 latency means and standard deviations at each electrode site for encoding and maintenance stages during I verbal and spatial tasks

	Verbal WM				Spatial WM			
	Encoding		Maintenance		Encoding		Maintenance	
	1-load	3-load	1-load	3-load	1-load	3-load	1-load	3-load
Fz	332.55 (36.61)	344.61 (52.94)	340.86 (36.41)	327.23 (41.10)	330.59 (42.89)	331.59 (57.79)	343.55 (49.02)	325.65 (39.34)
Cz	337.61 (30.25)	350.45 (55.31)	343.46 (33.88)	333.19 (45.91)	333.77 (45.85)	331.83 (57.69)	331.81 (46.10)	329.82 (42.04)
Pz	339.69 (34.68)	336.84 (43.20)	333.18 (29.93)	329.56 (35.35)	343.57 (50.50)	328.25 (48.66)	344.03 (55.63)	337.19 (44.53)
F3	332.59 (37.77)	337.88 (49.44)	340.64 (39.49)	332.58 (43.65)	325.27 (33.08)	325.58 (50.02)	327.93 (40.70)	331.14 (50.42)
C3	333.94 (32.26)	340.39 (57.66)	351.10 (30.18)	326.89 (47.54)	327.23 (33.22)	326.85 (51.98)	328.73 (36.00)	328.21 (46.96)
P3	333.38 (34.86)	340.00 (40.63)	346.43 (36.93)	329.71 (39.39)	344.01 (53.47)	323.58 (35.51)	339.79 (35.41)	333.71 (47.28)
F4	335.83 (37.13)	340.63 (48.52)	344.44 (37.21)	322.47 (37.81)	321.71 (29.58)	325.93 (54.73)	322.57 (39.21)	329.73 (47.44)
C4	347.25 (48.07)	344.34 (46.07)	342.81 (32.16)	328.94 (41.33)	331.24 (45.21)	322.31 (49.87)	337.78 (36.81)	332.79 (47.17)
P4	341.89 (30.63)	334.31 (34.26)	351.32 (24.93)	324.51 (33.34)	337.54 (52.11)	332.41 (40.94)	337.98 (40.39)	342.14 (47.61)