Electrophysiological Correlates of Working Memory across Modalities

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RUNNING HEAD: WORKING MEMORY ACROSS MODALITIES
Abstract

Using Baddeley’s (1982) working memory model, this study examined working memory across modalities. Event-related potentials (ERPs) were recorded during two tasks replicated in auditory and visual modalities. Tasks tapped sustained attention and working memory using variations of the classic n-back task. Analyses focused on the P300 as it is theorized to be sensory nonspecific. Results show differences in initial sensory ERP components reflecting the modality tested. P300 activity, maximal at PZ, with variations in amplitude as a function of task were found. These findings are discussed in relation to the central executive system in working memory.

Descriptors: working memory, attention, central executive, event related potentials, cross-modality
Electrophysiological Correlates of Working Memory across Modalities

Working memory encompasses the processes involved in the control, manipulation, and active maintenance of task relevant information (Miyake & Shah, 1999). Baddeley (1982) proposed one of the most prominent models of working memory in the current psychological literature. In this model working memory consists of a central executive system that controls modality specific subsystems, including an auditory loop and visuo-spatial sketchpad, that allow for the holding and processing of information. The phonological loop is a speech-based storage system in which information can be rehearsed (subvocally). In contrast, the visuospatial sketchpad retains visual and spatial information. These systems interact and are controlled by a central executive system. The central executive system is driven by attentional processes that direct attentional focus towards the subsystem necessary for the working memory task being performed. It is based on Norman and Shallice’s (1986) supervisory attention system that functions during tasks that require conscious control, or the selection and coordination of, information processing. Unlike the sensory subsystems, Baddeley suggests that the central executive is independent of the modality of the information being processed (Baddeley & Logie, 1999). The goal of this study is to increase our understanding of working memory by improving upon earlier studies in three ways by; a) using methods with higher temporal resolution, b) studying working memory across modalities, and c) using tasks that are non-semantic in nature.

Working memory is theorized to have its neural correlates in various areas of the brain; the sensory system involved, as well as a network of prefrontal, frontal, parietal, and medial frontal cortices (e.g. Bunge, Klingberg, Jacobsen, & Gabrieli, 2000; D’Esposito, Detre, Alsp, Shin, Atlas, & Grossman, 1995; Fiez, Raife, Balota, Schwarz, Raichle, & Petersen, 1996; Halgren, Boujon, Wang, & Chauvel, 2002; Kiss, Pazderka-Robinson, & Floden, 2001; Smith, Jonides, Marschuetz, & Koepper, 1998; Swartz, Halgren, Fuster, Simpkins, & Mandelkern, 1995; Ungerleider, Courtney, & Haxby, 1998). While there is evidence
suggesting that the sensory subsystems function within sensory cortical association areas (Fiez et al., 1996; Halgren et al., 2002; Swartz et al., 1995; Smith et al., 1998; Ungerleider et al., 1998), the neural basis of the central executive remains less clear. Recent MRI studies have attempted to disentangle the neural structures involved in attention from those involved in data processing systems (Posner & Peterson, 1989; Posner & Raichle, 1994). However, the attention and processing subsystems are highly interconnected and thus localizing a “central executive” has remained elusive (D’Esposito, Detre, Alsop, Shin, Atlas, & Grossman, 1995). One reason for this may be the poor temporal resolution of MRI techniques that focus on the location of activation rather than the chronometry of mental events. To address this concern, event related potential (ERPs) were used in this study to examine the on-line functioning of working memory. Previous ERP research of working memory suggests that activation of sensory areas associated with initial perceptual processing occurs in the first 130 milliseconds. Early sensory processing is often associated with sensory ERP components such as the N100 and P200 (Rugg and Coles, 1995). Following initial perceptual processing, activation of sensory areas related to later processing may appear up to 800ms after the presentation of an input stimulus (Halgren et al., 2002). Later activation of sensory areas has been associated with functioning of the visuospatial sketchpad and auditory loop. However, it has been difficult to demonstrate activation of one of these subsystems without the other (Halgren et al., 2002; Gevins et al., 1996; Owen, 1997; Ungerleider et al., 1998). In addition, activity associated with calculations and updating of working memory have been postulated to occur anywhere from 300 to 600 milliseconds after stimulus onset (e.g. Halgren et al., 2002; Kiss, Pazderka-Robinson, & Floden, 2001; Kiss, Pisio, Francois, & Schopflocher, 1998; McEvoy, Pelloughoud, Smith, & Gevins, 2001; McEvoy, Smith, & Gevins, 1998; Talsma, Wijers, Klaver, & Mulder, 2001). Thus, dissociating later sensory processing from sensory non-specific updating of working memory has been difficult. The primary component typically associated with later processing in working memory has been the P300. The P300 is considered an index of evaluation
processes rather than the selection, preparation, and execution of motor responses (e.g. Magliero, Bashore, Coles, & Donchin, 1984; Pelosi & Blumhardt, 1999) and has been used in a multitude of studies examining working memory function (e.g. McEvoy, Smith, & Gevins, 1998; Talsma, Wijers, Klaver, & Mulder, 2001; van Laar, Volkerts, Verbaten, Trooster, Megen, & Kenemans, 2002). Additionally, studies suggest that amplitude of the P300 decreases as a function of working memory load (Houlihan, Stelmack, & Campbell, 1998). Thus, this study will use the P300 to examine the on-line functioning of working memory.

In addition to using techniques with better temporal resolution, a second way in which studies have sought to clarify functioning of working memory is by using the central executive’s lack of modal sensitivity in contrast to sensory specific subsystems (e.g. D’Esposito, Detre, Alsop, Shin, Atlas, & Grossman, 1995; Kiss et al., 2001). For example, Kiss et al. (2001) used working memory tasks involving memory for digits presented visually or auditorily. Results of this study suggest that during updating, a positive potential can be found over the parietal sites (i.e. PZ) later in processing. The latency of the positive component varied by modality; the visual stimuli at approximately 555 ms and the auditory stimuli at approximately 590 ms, however, the topography remained consistent across modalities. Using tasks cross-modally in this study will help to clarify activity related to sensory subsystems in relation to non-sensory specific working memory processes.

One potential concern with previous studies of working memory across modalities is that the tasks have involved semantic information (e.g. D’Esposito, Detre, Alsop, Shin, Atlas, & Grossman, 1995; Kiss et al., 2001). Previous studies have shown that semantic processing affects eletrophysiological responses (e.g. Monetta, Tremblay, Joanette, 2003). Using semantically based stimuli is problematic as it creates a potential confound. Specifically, it is unclear if the positive potentials found in this and other similar studies are a result of the updating of working memory perse or the interaction of working memory and semantic processing. Thus, this study used non-semantic auditory and visual stimuli to study processing during
working memory tasks. Studies examining modality differences in relation to the P300 using non-semantic stimuli suggest that while amplitude and latency may be affected by modality, topography is not (Dujardin, Derambure, Bourriez, Jacquesson, & Guieu, 1993; Sangal & Sangal, 1996; Snyder, Hillyard, & Galambos, 1980; Tekok-Kilic, Shucard, & Shucard, 2001). For example, Tekok-Kilic, Shucard, and Shucard (2001), found larger amplitude responses for a visual Go/No Go task than for an auditory one. In addition to differences in amplitude, latencies of the P300 for visual stimuli were longer. Based on these findings along with those of studies of working memory using semantically based tasks it is hypothesized that while both amplitude and latency differences will be found as a function of modality, no differences will be found in topography.

This study used four comparable tasks to elucidate processes involved in working memory. Within each modality (auditory and visual) two variations on the N-back task were utilized. The first task, a 0-back task, tapped sustained attention and arousal. This was done so that it could be used as a comparison to dissociate aspects of attention unrelated to working memory with those involved in working memory. A second task tapped working memory using a 2-back task that requires the rehearsal of information over time. While the N-back task has been used to explore topography changes in the P300 in relation to task familiarity and complexity (Segalowitz, Wintink, & Cudmore, 2001 and Winink, Segalowitz, & Cudmore, 2001), it has not been used in relation to the P300 to explore differences in working memory across modality.

There are several hypotheses motivating this study. First, while not the primary focus of this study, it is hypothesized that early sensory components (e.g. the N100 and P200) will differ along three dimensions – latency, amplitude, and topography - according to the modality in which the stimuli are presented. Second, later components, specifically the P300 will show differences in latency and amplitude as a function modality. Specifically, for visual tasks the P300 will show longer latencies and amplitudes. However, no
differences in the topography of the P300 are anticipated across modalities within the same task. Finally, there will be some differences in the topography of the P300 component between a baseline attention task and the working memory tasks with working memory tasks more centrally located and attention more parietal.

Method

Participants

Thirty-one participants were recruited from the undergraduate Introductory Psychology course or were graduate students or staff at the University of Minnesota. Data from 16 participants were excluded (1 for misunderstanding instructions on the 2-back task, 1 for being an age outlier (above the age of 50), 7 for technical difficulties with the equipment, and 7 for low performance on the tasks and/or excessive blink activity). Of the remaining 15 participants 9 were women and 6 were men with an average age of 22.6 (SD=4.2). All participants had normal or corrected to normal vision and hearing, were not currently on psychotropic medications, did not have a history of psychiatric problems, or a history of neurological trauma. Additionally, all participants were right handed. Participants were aware of the nature of the study, gave informed consent, and were debriefed as to the nature of the study again following participation. Participants received credit for class for their participation.

Stimulus Presentation

Visual stimuli were presented on a 38.1 cm computer monitor approximately 102 cm from the participant. Visual stimuli ranged in size from approximately 18.92 to 26.85 deg/visual angle for the 0-Back and 2-Back tasks. Auditory stimuli were presented though Sony MDR W08 headphones at approximately 70db. Each trial of visual tasks started with a blank screen (100ms) for baseline EEG recording followed by the presentation of a stimulus for 500ms. Following stimulus presentation participants were given 2000 ms to respond using a button box so that behavioral performance could be assessed. This was followed by an
inter-trial interval ranging from 50 to 200ms. EEGs were recorded continuously throughout each condition. The experiment was conducted in a room with normal ambient illumination.

Procedure

All participants were administered 6 conditions (only 4 of which are used in this study, the remaining 2 were also variants of the N-back task) divided into two sets of 3 (3 Auditory and 3 Visual). In each set, the 0-Back was presented first and the order of the other two tasks was counterbalanced across participants. The set order was also counterbalanced with half of the participants receiving the auditory task first and half the visual task. Each task was preceeded by a practice task of 10 trials and each experimental task consisted of 100 trials. Participants were instructed to keep muscle movements to a minimum (including eyeblinks). Both manual responses (using a button box) and ERPs were recorded.

Stimuli

The visual stimuli consisted of non-real objects called fribbles obtained from the Tarr lab website (http://www.cog.brown.edu/~tarr/). Ten different fribbles were used in the 0-Back and 2-Back (5 in each). Fribbles from different "families" were used to ensure objects could be easily distinguished from each other. Fribbles were presented in yellow on a blue background. The auditory stimuli consisted of 10 tones for the 0-Back and 2-Back (5 in each). Tones were produced with an electronic keyboard set to sound like a piano. Only notes within one octave of middle C were used and all were consonant (A,B,C,D,E,F or G). Notes were adjusted for length (500ms) and volume (approx. 65-75db) using Cubase software.

Tasks

0-Back. The 0-back task was based on the classic N-Back task. Participants were asked to remember a target stimulus (auditory or visual) and press a button each time that stimulus appeared. They were asked to press an alternate button every time any other stimulus was presented (see Figure 1). Five stimuli were used, one target and four non-targets. The target appeared 40% of the time, non-targets 60% of the time.
2-Back. For the 2-Back task, participants were asked to keep two stimuli in mind at all times. They were asked to respond to each stimulus by comparing the current stimulus to the one presented two previous to it (see Figure 1). They were asked to press one button if the current stimulus was the same as the one two before and a different button if they were different. Five different stimuli were used during this task. The target appeared 40% of the time, non-targets 60% of the time.

Electrophysiological Methods

Tin recording electrodes sewn into a close-fitting cloth cap were used to record ERP's (Electro-cap International). Participants were fitted with the correct size cap based on head circumference and the cap was held in place with a chin strap. Additional electrodes were placed on the mastoids (A1 and A2) for referencing purposes (affixed with EC2 cream and foam pads) and eye movements (EOG) were recorded using electrodes placed at the right supraorbital ridge and just below the right eye (affixed with eye collars). ERP's were recorded from 30 scalp sites using the modified 10/10 system. In addition to EOG and mastoids, recordings were taken from FZ, PZ, CZ, T3, T4, T5, T6, C3, C4, F3, F4, F7, F8, O1, O2, FC1, FC2, FC5, FC6, CP1, CP2, CP5, CP6, P3, P4, AF3, AF4, AF7, AF8, and ground. Electrode impedances were maintained below 10 KΩ. All scalp electrodes were edited for artifacts and referenced to the scalp electrode CZ and then re-referenced offline to linked mastoids. EEG data were acquired with a Grass Neuro Acquisition System® with Model 12A5 amplifiers. The gain was set to 50,000 for all scalp leads. The gain for EOG was set at 5,000. A bandpass filter was set to .1 and 30 Hz, and a 60 Hz notch filter was in place. The sampling rate was 200 Hertz (every 5 ms).

Data Processing and Reduction. Continuous EEG data for each subject were segmented into 2100ms windows (including 100ms for baseline correction) and edited by computer algorithm for artifacts using a regression algorithm (Gratton, Coles, & Donchin, 1983) included in ERPW, an ERP editing and averaging program developed for use in our laboratory. As data were segmented, data for trials with an incorrect
button response (misses and false alarms) were dropped and excluded from further analysis. After re-referencing the data to linked mastoids the data were segmented into 1500ms windows and cross-averaged. Data with excessive artifacts were rejected (a maximum of 3 bad channels was allowed for further processing). Artifacts included responses that exceeded the A-D unit values, exceeded +/- 100 microvolts, if EOG showed changes of greater than 100 microvolts within a 50ms window, if artifacts were detected in any of the 3 reference channels (A1, A2, or CZ), and if posttesting impedances were above 10KΩ. A blink correction algorithm (Miller et al., 1998) was used to correct for EOG influences. This algorithm compares deflections in the EOG with deflections in the EEG and computes a model of eye movement influences on EEG. This activity is then subtracted from the EEG. Behavioral response data collected for all conditions included reaction time, hits, misses, and false alarms.

EEG data were averaged separately for each task. Within each task data were averaged separately for the two responses acceptable in that task. The number of trials averaged was constrained such that there were an equal number of trials averaged for the two types of response acceptable for the task. Thus there were 40 possible cross-averages for each task. The P300 and earlier sensory components (N100 and P200) were determined using grand averages and a random sub-group of raw data of all four task types at all leads. Based on visual inspection of these grand averages the P300 was defined as the maximum positive deflection occurring between 270 and 600ms poststimulus. Amplitude was defined as the difference in microvolts between adjusted baseline (the average amplitude in the 100ms prior to stimulus presentation) and the point of maximum amplitude in the designated window. Latency was defined as the time from stimulus onset to the maximum amplitude of the chosen peak.

Data Analysis

Separate repeated measures Analysis of Variance (ANOVAs) were performed for raw P300 maximum amplitude and latency for two sets of leads. The first compared mid-line leads (FZ, CZ, and PZ)
as both visual inspection of grand means and previous research suggest that the P300 is maximal at central leads, particularly PZ. The second ANOVA compared activity during the P300 window in four quadrants (excluding central leads) averaging across 5 leads for each quadrant; frontal-left (F3, F7, AF3, FC1, and FC5), frontal-right (F4, F8, AF4, FC2, and FC6), parietal-left (T5, CP1, CP5, P3, and O1), and parietal-right (T6, CP2, CP6, P4, and O2). Greenhouse-Geisser epsilon (Gge) values (as described in Greenhouse & Geisser, 1959) were used to correct for degrees of freedom (df) in all analysis with more than 2 degrees of freedom (Picton et al., 2000). Statistics presented are Greenhouse-Geisser corrected degrees of freedom and F values. Factors included in analyses included modality (auditory or visual), task (0-back and 2-back), response (target or non-target), and lead or quadrant for physiological measures (e.g. FZ, CZ, PZ). All analyses were performed using SPSS 11.1 for windows.

Results

Behavioral Analysis

Behavioral data showed high levels of accuracy for all tasks (See Table 1). Due to high accuracy, error types were not analyzed. It was hypothesized that performance would be more accurate for the 0-back task in comparison with the 2-back task. To test this hypothesis a 2(mode)x2(task) repeated measures ANOVA was performed. As expected, there was a main effect of task, F(1,4)=58.12, p<.001. Performance was more accurate on the 0-back than on the 2-back task. There were no significant differences in accuracy across modalities. Reaction times were not analyzed as speed of response was not emphasized during instructions.

Physiological Analysis

As illustrated in Figures 2 and 3, visual inspection of grandmeans revealed three primary components, a centroparietal N100 (auditory tasks), occipital P200 (visual tasks), and a centroparietal P300. As only the P300 was seen across modalities it was the primary focus of analyses. The P300 component was
analyzed for peak amplitude and latency. Mode, task, response (i.e., target/non-target), and lead were used in 2x2x2x3 or 4 repeated measure ANOVAs for analyses.

**P300.** To test the hypotheses that the later P300 component would vary in topography as a function of task but not modality two 2(mode)x2(task)x2(response)x3(lead) Repeated Measures ANOVA were performed for central leads. Additionally, a second Repeated Measures ANOVA, 2(mode)x2(task)x2(response)x4(quadrant), was used to further examine potential topography differences.

**Maximum Amplitude of the P300 at central leads.** To test hypotheses that there would be differences in amplitude as a function of modality but not of topography at central leads, a 2(mode)x2(task)x2(response)x3(lead) ANOVAs was performed. The maximum P300 amplitude showed significant main effects of modality, task, response, and lead, F(1,14)=26.55, p<.001; F(1,14)=9.39, p=.008, F(1,14)=5.8, p=.030, and F(1.2,16.3)=79.18, p<.001. There were significant interactions between mode and task, mode and lead, and response and lead, F(1,14)=8.93,p=.010; F(1.4,20.0)=7.99,p=.002; and F(1.8,25.6)=3.77,p=.040.

It was hypothesized that differences would be found in amplitude between visual and auditory P300’s. As expected, P300 maximum amplitude was greater for visual as compared to auditory tasks. The interactions found between mode and task and mode and lead may be a function of a disproportionately large response on the visual 0-back (see Figure 2c). In addition to modality effects, there was an effect of task. As has been found in previous studies (Houlihan et al., 1998) amplitude was greatest for the visual 0-back and slightly smaller for the 2-back. However, the auditory 2-back had a larger amplitude than the auditory 0-back. Despite these differences as a function of task and modality, there was a main effect of response, with greater amplitude found for target as compared to non-target stimuli. The interaction between response and lead may be a reflection of larger responses to targets as compared to non-targets at PZ. Finally, it was hypothesized that the P300 would be maximal at PZ for the 0-back task and more centro-parietal for the 2-
back task. The main effect of lead confirmed an increase from FZ to PZ with a maximum amplitude at PZ. However, no differences in topography were found between the 0-back and 2-back tasks as the P300 was maximal at PZ for both types of tasks.

**Latency to Peak of the P300 at central leads.** To test hypotheses that there would be differences in latencies of the P300 as a function of modality, a 2(mode) x 3(task) x 2(response) x 3(lead) ANOVA was performed. The latency to peak of the P300 showed significant main effects of modality and task, F(1,14)=41.92, p<.001 and F(1,15)=12.49, p=.003. Additionally, there were significant interactions between mode and task and mode and lead F(1,14)=6.58, p=.022 and F(2,27.54)=5.16, p=.013.

It was hypothesized that differences in latency would be found between visual and auditory P300’s. As expected, the P300 latency was longer for visual as compared to auditory tasks. Additionally, there was a main effect of task. However, this latency difference may be a function of a disproportionately long latency for the visual 0-back condition (see Figure 2). This is also likely the source of the mode by task interaction. Finally, there was an interaction of mode and lead. This interaction stems from longer latencies for visual tasks particularly at PZ.

**Maximum amplitude of P300 at non-central leads.** To follow-up analyses at central leads a second ANOVA was performed on non-central leads. This was done to test hypotheses that there would be differences in amplitude as a function of task and modality, but no differences in topography (using quadrants that exclude central leads). A 2(mode) x 2(task) x 2(response) x 4(quadrant) ANOVAs was performed to test this hypothesis.

The maximum P300 amplitude showed significant main effects of modality, task, and quadrant, F(1,14)=17.18, p=.001; F(1,14)=5.41, p=.036, and F(1.6,22.6)=57.09, p<.001. There were significant interactions between mode and task, and response and quadrant, F(1,14)=7.66, p=.015 and F(1.8,25.6)=3.75, p=.041.
As hypothesized for the P300 at central leads, non-central leads also showed a main affect of modality and task. These effects reflect greater responses for visual as compared to auditory tasks and greater response for 0-back for the visual task and 2-back for the auditory task. These findings suggest that difficulty does not account for amplitude differences. As with central leads this difference is reflected in a significant interaction between mode and task. Additionally, a mode by lead interaction was found reflecting larger responses for visual stimuli in the two posterior quadrants. Finally, there was a main effect of quadrant stemming from greater responses at the two posterior quadrants.

**Maximum latency of P300 at non-central leads.** To follow-up analyses at central leads a second ANOVA was performed on non-central leads. This was done to test hypotheses that there would be differences in latency as a function of task and modality, but not an effect of topography (using quadrants that exclude central leads). A 2(mode) x2(task )x2(response) x4(quadrant) ANOVAs was performed to test this hypothesis.

The maximum P300 latency showed significant main effects of modality and task F(1,14)=19.51, p=.001 and F(1,14)=16.01, p=.001. There were significant interactions between mode and task, mode and quadrant, and a mode by task by response by quadrant interaction F(1,14)=18.26,p=.001; F(2.2,31.2)=7.97,p=.001 and F(2.4,34.2)=7.67, p=.001.

As with central leads, there was a main effect of modality and task showing longer latencies for visual as compared to auditory tasks and longer latencies for the 0-back tasks compared to the 2-back tasks. As with amplitude interactions, there were interactions between mode and task as a function of greater latencies to the visual 0-back task. There was also an interaction between mode and quadrant that reflects longer latencies for visual tasks particularly in the two posterior quadrants.

**Summary of the P300.** As expected there were differences in the P300 as a function of task and modality. As has been shown in previous studies (Tekok-Kilic, Shucard, & Shucard, 2001), the P300 was
greater in amplitude to visual as compared to auditory tasks. Additionally, the latency to peak was longer for visual as compared to auditory tasks. There were also differences in amplitude as a function of task. However, while differences in amplitude of the P300 were consistent with previous research for visual tasks (0-back greater than 2-back), this was not true for auditory tasks (Houlihan, Stelmack, & Campbell, 1998). Amplitude was greatest for the 2-Back task among the auditory tasks. Moreover, there were not differences in topography as a function of task, the P300 was maximal at PZ for all tasks. Follow-up quadrant analyses supported these findings and suggest that the topography of the P300 does not vary between attention and working memory tasks.

Discussion

The present study was designed to extend existing research on working memory by examining it in a cross-modal context using non-semantic tasks. By using cross-modal tasks this study maximized properties of working memory (as proposed by Baddeley, 1982) that would allow for the dissociation of sensory sub-systems from the central executive. Additionally, the use of non-semantic tasks reduces the potential confound of semantic processing altering the P300 observed during working memory.

Modality effects. It was hypothesized that modality would affect early sensory components, but have little affect on later components associated with working memory. As expected, there were differences in latency, amplitude, and topography in early sensory components. Specifically, an auditory N100 that was maximal at central leads was found in both auditory tasks. However, this N100 was not found in visual tasks suggesting that it is sensory specific. In addition to an auditory N100, a visual P200 was found at occipital leads. As with the N100, the P200 appears to be sensory specific, appearing only in visual leads. However, upon inspection of grandmeans, there does appear to be an earlier positive component (approximately 170ms) that is more fronto-central that appears in both auditory and visual tasks (see Figure 2). While in this
study it was difficult to determine if this was an early appearance of the later P200, future studies should investigate this possibility.

In contrast to early sensory components, the majority of studies suggest that the topography of the P300 is sensory nonspecific (Dujardin, Derambure, Bourriez, Jacquesson, & Guieu, 1993; Sangal & Sangal, 1996; Snyder, Hillyard, & Galambos, 1980). However, studies do suggest it is affected by task requirements (Tekok-Kilic, Shucard, & Shucard, 2001). Findings from this study suggest that while task requirements affect the overall latency and amplitude of the P300, topography is not affected for the attention and working memory tasks used in this study.

Johnson (1993) proposed that amplitude and latency provide information concerning the degree and timing of neural activation. Consistent with previous studies (e.g. Sangal & Sangal, 1996) the P300 found in this study was greater in amplitude for visual as compared to auditory tasks. While accuracy of performance does not suggest the visual tasks were more difficult (in fact the opposite is true), visual tasks appear to invoke greater neural responses. Moreover, amplitude of the P300 differed as a function of task and difficulty; highest for the visual 0-back and auditory 2-back. Thus, P300 amplitude in this study was influenced by two factors (mode and task) that worked in concert. In addition to amplitude differences, longer latencies found in this and other studies (e.g. Picton, Stuss Champagne, & Nelson, 1984), suggest differences in cortical transmission time for visual information as compared to auditory information prior to activation associated with the P300. As latency differences were also found as a function of task type, future studies should take both modality and task complexity into account when examining the P300.

**Task Effects.** Previous studies have shown differences in amplitude as a function of task demands. It was hypothesized that the topography of the P300 would be more fronto-central for the working memory task in relation to the attention task. This hypothesis was based on studies that suggest anterior cingulate activation during working memory tasks that have been correlated with ERP activity at more centroparietal
leads. However, while there were differences in both amplitude and latency as a function of task, there were no differences in topography. The P300 was maximal at PZ for tasks that tapped attention and working memory. While differences were not found in this study, the trade-off for getting high temporal resolution is lower spatial resolution. Thus, future studies should seek ways to improve spatial resolution using high-density recording systems or improve temporal resolution with methodologies such as fMRI that have good spatial resolution.

In summary, there were several important findings from this study. The primary goal of this study was to examine working memory using ERPs (a technique with high temporal resolution) cross-modally to better dissociate aspects of working memory associated with sensory processing from those of later processing associated with the central executive. In addition to modality differences in topography for early sensory processing (i.e. the N100 and P200), both amplitude and latency differences were found as a function of modality in the P300. However, these differences were influenced by the task requirements. The topography of the P300 was not affected by task or modality extending previous research that the P300 is modality nonspecific for tasks involving attention and working memory.

Additionally, the research presented here is important in that it extends previous research by using cross-modal tasks that do not rely on the processing of semantic information. Previous studies on working memory have used stimuli such as words or digits that require semantic processing in both modalities that could have contributed to similarities in the P300. As stimuli used in this study were non-semantic in nature it helps clarify the processes that contribute to the P300 observed during working memory tasks.

It is important to utilize models of cognition that can be connected to neurological substrates. This study provides further evidence that Baddeley’s model of working memory can be linked to neurological function as seen here using ERPs. However, the P300 is a complex component that is likely to be a composite of activity from multiple neural generators. Additionally, the P300 in this study was found in
both types of tasks suggesting cognitive processes that occur in tasks as simple as a 0-back that theoretically requires primarily sustained attention (i.e. vigilance) share neurological substrates with more complex functions such as working memory. Thus it is important to continue to find new ways of examining working memory that dissociate working memory from other associated processes.
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**Table 1.** Means (standard deviations) of behavioral responses. Accuracy is reported in % correct.

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<td>0-Back</td>
<td>97.13(2.2)</td>
</tr>
<tr>
<td>Altered 0-Back</td>
<td>96.19(2.8)</td>
</tr>
<tr>
<td>2-Back</td>
<td>85.94(7.1)</td>
</tr>
<tr>
<td><strong>Auditory</strong></td>
<td></td>
</tr>
<tr>
<td>0-Back</td>
<td>95.31(5.0)</td>
</tr>
<tr>
<td>Altered 0-Back</td>
<td>97.06(2.2)</td>
</tr>
<tr>
<td>2-Back</td>
<td>81.63 (10.3)</td>
</tr>
</tbody>
</table>
Figure Captions

**Figure 1.** Tasks. a) 0-Back task, b) 2-Back task.

**Figure 2.** Auditory vs. Visual P300 at central leads. ERP at FZ, CZ, and PZ for auditory and visual tasks collapsed across response (target/non-target). Figure shows both P300 and N100.

**Figure 3.** Auditory vs. Visual P300 at non-central leads. ERP at representative leads for each of four quadrants F3 (frontal-left), F4 (frontal-right), O1 (posterior-left), O2 (posterior-right). Figure shows P200.
a)

Non-Target

Target

Non-Target

Target

Time
b)

Non-Target

Non-Target

Non-Target

Target

Target