Event-Related Potential (ERP) Studies of Spatial Working Memory

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Abstract of the Dissertation

Event-Related Potential (ERP) Studies
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This dissertation aims to characterize the neural processes in association with the updating and storage of spatial information. Selective information processing has been suggested as the underlying mechanism for updating and selective maintenance of object information in working memory. It is unclear whether similar mechanism is involved in updating spatial information. Furthermore, it is unclear whether the neural representation of no longer relevant spatial information would show transient or sustained effects on working memory. Two event-related potentials (ERPs) experiments were conducted to examine (1) the neural processes involved in selecting relevant spatial locations from working memory and the subsequent effect on recognition, and (2) the timing at which relevant and no longer relevant spatial locations were separately represented and whether the post-updating neural activity was modulated by different amounts of relevant and no longer relevant information. Behavioral and neural data were collected from 54 participants in two experiments. Participants performed a variant of the delayed recognition paradigm, in which a memory selection cue was inserted during the retention interval to indicate memory updating. Results from Experiment 1 showed that the instruction cue modulated the neural activity of four prominent ERP components between 140-700 ms after cue onset. These components reflect processing of cue meaning, refocusing of relevant information, memory retrieval of relevant information, and content reorganization. Successful working memory updating was also found to modulate the behavioral and neural responses to recognition. Results from Experiment 2 showed separation of neural representation of relevant and no longer relevant information within the first 300 ms of the post-updating interval. Neural representation of relevant information showed strong and widespread sustained effects over the left frontal to parietal regions. Neural representation of no longer relevant information, in contrast, showed a weak sustained effect and was restricted to the left frontal region. The findings suggested that updating of spatial working memory involved several prominent neural processes, which began early in the cue period. Also, both relevant and no longer relevant information showed sustained effects on maintenance throughout the delay period.

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Abbreviations

CDA	contralateral delayed activity
EEG	electroencephalography
EOG	electrooculogram
ERP	event-related potential
fMRI	functional magnetic resonance imaging
NSW	negative slow wave
PET	positron emission tomography
PI	Proactive Interference

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1. General Introduction

Working memory refers to a system that supports temporary maintenance and manipulation of information required for completing complex cognitive tasks (Baddeley & Hitch, 1974). Spatial working memory is specifically for maintaining and manipulating information about the locations of objects. The working memory system involves various cognitive components or processes for storage, rehearsal, and executive control functions to subserve maintenance and manipulation (Baddeley, 1986; see review by Jonides et al., 2004). The "executive control" plays an important role in supporting manipulation of the working memory content (Baddeley, 1986). It has been conceptualized to involve three main functional components: shifting (shifting attentional focus between tasks, operations, or mental sets; Baddeley, 1992; Luria, 1966; Monsell, 1996), updating (monitoring and coding of incoming information for task relevant information, and actively adding new or replacing old information to fulfill the current task goals; Lehto, 1996; Morris & Jones, 1990), and inhibition (resisting external distraction and preventing interference from no longer relevant memories; Nee et al., 2012).

Neural substrates of spatial working memory

The delayed-response paradigm (e.g., delayed-match/non-match task, delayed-recognition task) has been widely used in studying working memory in electrophysiological and neuroimaging studies. In a typical delayed-response paradigm, subjects are required to remember and manipulate the information (e.g., color, location, shape, orientation, size, etc) of any sensory stimulus over a delay period after the stimulus disappears. Then, the subjects are asked to make simple judgment on whether the probe matches the target or not. Sustained neural activity observed during the delay period is considered as the neural substrate of working memory (e.g., electrophysiological studies: Chafee & Goldman-Rakic, 1998; Funahashi, Bruce, Goldman-Rakic, 1990, 1991; Fuster & Alexander, 1971; Goldman-Rakic, 1987; neuroimaging studies: Courtney, Petit, Maisog, Ungerleider, & Haxby, 1998; Leung, Gore, & Goldman-Rakic, 2002; Leung, Seelig, & Gore, 2004; Mecklinger & Pfeifer, 1996; Rolke, Heil, Hennighausen, Häussler, & Rösler, 2000).

The prefrontal cortex has been consistently implicated to play an important role in working memory by electrophysiological and neuroimaging studies (e.g., Courtney, 2004;

Friedman & Miyake, 2004; Fuster, 2001; Goldman-Rakic, 1987, 1995; 1996; Leung et al., 2002; Nee et al., 2007; Smith & Jonides, 1999). According to the materials-dependent hypothesis, spatial working memory showed specific neural substrates (e.g., D'Esposito et al., 1998; Goldman-Rakic, 1987; Kelley et al., 1998). Goldman-Rakic and colleagues conducted a series of electrophysiological studies demonstrating that the dorsolateral prefrontal cortex (DLPFC) was involved in the processing of spatial working memory, while the ventrolateral (VLPFC) was involved in the processing of non-spatial and object working memory (e.g., Fuster, 2001; Wilson, O'Scalaidhe, & Goldman-Rakic, 1993; see reviews by Goldman-Rakic, 1995; Levy & Goldman-Rakic, 2000).

Neuroimaging studies on human subjects also provided evidence of separate neural substrates for spatial and non-spatial working memory (e.g., Courtney, Ungerleider, Keil, & Haxby, 1996; Cohen et al., 1997; Ungerleider & Mishkin, 1982). Courtney and colleagues (1996) using positron emission tomography (PET) demonstrated that the superior and inferior parietal cortices and the superior frontal sulcus were involved in spatial working memory, while the inferior frontal cortex was involved in face working memory. Findings from functional resonance magnetic imaging (fMRI) studies also showed that the prefrontal cortex and the posterior association areas (e.g., parietal cortex, precuneus, superior parietal lobule, and inferior parietal lobule) were involved in working memory (e.g., Friedman & Miyake, 2004; Leung, et al., 2002, 2004; Passingham & Sakai, 2004; Smith & Jonides, 1999). In particular, the prefrontal cortex was involved in maintenance and manipulation of spatial and visual information, while the parietal cortex was involved in maintenance of spatial (e.g., Leung et al., 2002, 2004) and visual information (e.g., Passingham & Sakai, 2004; Todd & Marois, 2004). Within the prefrontal cortex, some findings suggested that the right lateral prefrontal cortex was more for processing spatial or non-verbal working memory, while the left lateral prefrontal cortex was more for processing non-spatial or verbal working memory (e.g., D'Esposito et al., 1998; Kelley et al., 1998).

In electroencephalography (EEG) studies, the sustained activity over the delay period is measured by the negative slow wave (NSW), which begins around 250 ms after stimulus onset and lasted till the end of the delay period over several seconds (Mecklinger & Pfeifer, 1996; Rolke et al., 2000). The maximum amplitude of the NSW shows differences in topographical distributions between spatial and non-spatial information. Maximum amplitude of the NSW for spatial information was observed over the parietal regions, while that of object or verbal information was observed over the frontal regions (e.g., Mecklinger & Pfeifer, 1996; Rolke et al., 2000; Ruchkin, Johnson, Grafman, Canoune, & Ritter, 1992).

Cognitive models

The working memory system is limited in capacity (see reviews by Baddeley, 1986; Cowan, 2001). The capacity of remembering locations of objects is about five (Jiang, Olson, Chun, 2000; Smyth & Scholey, 1992), and features of objects is about four (Cowan, 2001). Individual visual working memory capacity differs with an average of 1.5 to 6 items (Vogel & Awh, 2008; Vogel & Machizawa, 2004). To account for its limited capacity, two cognitive models (Cowan, 1995; Oberauer, 2002) described the working memory system as multi-components. Cowan (1995) distinguished the working memory system into two parts: the "activated part of long-term memory" and the "focus of attention." The "activated part of long-term memory" refers to the part of the system where information that is activated but not relevant to the current task goals is stored. Information stored in this part of the system cannot be manipulated unless the information is being selected and moved to the "focus of attention." This part of the system has no capacity limit. However, "links" to this information could be lost over time through decay or interference. Information that is relevant to the task at hand is stored in the "focus of attention," where manipulation can take place. This part of the system is assumed to have a capacity limit to about four items.

Some studies challenged the view that the "focus on attention" allows four items to be manipulated at the same time (e.g., Garavan, 1998; McElree & Dosher, 1989). Rather, these studies found a much smaller capacity (~1 item). Oberauer (2002) then re-interpreted Cowan's concept of "focus of attention" into two different functional states: the "region of direct access" and the "focus of attention." The "region of direct access" holds a limited number of chucks of information, which is readily accessible and available to be used in the ongoing cognitive tasks. Within the "region of direct access" is the "focus of attention," in which only one item is being selected for working memory manipulations in favor of the ongoing cognitive tasks (Oberauer, 2002).

Working memory updating

Working memory updating refers to the cognitive processes involved in monitoring and coding of incoming information for task relevant information, and actively adding new or replacing old information to fulfill the current task goals (Lehto, 1996; Morris & Jones, 1990). Owing to the limited capacity of the working memory system, this updating function becomes crucial to the efficient use of the capacity so as to ensure good working memory performance. Working memory updating has been considered as a key element of cognitive control, which provides reliable prediction of individual differences and fluid intelligence (Miyake et al., 2000). Therefore, it is important to understand the underlying cognitive and neural processes of working memory updating.

Cognitive processes of working memory updating

A recent study by Ecker and colleagues (2010) revealed that working memory updating involves three cognitive components: retrieval (select and use task relevant information that is no longer present physically), transformation (add new information to the original working memory content), and substitution (replace old with new information in working memory; Ecker, Lewandowsky, Oberauer, & Chee, 2010). In a series of behavioral experiments, Ecker and colleagues (2010) showed that the three components contributed to the updating performance. Further, the structural equation models showed that individual's working memory capacity could be used to predict working memory updating performance involving the retrieval and transformation components, but not the substitution component. This segregation suggested that the three updating components were partially independent from each other.

Neural processes of working memory updating

Working memory updating is usually investigated in the form of selective information processing (Lehto, 1996; Morries & Jones, 1990). Selective information processing has been used in terms of selective encoding and selective maintenance in previous studies. Selective attention has been used as a mechanism for selective encoding, in which subjects are pre-directed to encode certain items or locations before their physical appearance. Memory selection, on the other hand, has been used as a mechanism for selective maintenance, in which certain items or locations were selectively retrieved and rehearsed in memory.

By organizing findings from previous studies, three event-related potential (ERP) components are shown to be related to working memory updating. Shorty after the presentation of a cue (<200 ms from stimulus onset), early visual-related ERP components (the P1 and N1 components) were observed. The P1 component is a positive deflection of the ERP waveform, which appears around 70-150 ms after stimulus onset. The N1 component is a negative deflection that follows P1, and appears around 150-190 ms after stimulus onset (Hillyard & Anllo-Vento, 1998). The generators of the P1 and N1 components are localized in extrastriate visual cortex (Hillyard & Anllo-Vento, 1998). An fMRI study has shown that these visual-related signals spread from occipital region (V1/V2 and cuneus) to parietal region (inferior parietal lobe), and then to frontal region (frontal eye field and middle frontal gyrus) at approximately 60-107 ms after stimulus onset (Simpson et al., 2011). These components were suggested to reflect attention-related processing of visual stimuli (e.g., directing attention or selective amplification of neural activity to the presented stimuli; Hillyard, Vogel, & Luck, 1998; or rapid re-focusing of attention to task relevant information after the presentation of task irrelevant distractors; Fukuda & Vogel, 2009). In particular, the frontal distributed P1/N1 component has been shown to associate with processing of cue meaning (e.g., Markowitz, Shewcraft, Wong, & Pesaran, 2011; Simpson et al., 2011; Theeuwes, 2010). One study further showed that this early frontal distributed component was specific to orienting attention to internal, rather than external, mental representations of spatial information (Griffin & Nobre, 2003).

A cue-related P300 component was also observed at a later time window. This cue-related P300 component corresponds to the P3b component, which is a positive, broadly distributed component with a topographical distribution over the posterior-parietal region and peaks around 300-800 ms after stimulus onset (Donchin, Kramer, & Wickens, 1986). The amplitude of this component has been shown to relate to working memory updating (Donchin & Coles, 1988; Rugg & Coles, 1995). An attentional blink study showed that the P300 compoent was absent in response to targets that were not detected, and hence, no updating occurred (Luck & Hillyard, 2000). Also, the amplitude of the P300 component has been suggested to reflect the degree of re-organization or evaluation of memory representations (e.g., Donchin et al., 1986). An enhanced P300 component was elicited by stimuli that were of high rather than low relevance to the task (e.g., Johnson & Donchin, 1980; Pritchard, 1981; Squires, Donchin, Herning, & McCarthy, 1977; Sutton, Tueting, Zubin, & John, 1967), or by stimuli that were of high rather than low salience to the task (e.g., Johnson, 1988, Picton, 1992).

The amplitude of the P300 component is also related to the maintenance of information in working memory. More commonly and specifically, this maintenance-related P300 component is referred to the NSW. It has been postulated that the amplitude of NSW reflects the activity of the excitatory postsynaptic potentials at the apical dendrites in the upper cortical layers (Birbaumer, Elbert, Canavan, & Rockstroh, 1990). NSW begins around 250 ms after stimulus onset and sustains over several seconds (hence, this component is termed "slow wave"). Its amplitude has been suggested to reflect the memory load maintained in memory (e.g., Mecklinger & Pfeifer, 1996; Rolke, Heil, Hennighausen, Häussler, & Rösler, 2000), as well as the rehearsal process in working memory (e.g., Ruchkin, Canoune, Johnson, & Ritter, 1995; Ruchkin, Johnson, Canoune, & Ritter, 1990; Ruchkin et al., 1992). It also shows different topographical distributions for different types of stimulus. For example, the maximum NSW for spatial stimulus was observed at the parietal brain regions (e.g., Mecklinger & Pfeifer, 1996; Rolke et al., 2000), while the maximum NSW for verbal and object stimuli was observed over the frontal brain regions (e.g., Barrett & Rugg, 1989; Lang, Starr, Lang, Lindinger, & Deecke, 1992; Mecklinger & Pfeifer, 1996; Rolke et al., 2000). Given its characteristics and specific topographical distribution, the NSW could be used as an indicator for assessing whether the sustained neural activity is modulated by the amount of task relevant and/or irrelevant spatial information, particularly over the parietal brain regions.

An integrative view on working memory updating

According to a neuroscience-based theory proposed by Miller and Cohen (2001), the updating process involves a top-down bias of information processing between the prefrontal cortex and parietal cortex. The theory proposes that the neural activity of the prefrontal cortex represents cognitive processes about task goals and the means to achieve the goals. The function of the prefrontal cortex is to provide goal-directed biasing signals to other brain structures (e.g., posterior association cortex) to "guide the flow of activity along neural pathways that establish the proper mappings between inputs, internal states, and outputs needed to perform a given task" (Miller & Cohen, 2001, p.167).

This theory is supported by neuroimaging studies in demonstrating that the prefrontal cortex provides biasing signals to select or update task-relevant information and/or to filter out task-irrelevant information from accessing the working memory storage in the parietal cortex (Bunge, Hazeltine, Scanlon, Rosen, & Gabrieli, 2002; Deco & Rolls, 2005; Desimone & Duncan, 1995; Miller & Cohen, 2001). Neural activity at the dorsolateral prefrontal cortex has been associated with the manipulation processes of working memory, while the neural activity at the ventrolateral prefrontal cortex has been associated with the maintenance and rehearsal processes (D'Esposito et al., 1998; Owen et al., 1999; Petrides, 1994). However, some studies found partial dissociation in the pattern of frontal and parietal activations during task conditions requiring the selection of particular locations from memory in comparison to shifting from one selected location to another (Bledowski, Kaiser, & Rahm, 2010; Bledowski, Rahm, & Rowe, 2009). Similar neural processes have also been suggested to involve in updating and maintenance of locations (Leung, Oh, Ferri, & Yi, 2007).

The results of overlapping or partial dissociation between brain regions on different working memory processes might be due to the low temporal resolution of the fMRI technique. The working memory system is flexible, adaptive, and dynamic so as to keep the content current and most relevant to the task goal by allowing adding of new information and replacement of old by new information. These neural processes are measured at a millisecond timescale. Therefore, ERP would be an appropriate approach as it provides high temporal resolution.

Using ERP to examine the neural processes involved in updating and maintenance of spatial working memory

Selective information processing has been suggested as the underlying mechanism for updating and maintenance of task relevant information, (e.g., Griffin & Nobre, 2003; Kuo, Stokes, & Nobre, 2012; Leung et al., 2007). A focus of this dissertation is to understand the effect of updating on the working memory content. Therefore, we focused on examining selective information processing at the memory level (i.e., memory selection) rather than at the perceptual level (i.e., selective attention). The understanding of the neural processes involved in selective information processing of spatial information is unclear. Only one ERP study, so far, has directly compared, and suggested the involvement of similar neural processes for selective attention and memory selection (Griffin & Nobre, 2003). Yet, object information was used as the stimuli in this study (Griffin & Nobre, 2003). It is unclear whether spatial information would elicit similar neural processes for memory selection as in the previous study. Also, it is not clear what precisely does the sustained maintenance-related neural activity represent. Results from neuroimaging and electrophysiology studies were mixed, as some studies suggest a sustained representation of task relevant information (e.g., Rainer, Asaad, & Miller, 1998; Sakai & Passingham, 2003; Vogel, McCollough, & Machizawa, 2005) while some studies suggest a sustained representation of task irrelevant information as well (e.g., Hasegawa, Peterson, & Goldberg, 2004).

To elucidate the ambiguity of the literature, this dissertation used ERP to examine the underlying mechanism between memory selection and maintenance. Variants of a delayed-recognition paradigm were used in two experiments, in which an instruction cue was inserted during the delay period to indicate memory updating. The aim of Experiment 1 was to characterize the neural processes involved in selecting relevant spatial locations from working memory, and reveal the subsequent effect on recognition. The aim of Experiment 2 was to find out the timing at which different neural representations were observed for relevant and no longer relevant spatial locations in working memory and whether the post-updating neural activity was modulated by different amount of relevant and no longer relevant spatial locations. The effects of individual differences in working memory capacity and sex on the neural activity observed during these two experiments were also measured.

2. The neural processes during selective updating of spatial information and the updating effect on subsequent recognition behavior

2.1. Introduction

Selective information processing is one of the proposed mechanisms of working memory updating (Lehto, 1996; Morris & Jones, 1990). Previous studies showed that neural processes in response to selective information processing were similarly involved in updating and maintenance of object information (e.g., Griffin & Nobre, 2003; Kuo et al., 2012; see review by Lepsien & Nobre, 2006). Spatial cues (a combination of color and location) were used in these studies to indicate which color stimuli remained relevant for the later recognition test. These studies have also examined ERPs elicited by task cues that were presented before or after the stimulus display (e.g., Griffin & Nobre, 2003; Kuo et al., 2012; see review by Lepsien & Nobre, 2006). Task cues presented prior to stimulus display elicited ERPs in relation to selective encoding of color information, while task cues presented after stimulus display elicited ERPs in relation to selective maintenance of color information (Griffin & Nobre, 2003; see review by Lepsien & Nobre, 2006). Directing spatial attention has been suggested as the underlying mechanism for selective encoding and maintenance of visual working memory (see review by Lepsien & Nobre, 2006). However, it is unclear whether similar or different neural processes are involved in selecting the spatial locations of visual targets in working memory (i.e., making use of color information to select task relevant locations).

Awh and colleagues (1995, 1998, 2000) conducted a series of behavioral and neuroimaging studies to examine the behavioral performance and neural processes involved in selective attention (i.e., selective encoding) and selective rehearsal (i.e., selective maintenance) in working memory for locations. Their results showed that similar visual-related neural processes (e.g., the P1 and N1 components) were involved in selective attention and selective rehearsal to the cued spatial locations (Awh et al., 2000). Yet, the neural responses to probes presented at the memorized/attended locations were stronger than the neural responses to the non-memorized/non-attended locations (Awh et al., 2000). The spatial locations involved in Awh and colleagues' study (2000) were either task relevant or task irrelevant. Hence, it is unclear whether selecting task relevant spatial locations among other no longer relevant locations would involve similar neural processes as observed in Awh and colleagues' study (2000). To our knowledge, no studies have directly examined selective processing of task relevant among no longer relevant spatial content and how such operations might change neural activity during memory updating, maintenance and recognition.

Selective information processing has also shown an influence on working memory performance and the associated neural activity at the response stage. Previous studies demonstrated that providing an instructional cue relative to a non-instructional or neutral cue to the subjects would lead to a facilitation effect in improving their response accuracy and/or response time (e.g., Griffin & Nobre, 2003; Nobre, Griffin, & Rao, 2008). Previous ERP studies showed that the amplitude of the P300 component in response to the probe could reflect the load of memory search, in which an enhanced P300 component was associated with a lower load of memory search (e.g., Brookhuis et al., 1981; Gomer, Spicuzza, & O'Donnell, 1976; Kok, 1997; Kotchoubey, Jordan, Grözinger, Westphal, & Komhuber, 1996; Nobre et al., 2008; see review by Kok, 2001). A recent ERP study examined the effect of instructional cue versus neutral cues on the memory search-related ERP component (Nobre et al., 2008). Their results revealed topographical segregation in the memory search-related ERP components between trials with instructional cue and trials with neutral cue (Nobre et al., 2008). A positive, parietal distributed P300 component was observed in trials with instructional cue, while a negative, frontal distribution N300 (called $N3_{RS}$) was observed in trials with neutral cue (Nobre et al., 2008).

Previous behavioral studies have also shown that following the presentation of an instructional cue that indicates working memory updating, the no longer relevant information could linger on and influence memory retrieval at recognition, resulting with the proactive interference effect (PI effect; Brown, 1954; Underwood, 1957). The PI effect is indicated by lower accuracy and/or longer response time to the no longer relevant information in comparison to the information that was not in the original memory set. Various frontally distributed negative ERP components were suggested to reflect this PI effect. Those ERP components include the N2 component (Du et al., 2008, which was later suggested to reflect recency manipulation, c.f. Zhang, Wu, Kong, Weng, & Du, 2010), the N450 component (Tays, Dywan, Mathewson, & Segalowitz, 2008; Tays, Dywan, & Segalowitz, 2009), and a negative component observed around 500 ms after stimulus onset (Yi & Friedman, 2011). Hence, the behavioral results and ERP components could be used to indicate whether our task manipulation would affect the subsequent recognition.

In this study, we examined the neural correlates related to memory selection and its effect on the subsequent recognition using a visuospatial delayed-recognition task with a cue manipulation similar to the designs used in previous neuroimaging studies (Leung & Zhang, 2004; Yi et al., 2009). We used ERP in this study for its high temporal resolution to account for the neural processes associated with working memory updating. We compared and contrasted the ERPs in the memory selection condition (selective maintenance of 2 out of the 4 initially remembered dot locations) with the ERPs in the non-selection condition (continue maintenance of the initially remembered 2 or 4 dot locations). It was hypothesized that if the working memory content was modified and reduced as instructed by the updating cue, the ERPs observed in the "memory selection" condition would be similar to those of the "two-item non-selection" condition, and both would be different from the ERPs of the "four-item non-selection" condition. In contrast, if the working memory content was not modified and reduced, the resulting ERPs on the "memory selection" condition would be similar to the ERPs of the "four-item non-selection' condition, and both would be different from the "two-item non-selection" condition.

2.2. Methods

Participants

Twenty-four healthy undergraduate students (12 male and 12 female; mean age of 20.71) participated and received course credits for their participation. Individual datasets were screened for large movement artifacts and trials with EEG voltages exceeding +/- 75 µV at any channel. As a result, two datasets were excluded, and data from 22 subjects (12 male and 10 female; mean age of 20.73) were included in the final analysis. All subjects had no history of neurological disorder, psychiatric disorder and drug abuse according to self-report and had normal or corrected-to-normal vision. Written informed consent, reviewed and approved by the Stony Brook University Institutional Review Board, was obtained from each subject prior to participation.

Spatial Working Memory Task with a Selection/Non-selection Cue

Figure 1 shows the three task conditions. We used the delayed-recognition paradigm with an informative cue inserted during the delay period (adapted and modified from Leung & Zhang, 2004). For the memory selection (MS) condition, each trial began with a fixation period (0.3 s).

The fixation period was followed by a stimulus display (0.5 s) showing four dots (half in blue and half in orange). The four dots indicated the dot locations to be remembered as the initial memory set. After a 2-second delay, a cue in either blue or orange color was presented for 0.5 s to indicate that only the dots in the cued color from the original memory set remained relevant for the subsequent recognition test. Thus, the final memory set size was reduced to two dot locations. Following a delay of 2 s after cue onset, a probe was presented for 0.5 s for the subjects to make a recognition response. The inter-trial interval (ITI) was 1.5 s. Each trial was 7.3 s long. For the control or non-selection conditions (NS2 and NS4), either two or four dots (half in blue and half in orange) were displayed initially and a cue was presented to indicate that the whole original memory set remained relevant for the recognition test.

In response to the probe, subjects made button presses to indicate whether the probe matched one of the dot locations in the final memory set. There were three response conditions for the MS condition: (1) *match* (Yes), the probe matched one of the two cued dot locations; (2) *high familiarity non-match* (No-HF), the probe matched one of the two non-cued or to-be-ignored dot locations; and (3) *low familiarity non-match* (No-LF), the probe was in a new location, which was not in the initial memory set. For the NS2 and NS4 conditions, there were only “Yes” and “No-LF” probes. The chance of match and non-match probes was equal. Half of the non-match probes were “No-HF” probes and the other half were “No-LF” probes. To reduce the effect of trial history, the design ensured that the probe of the current trial did not appear in the preceding two trials. The combinations of the study and probe locations were selected psuedorandomly without repetition. The different types of cue and probe were also selected psuedorandomly and counterbalanced across runs.

A total of 330 trials (320 experimental trials and 10 catch trials) were divided into 10 runs. Each run has two blocks [17 trials in the first block (1 catch trial followed by 16 experimental trials) and 16 trials in the second block] separated by a resting break (10 s).

Estimation of individual differences in Spatial Working Memory Capacity

At the end of the main task, each participant performed the conventional spatial delayed recognition task. The task format is the same as the main task, except there was a blank delay period of 2 seconds long without any cue before each recognition test. We varied the number of dots (1 to 7) presented in the stimulus display. Five set sizes of 1, 4, 5, 6 and 7 were used for the first six subjects, while five set sizes of 1, 2, 4, 6, and 7 were used for the rest of the subjects. The combinations of the study and probe locations were selected psuedorandomly without repetition. Each subject performed a total of 80 trials, each 5.5 s long. The trials were separated into four blocks with a resting break (10 s) in between. Working memory capacity of each individual was estimated using a standard formula, $K = S * (H-F)$, where K is the capacity score, S is the set size, H is the hit rate, and F is the false alarm rate (Cowan, 2001; Pashler, 1998). The average *k*-score of each individual was calculated by averaging the *k*-scores estimated for set sizes 4, 6, and 7.

Visual Stimuli, apparatus and general procedures

Visual stimuli were presented against a white background (RGB: 255, 255, 255). A 6x6 grid in light gray color (RGB: 220, 220, 220) with a visual angle of 8° x 8° was presented on the screen throughout the whole experiment. Dots in the study display were presented in two different colors [blue (RGB: 50, 50, 255) and orange (RGB: 255, 155, 50)] in different cells, marking the to-be-remembered dot locations. Instruction cues were presented in the form of a square (1.33°x1.33°) at the center of the screen. MS cues were presented in blue or orange color, and the NS cues were a checkerboard composed of both blue and orange colors. A circle was used as probe stimulus and was presented in black color (RGB: 0, 0, 0). Dots and circles had a visual angle of 0.846° in diameter.

Subjects were seated in a comfortable reclining chair, approximately 3 feet away from the screen in a dimly lit, sound-attenuating chamber. Subjects were instructed to sit in a relaxed manner, keep their eyes on the fixation cross at the center of the computer monitor, and remain as still as possible during the entire experiment. Stimuli were displayed and responses were recorded through E-Prime (ver. 1.1.4.1) on a PC (Dell, Optiplex 745) running Windows XP with a 19” flat-panel LCD monitor (Dell, Model 1908 FPI). Both speed and accuracy were emphasized in the instruction. Subjects were instructed to use their index and middle fingers to make key presses using a button box. The design of response and key were counterbalanced across subjects. Subjects practiced one to three task blocks (20 trials each) before the actual experiment and completed a post-session interview.

EEG Recording

Electroencephalography (EEG) was recorded continuously from 64 electrodes (a 64-electrode Quikcap, Neuroscan Inc., Sterling, USA) using Ag/AgCl electrodes according to the International 10-20 system. The fronto-central electrode was used as ground with linked-mastoid electrodes as reference. The horizontal electrooculogram (HEOG) was recorded between the outer canthi of the two eyes. The vertical electrooculogram (VEOG) was recorded from above and below the orbital region of the left eye. All electrode impedances were kept below 5 kΩ. The EEG and EOG signals were amplified with a 0.1-30 Hz bandpass filter and digitized at 500 Hz.

Data Analysis

For the behavioral data, trials with response time exceeding three standard deviations (SDs) from the mean of a given subject were removed from the analyses. Accuracy and response time of cues and probe types were analyzed using the repeated-measures analysis of variances (ANOVAs). Paired *t*-tests were used to test for behavioral facilitation and PI effects (see Tables 1 and 2).

For the EEG data, preprocessing was conducted using the EEGLab toolbox (Delmore, & Makeig, 2004) in MATLAB (The Mathworks, version 2008a). The EEG data were digitally filtered with 0.1 to 30 Hz bandpass and down sampled to 250 Hz. Stimulus-locked averages were constructed for correct trials. Incorrect trials were excluded from analysis. Single epochs were baseline-corrected using 100 ms pre-stimulus onset, and ended 1 s post-stimulus onset. Eye blinks, eye movement artifacts and body movement artifacts were removed from the averaged ERP waveforms using the independent component analysis (ICA) and by visual inspection. Each dataset included in the final data analysis had a minimum of 80% usable trials per condition.

For statistical tests, ERP signal at several electrodes was quantified as the area under the curve within the selected time windows relative to a 100 ms pre-stimulus baseline. ERPs elicited by the stimulus presentation and cue presentation were averaged separately according to the cue condition (MS, NS2, NS4). ERPs elicited by the probe presentation were averaged separately according to the cue condition (MS, NS2, NS4) and probe type (MS: “Yes”, “No-HF”, and “No-LF”; NS2 or NS4: “Yes” and “No”). The time windows used are as follows: from study onset, 140-250 ms, 380-530 ms, and 500-750 ms; from cue onset, 140-200 ms, 250-350 ms, 380-500 ms, and 500-700 ms; from probe onset, 250-450 ms and 450-650 ms. Repeated-measures

ANOVAs were used to test for the statistical significance of the main effects and condition by electrode interactions. Analyses were conducted using the ERP data from four midline electrodes (Fz, Cz, Pz and POz).

For all ANOVAs, the Greenhouse-Geisser correction was used to correct sphericity violations. The corrected probability values and degrees of freedom are used in this report. Bonferroni correction was applied to adjust for multiple comparisons.

2.3. Results

Behavioral data

We conducted separate one-way ANOVAs to test for the effect of cue on recognition responses to the "Yes" probes and "No" probes. The results showed significant differences among the three conditions in mean accuracy and response time to the "Yes" probes [$F(2, 42) = 42.20$, $p<.001$, and $F(2, 42) = 45.00$, $p<.001$, respectively; see *Table* 1]. Paired *t*-tests revealed significantly faster and more accurate responses to the "Yes" probes of the MS condition in comparison to the NS4 condition (*p*s < .001), but less accurate in comparison to the NS2 condition ($p < .001$). Similar main effects were observed for the "No-LF" probes [accuracy: $F(2, 42) = 8.89$, $p<.01$, and response time: $F(2, 42) = 69.20$, $p<.001$], with faster and more accurate responses to the MS condition in comparison to the NS4 condition (*p*s<.05) but slower in comparison to the NS2 condition ($p<.05$). Taken together, the recognition performance was facilitated by the selection cue as expected, though selectively holding two items out of four items is still not the same as holding an original memory set of two items (see Gorgoraptis, Catalao, Bays, & Husain, 2011).

To estimate the effect of PI from the no longer-relevant dot locations on recognition performance, we calculated the accuracy and response time differences between the "No-HF" and "No-LF" probes of the MS condition (*Table* 2). Responses to "No-HF" probes was on average less accurate and took slightly longer time compared to the "No-LF" probes [$t(21) = -3.70$, $p<.001$, and $t(21) = 2.25$, $p<.05$, respectively]. These results indicate that the no longer-relevant spatial information could still influence recognition behavior as observed in previous studies (e.g., Leung & Zhang, 2004; Oberauer & Kliegl, 2006).

Furthermore, we examined whether the high and low working memory capacity individuals showed differences in behavioral performance during the main task across the three task conditions (MS, NS2, and NS4; *Table* 3). The estimated *k*-score ranged from 2.46 to 5.42. Using the median score (4.19), subjects were divided into two groups: a high working memory capacity group (mean *k*= 4.86) and a low working memory capacity group (mean *k*= 3.39). We conducted mixed-effects analysis with group as the between-group factor and cue conditions as the within-group factor[1]. For the response accuracy data, the main effect of group was significant for responses to the "Yes" probes [high vs. low performers: 92.6% vs. 87.1%, *F*(1, 20) = 10.87, *p*<.01], the "No-HF" probes [high vs. low performers: 96.36% vs. 90.51%, *t*(20)=-2.38, *p*<.05, and the "No-LF" probes [high vs. low performers: 98.3% vs. 94.6%, *F*(1, 20) = 5.03, *p*<.05]. No significant interaction effect between group and condition was observed for the "Yes" probe [*F*(2, 40) = .21, *p*=.748], while significant interaction was observed for the "No-LF" probes [*F*(2, 40) = 6.01, *p*<.01]. Post-hoc t-tests revealed that the significant interaction was contributed by a significant difference between high and low performers' accuracy responses to the NS4 (*p*<.05), but not to the MS or NS2 conditions (*p*=.098, and *p*=.445, respectively).

For the response time data, the main effect of group did not reach significance for all probe types [high vs. low performers: "Yes", 513.39 ms vs. 595.82 ms, *F*(1, 20) = 3.84, *p*=.06; "No-HF", 523.560 ms vs. 603.984 ms, *t*(20)=1.79, *p*=.089; "No-LF", 538.67 ms vs. 597.06 ms, *F*(1, 20) = 1.92, *p*=.18]. No significant interaction effect between group and condition was found for the "Yes" probes [*F*(2, 40) = 1.63, *p*=.215], while significant interaction was observed for the "No-LF" probes [*F*(2, 40) = 4.04, *p*<.05]. However, post-hoc *t*-tests revealed no significant differences between high and low performers' response time to the "No-LF" probes among the three conditions (*p*s>.05), which may be caused by a high level of variance between the two groups.

For the PI effect in the MS condition (subtraction on the behavioral performance of the MS trials between "No-HF" and "No-LF" trials), no significant differences were observed between the high and low performers [PI on accuracy: high vs. low – -2.27% vs. -6.04%, *t*(20)=-1.76, *p*=.094; PI on response time: high vs. low – 8.65 ms vs. 23.61 ms, *t*(20)=1.04, *p*=.309]. In sum, individuals with lower working memory capacity, relative to those with higher working memory capacity, were less accurate during the updating task, while no difference in the PI effect was observed.

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[1] In regards to the analyses on the "No-HF" probe, since only the MS condition involved the "No-HF" probe, *t*-tests were conducted to compare the difference in behavioral responses to the "No-HF" probe between high and low performers.

We have also examined whether male and female differed in their behavioral performance. We conducted mixed-effects analysis with sex as the between-group factor and cue conditions as the within-group factor to examine whether male and female subjects showed differences in behavioral performance during the main task across the three task conditions (MS, NS2, and NS4)[2]. For the response accuracy data (*Table* 4), no significant main effect of sex was found for recognition responses to the "Yes" probes [male vs. female: 89.3% vs. 90.5%, $F(1, 20) = 0.35$, $p=.560$], the "No-HF" probes [male vs. female: 91.92% vs. 95.25%, $t(19.05) = -1.28$, $p=.215$], and the "No-LF" probes [male vs. female: 95.5% vs. 97.6%, $F(1, 20) = 1.29$, $p=.269$]. Significant interaction effect between sex and condition was observed for responses to the "Yes" probes [$F(1.60, 31.93) = 5.55$, $p<.05$], but not for responses to the "No-LF" probes [$F(1.11, 22.18) = .55$, $p=.49$]. Post-hoc *t*-tests showed that the significant interaction to the "Yes" probes was contributed by a significant difference between male and female's response accuracy to the "Yes" probes of the NS2 condition ($p<.05$), but not to the MS or NS4 conditions ($p=.944$, and $p=.640$, respectively). For the response time data (*Table* 4), a significant main effect of sex was observed for recognition responses to the "Yes" probes [male vs. female: 509.46 ms vs. 608.78 ms, $F(1, 20) = 6.03$, $p<.05$], while no significant effect to the "No-HF" probes and marginally significant effect to the "No-LF" probes were observed ["No-HF": male vs. female: 521.73 ms vs. 614.23 ms, $t(16.24) = -2.05$, $p=.057$, and "No-LF": male vs. female: 529.92 ms vs. 613.39 ms, $F(1, 20) = 4.32$, $p=.051$]. No significant interaction effects between sex and condition were observed for responses to the "Yes" probes [$F(1.47, 29.31) = .865$, $p=.400$], and "No-LF" probes [$F(1.72, 34.32) = 1.10$, $p=.336$]. For the PI effect in the MS condition (*Table* 4), no significant differences were observed between male and female performers [PI on accuracy: male vs. female – -4.28% vs. -4.00%, $t(18.67)=-.13$, $p=.900$; PI on response time: male vs. female – 8.30 ms vs. 25.52 ms, $t(18.95)=-1.20$, $p=.244$]. In sum, male responded faster than female.

ERP data

Memory load effect on initial encoding-related neural activity

We examined the effect of memory load on neural activity during the initial encoding and delay period in order to replicate findings in previous working memory studies (e.g., Eimer,

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[2] In regards to the analyses on the "No-HF" probe, since only the MS condition involved the "No-HF" probe, *t*-tests were conducted to compare the difference in behavioral responses to the "No-HF" probe between male and female subjects.

1993; Handy & Mangun, 2000; Mecklinger & Pfeifer, 1996; Morgan, et al., 2010; Rolk et al., 2000; Ruchkin et al., 1990, 1992, 1995). *Figure* 3 shows the variations in ERPs with increasing number of to-be-remembered dot locations presented in the study display. Significant condition by electrode interactions were observed between 140-250 ms and 380-530 ms after study onset [$F(2.30, 48.26) = 15.85$, $p < .001$, and $F(2.71, 56.99) = 7.95$, $p < .001$, respectively]. Paired *t*-tests showed that the differences were between the low load (NS2) and high load (NS4 or MS) conditions, especially over the frontal-midline electrode (*p*s<.05). The differences between the two high load conditions (MS and NS4) were not significant across all electrodes (*p*s>.05). In addition, a negative slow wave differentiating the NS2 from the NS4/MS conditions was observed at 500-750 ms after study onset over the parietal-occipital-midline electrodes [condition by electrode interaction: $F(2.56, 53.76) = 14.25$, $p < .001$].

Cue-related neural processes reflecting selective information processing of spatial working memory

To directly examine neural responses to selective updating of spatial working memory, we compared the ERPs elicited by the selection cue for the MS condition to those elicited by the non-selection cue for the NS2 and NS4 conditions (see *Supplementary Figure* 1 for the whole trial averaged waveforms). The averaged waveforms related to the cue (*Figure* 4a) revealed several prominent neural processes at the following time windows starting from cue onset: 140-200 ms, 250-350 ms, 380-500 ms and 500-700 ms.

For the early time window (140-200 ms), the main effect of cue (MS/NS4/NS2) and a cue by electrode interaction were significant [$F(2, 42) = 4.38$, $p < .05$, and $F(1.92, 40.23) = 12.66$, $p < .001$, respectively; see *Figure* 4a]. Paired *t*-tests showed that the ERPs were less positive in the selection condition (MS) in comparison to the non-selection conditions (NS2 and NS4) at the frontal- and central-midline electrodes *(ps*<.01). This effect may reflect early differential processing of cue meaning as seen in previous studies (e.g., Markowitz et al., 2011; Simpson et al., 2011; Theeuwes, 2010; see Discussion). While this effect may also be caused by differences in visual appearance between the MS and NS cues, little or no differences between the two cue types were found at the electrodes expected to show the largest visual sensory effect (parietal-occipital and occipital electrodes, *p*s>.05).

For the early-mid time window (250-350 ms), by visual observation, the averaged waveform elicited by the MS condition was more negative than those elicited by the NS conditions (*Figure* 4a). However, we did not find significant main effect of cue or interaction between cue and electrode [$F(1.90, 39.94) = 2.22$, $p=.124$, and $F(2.02, 42.47) = 1.13$, $p=.333$, respectively]. This neural activity could possibly reflect re-focusing of attention to the task relevant information after the subjects have processed the meaning of the cues (Fukuda & Vogel, 2009). In Fukuda and Vogel's study (2009), the neural activity related to re-focusing of attention was measured as the difference in mean amplitude between ipsilateral and contralateral waveforms (contralateral delayed activity; CDA) recorded at the posterior parietal, lateral occipital and posterior temporal electrode sites. Therefore, we further conducted paired *t*-tests between the MS and NS (averaging across the area under curve for the NS2 and NS4 conditions) conditions specifically at the parietal and parietal-occipital midline electrodes. Significant results were observed [Pz: $t(21) = -2.68$, $p<.05$, and POz: $t(21) = -2.50$, $p<.05$]. These suggested that the neural activity during this time window may reflect rapid re-focusing to the task relevant information, which was required in the MS, but not in the NS conditions.

For the mid time window (380-500 ms), a prominent positive ERP component showed a significant cue by electrode interaction [$F(2.72, 57.13) = 13.34$, $p<.001$; see *Figure* 4a]. The main effect of cue was not significant [$F(2, 42) = 1.57$, $p=0.22$]. Paired *t*-tests revealed a heightened positivity at the frontal-midline electrode for the NS4 condition in comparison to the MS condition ($p<.01$; see *Figure* 4b for topography) and the NS2 condition ($p=.04$ but not significant after multiple comparisons correction), whereas the ERPs were comparable between the MS and NS2 conditions ($p=.41$). Neural activity during this time window may reflect selective retrieval of the task relevant dot locations: four dot locations in the NS4 condition and two in the MS and NS2 conditions.

For the late time window (500-700 ms), the main effect of cue and a cue by electrode interaction were significant for this positive slow wave [$F(2, 42) = 6.08$, $p<.01$, and $F(3.05, 63.94) =10.72$, $p<.001$, respectively; see *Figure* 4a]. Paired *t*-tests revealed that the difference in ERPs between the MS and NS2/NS4 conditions were significant at the parietal- and parietal-occipital-midline electrodes (*p*s<.01). The ERP differences between the MS and NS2/NS4 conditions did not reach significance at the frontal midline electrode (see *Figure* 4b for topography). These results suggested further differences in neural processing of spatial working memory during the selection cue condition in comparison to the non-selection cue conditions at this later time.

Cue effect on probe-related neural activity

The effect of selective information processing (reducing memory load from 4 to 2 in the MS condition) on neural activity during the probe stage is evident across all electrode sites (*Figure* 5a and 5b). At this point, four dot locations were required to be held in the NS4 condition versus two dot locations in the MS and NS2 conditions. The main effect of cue and a cue by electrode interaction were significant for an earlier time window [250-450 ms: $F(2, 42) =29.56, p<.001$, and $F(2.70, 56.64) = 3.68, p<.05$, respectively]. Paired *t*-tests revealed that the ERPs for the NS4 probes were significantly less positive relative to the NS2 and MS probes across the four midline-electrodes (*p*s<.001), whereas negligible differences were observed between the MS and NS2 probes (*p*s>.05). For a later time window (450-650 ms), the main effect of cue did not reach significance [$F(2, 42) = 2.40, p=.10$) but the cue by electrode interaction was significant [$F(1.94, 40.76) = 5.95, p<.01$; see *Figure* 5a and 5b]. Similar effects were found when only the "Yes" probes of the three task conditions were examined [main effect: 250-450 ms, $F(2, 42) = 17.59, p<.001$, and 450-650 ms, $F(2, 42) = 3.72, p<.05$, and interaction effect: 250-450 ms, $F(2.75, 57.69) = 1.78, p<.17$, and 450-650 ms, $F(2.28, 47.81) = 3.81, p<.05$; data not shown]. These results demonstrated that the selection cue modulated the pattern of neural activity during probe recognition, for which the MS condition became similar to the NS2 condition and both of them were different from the NS4 condition.

We also examined the PI effect by comparing ERPs in correspondence to the two types of No probes of the MS condition (i.e., "No-HF" versus "No-LF"). For the early window after probe onset (250-450 ms), no significant effects were observed (*p*s >0.15, respectively). The interaction between probe by electrode was significant at the later time window after probe onset [450-650 ms: $F(1.31, 27.59) = 4.52, p<.05$, see *Figure* 5c and 5d]. Paired *t*-tests revealed that the ERPs in response to the "No-HF" probes were more positive than those to the "No-LF" probes at the frontal-midline electrode ($p<.05$).

Effects of individual differences on neural activity

We further examined whether individual differences in working memory capacity contributed to the different patterns of neural responses described above. We divided the subjects into two groups according to their estimated working memory capacity (high vs. low working memory capacity, see *Behavioral* results). We conducted mixed-effects analysis with group as the between-group factor, and with condition and electrode as the within-group factors. Significant group effects and across subject correlations were observed for the study and probe stage but not for the cue stage.

For the study stage, only a significant group by condition interaction was found between 380-530 ms after study onset [$F(1.91, 38.12) = 3.84$, $p<.05$]. Post-hoc analysis revealed that the high performance group did not show a significant main effect of condition ($F<1$) but a significant condition by electrode interaction was observed [$F(2.03, 20.32) = 3.51$, $p<.05$]. In contrast, the low performance group showed a significant main effect of condition [$F(2, 20) = 7.58$, $p<.01$] and a condition by electrode interaction [$F(2.02, 20.17) = 4.95$, $p<.05$]. In addition, individual differences in working memory capacity scores were negatively correlated with load-related differences in ERP amplitudes during this time window at the frontal-midline electrode [MS vs. NS2: $r(22) = -.53$, $p<.05$; see *Figure* 6a]. Similar effects were also found at several other electrodes [NS4 vs. NS2 at the central-midline electrode: $r(22) = -.48$, $p<.05$; MS vs. NS2 at the central-midline electrode: $r(22) = -.53$, $p<.05$, and parietal-midline electrode: $r(22) = -.44$, $p<.05$]. A negative correlation was also observed for the negative slow wave (500-750 ms) between individual differences in working memory capacity and load-related differences in ERP amplitudes [MS vs. NS2 at the frontal-midline electrode, $r(22) = -.51$, $p<.05$; see *Figure* 6b]. In sum, the results on the study stage showed that subjects with lower working memory capacity showed greater neural responses in the high load conditions (NS4 and MS) relative to the low load condition (NS2) during the initial encoding stage, while subjects with higher working memory capacity did not show differences between the high and low load conditions.

For the probe stage, we observed positive correlations across subjects between their PI index (accuracy difference between the “No-HF” and “No-LF” probes) and ERPs for the MS condition at 250-450 ms after probe onset at the central- and parietal-midline electrodes [$r(22) = .46$, $p<.05$, and $r(22) = .49$, $p<.05$, respectively; see *Figure* 6c and 6d]. Subjects with less positive ERPs for the MS condition (i.e., more similar to the NS4 condition) showed greater PI effect.

Effects of sex on neural activity

We have also conducted mixed-effects analysis to examine whether male and female would show differential pattern of neural activity. Sex was used as the between-group factor while condition and electrode were used as the within-group factors. Although we found behavioral differences between male and female subjects, no significant differences in the neural data were observed across all stages (*p*s>.05).

2.4. Discussion

Using a delayed-recognition paradigm with an updating cue inserted during the retention interval, we revealed that spatial working memory updating is not a single event but a sequence of neural processes. Our results revealed four prominent neural processes associated with the memory selection process (MS vs. NS4 or NS2) between 140-700 ms after cue onset. Our data showed that the cue-elicited ERPs were modulated by the memory selection process (MS vs. NS4 or NS2) shortly after cue onset (about 140-200 ms and 250-350 ms) and at a later time window (500-700 ms). The cue-elicited ERPs were also modulated by the post-cue memory load [4 locations (NS4) vs. 2 locations (MS and NS2)] at an intermediate time window (380-500 ms). These different neural processes may serve as components of cognitive processes required by spatial working memory updating such as the processing of cue meaning, selective retrieval, and content re-organization. The memory selection process also modulated behavioral and neural responses associated with the subsequent recognition task. In addition, we observed individual differences in ERPs at the initial encoding stage and recognition stage. The results might suggest that neural representation of spatial working memory has some degree of dependence on individual's working memory capacity and updating strategy. Effect of sex on differences in ERPs was found to be minimal.

Initial memory load effect

The results during the initial encoding and delay period were as expected, and have replicated results of previous studies (e.g., Eimer, 1993; Handy & Mangun, 2000; Mecklinger &

Pfeifer, 1996; Morgan, et al., 2010; Rolke et al., 2000; Ruchkin et al., 1990, 1992, 1995). We found that at the frontal and parietal-occipital midline electrodes, the ERPs differed between the low (NS2) and high load (MS and NS4) conditions, while the ERPs of the two high load conditions did not show any significant difference. A null result between the MS and NS4 conditions at the study stage suggested that the dot locations were encoded equally well. Any subsequent differences between the MS and NS4 conditions at the cue and post-cue delay period would likely reflect the effects of memory selection.

Early processing of cue meaning

An enhanced N1 component was observed in response to the memory selection cue at 140-200 ms after cue onset. The result seems to reflect an early neural processing of cue meaning. One may argue that an enhanced N1 component to the MS condition may be caused by differences in visual appearance between the selection and non-selection cues. Attention to or selection of non-spatial features (e.g., color, shapes, motion, etc) has been shown to elicit a later N1 component at about 150 ms after cue onset (e.g., Anllo-Vento & Hillyard, 1996; Eimer, 1995; Heslenfeld, Kenemans, Kok, & Molenaar, 1997). Since all visual cues used in this experiment were in the form of non-spatial features (i.e., colors), a similar level of neural activations was expected to be elicited by both the selection and non-selection cues. If the N1 component was sensitive to the complexity of visual features, one would expect to observe an enhanced signal to the non-selection cue as it has more color contrast features (e.g., Johannes, Munte, Heinze, & Mangun, 2003; Luck et al., 1994; Martinovic, Mordal, & Wuerger, 2011). Yet, a more negative N1 component was observed for the selection cue. This suggested that the neural component was possibly driven by the processing of cue meaning instead of visual features (e.g., Awh et al., 2000). In Awh and collegues' study (2000), similar early ERPs around 100 ms (i.e., the P1 and N1 components) were observed when subjects were cued to rehearse specific spatial locations in working memory and when they attended to specific locations on the stimulus display. The early ERPs elicited by the cue could reflect attention processes during spatial working memory rehearsal as suggested by the investigators. Alternatively, these early ERPs could reflect an early processing of cue meaning. The subjects might have retrieved or re-activated the spatial representations of the cued locations upon seeing the rehearsal cue.

Previous human psychophysiology and non-human primate electrophysiology studies found that neural activity in correspondence to goal-driven visual selection as early as 150 ms following stimulus onset, and even earlier neural activity in correspondence to stimulus-driven visual selection (e.g., Markowitz et al., 2011; Theeuwes, 2010). Our subjects were well trained on using the visual cues to carry out the two task conditions. The N1 component observed around 140-200 ms after cue onset supported the interpretation of goal-directed processing of the visual cues (Simpson et al, 2011). A similar N1 component was observed in previous studies in correspondence to visuospatial cues used to direct the selective encoding of particular colors in stimulus displays or the selective maintenance of particular memorized colors (Griffin & Nobre, 2003; Nobre et al., 2004). Taken together, the enhanced ERPs at this early stage in correspondence to the visual cues could be used for guiding the subsequent mnemonic processes such as selective retrieval and maintenance of task relevant information.

Re-focusing on task relevant information

Previous ERP studies suggested that re-focusing of attention to task relevant information occurs quickly (about 100-300 ms after stimulus onset) (e.g., Awh et al., 2000; Kuo et al., 2012; Fukuda & Vogel, 2009). This rapid re-focusing ERP component was evident by an enhanced N1/P1 complex to the attended target locations rather than distractor locations (Fukuda & Vogel, 2009). Fukuda and Vogel (2009) measured human's ability in rapidly reallocating attention to spatial targets after the presentation of distractors. Their results showed that such ability varied across individuals and the result was correlated with individual differences in working memory capacity (Fukuda & Vogel, 2009). In their experiment (Fukuda and Vogel, 2009; Experiment 1), subjects were first presented with a spatial cue indicating the location that was relevant for the recognition test. It was then followed by a brief presentation of a study array of target and distractors. After a brief delay, the subjects were asked to judge whether the probe appeared at the target or distractor locations in the probe-present trials, or make no judgment in the probe-absent trials. This study first measured the mean amplitude difference between the ipsilateral and contralateral neural activity related to the attention-related P1/N1 complex at the posterior parietal, lateral occipital and posterior temporal electrode sites. Their results showed that low capacity individuals showed negligible difference in the P1/N1 complex between trials where the probes were presented at the target locations versus at the distractor locations. This indicated the low working memory capacity individuals were less able to disengage attention from the distractor and re-focus attention to the target locations. In contrast, high working memory capacity individuals were more capable in re-orienting attention to task relevant information (Fukuda & Vogel, 2009). Since Fukuda and Vogel's study focused on examining the probe-elicited ERPs and within a restricted time window (analysis time window was between 75-150 ms after probe onset, and figures were presented up to 300 ms after probe onset), we were not able to draw direct comparison between our results with their results. Yet, our task also included presenting probes at locations of the no longer relevant dots (similar to Fukuda & Vogel's condition of probe presented at the distractor location), which can be considered as distractors in memory. In our experiment, after the presentation of the updating cue, only the MS trials involved relevant and no longer relevant information; whereas all information in the NS trials were task relevant. Hence, the more negative cue-elicited ERPs at the early time window (between 250-350 ms after cue onset) on MS trials compared to the NS trials could potentially reflect re-focusing to task relevant information.

Selective information processing of relevant spatial information

Our ERP data showed that at 380-500 ms after cue onset, neural activity in correspondence to the MS condition became more similar to the two-item control condition (NS2) instead of the four-item control condition (NS4) at the frontal electrode sites. Previous ERP studies have examined selective processing at different stages of visual working memory. Some investigators examined the effect of stimulus selection on visual working memory by presenting a visuospatial cue prior to the stimulus array (i.e., a pre-cue) to instruct subjects to either remember the visual stimuli presented on the left or the right side of the screen (McCollough, Machizawa, & Vogel, 2007; Vogel & Machizawa, 2004, Vogel et al., 2005). Other investigators, as in our study, examined the effect of memory selection by presenting a visuospatial cue after the stimulus array (i.e., a retro-cue) to instruct subjects to selectively maintain certain memorized colors while ignoring the non-cued ones (e.g., Griffin & Nobre, 2003; Kuo et al., 2012; Nobre et al., 2008; review by Lepsien & Nobre, 2006). Visual inspection of the graphs in these previous reports (e.g., Kuo et al., 2012; McCollough et al., 2007; Vogel & Machizawa, 2004, Vogel et al., 2005) suggested that starting around 200 ms after the presentation of the stimulus array or the retro-cue, the neural activity reflected the number of to-be-remembered items. Together with these previous findings, our new finding showed that the selective retrieval of spatial working memory happened within the first 500 ms following cue presentation.

Similar to this experiment, Kuo and colleagues (2012) examined the changes in ERPs during visual working memory following the presentation of a selection cue or a non-selection cue (called neutral cue in their report). They showed that the ERP amplitude measured at 500-800 ms after cue onset was comparable for the two selection conditions (selecting one item from working memory of two or four items), while a difference in neural activity was observed when two and four items were maintained in the neutral conditions. Our data, however, showed that the ERPs between the two conditions of similar post-cue memory load (MS and NS2) were comparable during 380-500 ms after cue onset, but segregated afterwards during 500-700 ms after cue onset. The two non-selection conditions, NS2 and NS4, while of different memory load, were comparable at this later post-cue window. It was unclear what neural processes were involved during memory selection in the Kuo and colleagues' study (2012), as there were no direct comparisons between the selection and neutral conditions, and the size of the post-cue memory set was different across their selection, neutral two and neutral four conditions (one, two, and four items, respectively).

Previous neuroimaging studies have shown that the prefrontal cortex and posterior parietal areas were involved in selecting and maintaining task relevant spatial information from working memory (e.g., Bledowski et al., 2009; Leung et al., 2007; Rowe & Passingham, 2001; Rowe, Hughes, Eckstein, & Owen, 2008). Using a different paradigm and task materials (e.g., verbal materials and line drawing of objects and abstract visual patterns), Johnson and colleagues (2003, 2005, 2007) found that similar regions were involved in the refreshing operation, where subjects were asked to think back to one of the recently seen stimuli. Although the origins of the ERP signals were not exact, the observed frontally distributed selective retrieval effect could be involved in the brain regions revealed by the neuroimaging studies. Griffin & Nobre (2003) also found increase in ERPs at the frontal electrodes at 360-480 ms following the onset of the retro-cue, and interpreted that as shifting spatial attention to the relevant color targets. Since they did not include a control condition, it is unclear whether their observation reflected merely a general shift of spatial attention or a specific shift of attention to select the task relevant items (i.e., selective retrieval of the cued color). The significant differences between the MS/NS2 conditions and the NS4 condition during 380-500 ms after cue onset in our study suggested that this ERP was likely to be specific in selecting the task relevant items from spatial working memory. Since color was used to cue the memorized spatial locations in our task and spatial direction was used to cue the memorized colors in the other studies (Griffin & Nobre, 2003; Kuo et al., 2012), future studies are needed to directly compare between spatial features (i.e., locations) and object features (e.g., colors) in the same paradigm to better understand the generality or specificity of the neural activity observed during working memory updating.

Subsequent effect of memory selection on content re-organization or evaluation of information

Neural activity at 500-700 ms after cue onset was found to differentiate the memory selection condition from the two non-selection conditions in the parietal electrode sites. The observed neural activity shared properties (e.g., time interval and topography) of the P300 component. An enhancement of the P300 component at the frontal electrodes has been commonly associated with context updating (e.g., Donchin, 1981; Johnson & Donchin, 1982; Kok, 2001; but see Lenartowicz, Escobedo-Quiroz, & Cohen, 2010), which refers to the cognitive processes for changing the mental representation and action plan in accordance to the current task goal (Donchin, 1981; Jonhson & Donchin, 1982; see review by Donchin & Coles, 1988). In contrast, the neural activity observed in our experiment was stronger at the parietal electrode sites. This observed neural activity may not necessarily reflect context updating of the visuospatial content of working memory; rather it might suggest other processes (Lenartowicz et al., 2010).

The observed parietal-distributed neural activity could reflect the re-organization of information involved in the memory selection condition, in which the representations for dot locations could now be organized or categorized as relevant or no longer relevant after the presentation of the updating cue. Previous ERP studies using the running span task demonstrated that updating as opposed to maintenance enhanced late parietal positivity (i.e., positive deflection starting at 450-650 ms after stimulus onset, and lasted till 900 ms; e.g., Kiss, Pazderka-Robinson, & Floden, 2001; Kiss, Pisio, Francois, & Schopflocher, 1998). This effect was postulated to reflect reorganization of the memory content, which is in corroboration with our observations in this time window.

This parietal-distributed neural activity has also been suggested to reflect the process of evaluation of memory representations (e.g., Donchin et al., 1986). Evaluation can be considered as a broad term that encompasses factors like task relevance, salience of stimulus, task difficulty, etc (see Kok, 2001 for review). Enhanced amplitude of the P300 component was related to an increase in task relevancy (e.g., Johnson & Donchin, 1982; Pritchard, 1981; Squires et al., 1977; Sutton et al., 1967), and stimuli saliency (e.g., Johnson, 1988, Picton, 1992). In our study, we observed an enhanced P300 component for the MS condition but not for the NS conditions. This could be due to the heightened relevance of the cued memory representations in the MS condition or the high salience of the MS cue, which required a behavioral change in the MS trials as opposed to the NS trials.

Our result could not be explained by task difficulty. The MS condition is more difficult than the NS conditions, as it might involve additional cognitive demands/operations in updating the memory content. If task difficulty was related to a poorer behavioral performance, we would expect the worst performance in response to the MS trials than the NS trials. Yet, the behavioral performance on the MS trials was only slightly worse than the NS2 condition but significantly better than the NS4 condition. Hence, it is more likely that the ERPs observed in this time window are manifested from the post-cue evaluation of working memory content for task relevance and salience during the MS trials.

Memory updating modulates memory search during probe recognition

Besides influencing the post-cue neural activity, the selection cue also influenced later recognition performance and the associated neural responses. As expected, we observed improved behavioral performance for the memory selection condition relative to the four-item control condition as in previous studies of cueing effects (e.g., Awh et al., 1995, 1998; Awh & Jonides, 1998; Griffin & Nobre, 2003; Landman, Spekreijse, & Lamme, 2003; Lepsien, Griffin, Devlin, & Nobre, 2005; Makovski & Jiang, 2007; Makovski, Sussman, & Jiang, 2008; Nobre, et al.,2008; Sligte, Scholte, & Lamme, 2008). Our ERP data further demonstrated that neural activity during probe recognition on the memory selection trials is more similar to that of the two-item control trials and different from that of the four-item control trials. This suggested that during probe recognition on the memory selection trials, subjects were searching through a memory set of a reduced set size (2 items) similar to the NS2 trials rather than searching through the entire original set (4 items).

Further, our neural data showed a central-parietal positivity that closely resembled the typical P300 component observed in recognition studies. It has been consistently shown that the amplitude of the P300 component reflect the load of memory search involved at recognition (e.g., Gomer et al., 1976; Brookhuis et al., 1981; Kotchoubey, Jordan, Grözinger, & Westphal, 1996; Kok, 1997; see Kok, 2001 for review). An enhancement of the P300 component is observed when a smaller amount of information is needed to search through in memory (i.e., a more efficient memory search).

Our ERP results during the post-cue recognition are in contrast to a recent study by Nobre and colleagues (2008), which suggested a specific ERP component (called $N3_{RS}$) as an indicator of facilitation in memory search for biased processing of cued color working memory. These investigators found that the spatial retro-cue condition in comparison to the control uninformative cue condition lacked a fronto-centrally distributed load-sensitive component ($N3_{RS}$), which was observed around 300 ms after probe onset. However, this component may not necessarily be related to the presence or absence of an informative cue. If this component was only observed with an uninformative cue, then we would expect that after probe onset, the ERPs in response to the NS2 condition would be more negative than the ERPs in response to the MS condition although both conditions involved two items in the final memoranda. Given the similar amplitudes of neural activity between the MS and NS2 conditions, and significantly smaller amplitudes of the NS4 condition, our data seems to suggest that the $N3_{RS}$ component could merely reflect the memory search load at recognition.

While memory search seemed to be facilitated by the information cue, the residual memory of the no longer relevant information remained to influence probe recognition. This PI effect was revealed by the poorer performance on rejecting the familiar No probes (“No-HF”) than the non-familiar novel No probes (“No-LF”). The results were consistent with a previous study using a spatial working memory task (Leung & Zhang, 2004), and in a previous study using a non-spatial working memory task (Yi et al., 2009). A difference in frontal positivity (a frontal P300 component) was observed between 450-800 ms after probe onset when contrasting the neural activity elicited by the “No-HF” and “No-LF” probes. The amplitude of the frontal P300 component was suggested to be associated with an increase in decisional demand before a response was conducted (Johnson & Donchin, 1982). In our paradigm, subjects may first deemed a “No-HF” probe as familiar as a “Yes” probe, as both probe types have been presented at the study display and were equally well encoded into the initial memory set. Yet, to make correct judgment, increase in decisional demand may be needed to reject the more familiar “No-HF” probe as observed in our data.

Further, our results did not show any PI-related ERP components as reported by the few ERP studies on proactive interference, which all used non-spatial visual materials (e.g., Du et al., 2008; Tays, Dywan, Mathewson, & Segalowitz, 2008; Tays, Dywan, & Segalowitz, 2009; Yi & Friedman, 2011; but see Zhang, Wu, Kong, Weng, & Du, 2010 for suggesting a parietal late posterior complex difference). One major difference between these previous studies and our current study is that the PI effect in our behavioral data was smaller and not consistent across subjects. This small behavior effect is in sharp contrast with the strong PI effect commonly found in verbal studies, probably due to the differences in selective processing of spatial and verbal information as we have previously shown (see Leung & Zhang, 2004; Zhang, Leung, & Johnson, 2003).

The effect of individual differences in working memory capacity on working memory performance

Our results showed that individual differences in spatial working memory capacity modulated the neural activity during the stage of initial encoding in the updating task (380-530 ms after study onset). Similar individual differences in visual working memory capacity and load-related CDA at 300-900 ms after stimulus display were previously shown by Vogel and colleagues (e.g, Vogel & Machizawa, 2004; Vogel et al., 2005; see review by Drew & Vogel, 2009). Their results showed a strong positive correlation between working memory capacity and changes in ERP amplitudes from set size 2 to 4 (Vogel & Machizwa, 2004). This indicated that subjects with low, in comparison to high, working memory capacity showed little increase in the load-related neural activity from set size 2 to 4 items (Vogel & Machizwa, 2004). Furthermore, the effects of individual differences observed in these previous studies were mainly over the posterior parietal and lateral occipital electrode sites. In contrast, our results during 380-530 ms after the display of the study dot locations were more widespread (frontal, central and parietal electrode sites).

At a later time window, 500-750 ms after study onset, we observed a negative correlation between individual differences in working memory capacity and load-related differences in ERPs at the frontal electrodes. This may appear to be at odds with other ERP results showing a stronger effect of memory load on the slow wave over the more posterior electrode sites and with previous findings of load-related CDA effects (e.g., Vogel & Machizawa, 2004; Vogel et al., 2005). Our finding of individual differences in the frontal electrode sites may be a manifestation from the recruitment of different brain regions or brain mechanisms by the high and low performers. Greater frontal activity in high compared to low memory load conditions was observed in previous neuroimaging studies of working memory (e.g., Nagel et al., 2009; Shucard, Tekok-Kilic, Shiels, & Shucard, 2009). It is possible that, as suggested by the group differences observed between 380-530 ms after study onset, the low performers may have a less accurate representation of information or experienced more difficulty in the high load condition (4 items). They may thus recruit the frontal regions besides the parietal regions for processing information in the high load condition. While the subjects with low working memory capacity may have struggled with the initial encoding, the group differences in cue-elicited ERPs between the two groups did not reach significance. Poor initial encoding of information, however, affected later recognition performance. This led to the situation that subjects with lower working memory capacity were less efficient in searching through the updated memory set for the selection condition, and showed greater PI effect.

The effect of sex on working memory performance

In this experiment, we did not observe any significant difference in neural activity between male and female subjects at the initial encoding, memory selection and recognition periods. In terms of behavioral results, male subjects responded faster than female subjects. This could reflect a possible difference in the use of strategy or decision making. In the post-test interview, we asked the subjects to describe the strategy that they have used to remember the dot locations. Our results showed that male subjects tended to remember the gist of where the dots were by remembering the quadrants that the dots appeared or the spatial relationships among dots by forming some sort of patterns[3]. In contrast, female subjects tended to remember the details by assigning numbers to the grids, and memorized the specific grid numbers that the dots appeared. It is possible that by remembering the gist, responses would be faster for male than

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[3] It is important to note that when designing the experiments, dot locations that would form any meaningful patterns (e.g., squares, rectangle, hexagon, trapezoid, parallelogram, etc), or more than two dots in one column or row were excluded.

female. Since the task was not difficult as revealed by high task accuracy (above 80% for all task conditions); accuracy was less affected by the difference in the use of strategy.

Previous studies showed a general bias that males outperformed females in spatial abilities involved in mental rotations and spatial perception (e.g., Harris, 1981; Linn & Petersen, 1985; Voyer, Postma, Brake, & Imperato-McGinley, 2007; Voyer, Voyer, & Bryden, 1995), while females outperform males in spatial memory (i.e., memory of the locations of objects; Silverman & Eals, 1992). A previous report on sex differences in finding routes to a destination revealed that males and females used different strategies in completing the same task (Lawton, 1994). Lawton (1994) found that males tended to form spatial relationships among reference points (i.e., orientation strategy of way finding), while females tended to remember the features along the route (i.e., route strategy). Together, these self-reported strategies use might lead to different behavioral performance between male and female.

The differences in the use of strategies in spatial tasks could be due to biological differences between male and female (e.g., Casey & Barbeck, 1990; Williams, Barnett, & Meck, 1990). Williams and colleagues (1990) found that male rats relied more on using the geometrical or configurational cues in navigating in a maze, while female rats relied more on using the landmarks besides configurational cues. These sex differences could be attributed to the different hormonal levels of male and female. Previous studies on rat have shown that high levels of estrogen in female rats were correlated with low spatial ability, while low level of testosterone has been shown to correlate with high spatial ability (e.g., Frye, 1994; Hampson, 1990; Healy, Braham, & Braithwaite, 1999; Sherry & Hampson, 1997). Yet, sex difference in spatial task could be reversed by manipulating the hormonal level neonatally (e.g., Williams et al., 1990).

3. The effects of relevant and irrelevant spatial information on the sustained memory-related neural activity

3.1. Introduction

Results from Experiment 1 revealed that selecting task relevant information from memory involved several neural processes within the first second from cue onset. This included processing of cue meaning, re-focusing of attention, selective retrieval of task relevant information, and re-organization or evaluation of the working memory content. In this study, our focus is to further examine the memory-related sustained neural activity (i.e., one second after cue onset till the end of the delay period) in correspondence to the varied amount of relevant and no longer relevant spatial information in working memory. The goal is to reveal the timing that spatial information being separated by the selection process, and whether the no longer relevant information would modulate the memory-related sustained neural activity in spatial working memory.

Demonstrated by a behavioral experiment (Oberauer, 2001), separation of relevant and no longer relevant information occurred in about 1 second after the selection process has begun. Afterwards, the relevant and no longer relevant items were assumed to be stored differently (Oberauer, 2001). Results of this behavioral study showed that, in comparison to words not in the original memory set, having memoranda of the no-longer relevant words yielded longer response time to correctly reject the no-longer relevant words. Its negative impact on response time lasted for up to 5 seconds after the selection process has begun. Our lab further showed that this behavioral cost could last for up to 9 seconds during the delay period (counting from the offset of the selection cue) in a memory updating study using digits (Yi, Drisen, & Leung, 2009). Taken together, these findings seemed to suggest that relevant and no longer relevant information were being stored differently, such that relevant and no longer relevant information exerted different effects on the transient (within 1 second) and sustained (beyond 1 second) neural activities. It is unclear whether separation of spatial information would take the same amount of time as in verbal working memory, and whether relevant and no longer relevant spatial information would exert similar or different modulating effects on the transient and sustained neural activities.

Transient and sustained neural representations of task relevant information have been shown in the prefrontal cortex (specifically, the dorsolateral prefrontal cortex), which were suggested to reflect selection and maintenance of task relevant information, respectively (e.g., Desimone & Duncan, 1995; Miller, Erickson, & Desimone, 1996; Rainer et al., 1998; Rao, Rainer, & Miller, 1997; Sakai & Passingham, 2003; see review by Postle, 2006). Sustained neural representation of task relevant information was also observed at the posterior association areas (e.g., parietal cortex, precuneus, superior parietal lobule, and inferior parietal lobule) for maintenance of task relevant spatial (e.g., Leung et al., 2004, 2007) and visual information (e.g., Passingham & Sakai, 2004; Todd & Marois, 2004). Relatively fewer studies have examined the fate of the neural representation of irrelevant or no longer relevant information. Recently, using fMRI, Xu (2010) demonstrated that irrelevant object information was represented transiently by the lateral occipital complex, and the magnitude of neural representations was affected by the encoding demand of the relevant object information. In Xu's study (2010), retention of irrelevant information (i.e., shapes of objects) measured at the lateral occipital complex was short-lived and only existed during the encoding, but not the delay, period. However, the strength of the transient representation of irrelevant information increased only when the encoding demand of the relevant information (i.e., color of objects) was low (from set size of 1 to 2), but not high (from set size 2 to 6; Xu, 2010). Since task irrelevant object information was never relevant for the working memory task in Xu's study (2010), it is unclear whether information which has been relevant previously but no longer relevant for the current task goal would show similar transient effect. Furthermore, it is unclear how no longer relevant information would yield a longer lasting effect on neural activity as observed in many previous studies.

In contrast to a transient representation of irrelevant object information, sustained representation of irrelevant spatial information has been observed in a single-unit recordings study (Hasegawa et al., 2004). Hasegawa and colleagues (2004) used an oculomotor delayed match/nonmatch-to-sample task to examine the patterns of neural activity of the prefrontal cortex (specifically in the caudal part of the dorsolateral prefrontal cortex corresponding to areas 46 and 8a, and the frontal eye field) during the "look" and "don't look" conditions. In this study, two rhesus monkeys were instructed by the cue as where to look ("look" condition) in the match trials or where not to look ("don't look" condition) in the non-match trials during the sample periods. The instructional cue and the sample location were presented simultaneously for 500 ms. Results at the sample cue period showed that while a majority of the prefrontal neurons did not distinguish between the "look" or "don't look" conditions, a small portion of the prefrontal neurons showed dissociable patterns of neuronal firing to the "look" and "don't look" conditions.

This suggested that some prefrontal neurons showed selection activity and began to code for the task-relevant and task-irrelevant spatial information within 500 ms since the sample onset. Furthermore, sustained representations of relevant and irrelevant spatial information were found throughout the 1-1.5 s delay period. Although Hasegawa and colleagues' (2004) results showed that the monkeys' prefrontal neurons maintained memory of relevant and irrelevant spatial information, the irrelevant spatial locations were never deemed as relevant. Hence, it is unclear whether similar memory-related sustained neural activity would be found for no longer relevant spatial information.

A variant of a visuospatial delayed-recognition task as in Experiment 1 was used. We compared and contrasted neural activity in response to the relevant load effect (High-Rel minus Low-Load) with those in the irrelevant load effect (High-Irrel minus Low-Load) to answer two questions. First, at which time point did the neural representations of relevant and no longer relevant spatial information being separated? Second, whether the amount of relevant and/or no longer relevant spatial information would modulate the memory-related sustained neural activity during the delay period? If only task relevant spatial information would modulate the sustained activity, the resulting sustained neural activity would be varied by the amount of relevant dot locations. If both task relevant and no longer relevant spatial information would modulate the sustained activity, the resulting sustained neural activity would be varied by the amount of relevant and no longer relevant dot locations across different electrode sites.

3.2. Methods

Participants

Thirty-six healthy undergraduate students (16 male and 20 female; mean age of 19.72) participated and received course credits for their participation. Datasets were screened for drifting, large movement artifacts and trials with EEG voltages exceeding 100 μV measured from peak-to-peak at any channel. As a result, four datasets were excluded, and data from 32 subjects (15 male and 17 female; mean age of 19.50) were included in the final analysis. All subjects had no history of neurological disorder, psychiatric disorder and drug abuse according to self-report and they had normal or corrected-to-normal vision. Written informed consent, reviewed and approved by the Institutional Review Board of Stony Brook University, SUNY, was obtained prior to participation.

Spatial Working Memory Task with a Selection Cue

Figure 7 shows the four task conditions. We used the delayed-recognition paradigm with an informative cue inserted during the delay period (adapted and modified from Leung & Zhang, 2004 and Oberauer, 2001). Each trial began with a fixation period (0.3 s). The fixation period was followed by a stimulus display (0.5 s) showing two, four or six dots (one or three dots in blue and one or three dots in orange). These are the dot locations to be remembered as the initial memory set. After a 2-second delay, a cue in either blue or orange color was presented for 0.5 s to indicate that only the dots in the cued color from the original memory set remained relevant for the subsequent recognition test. The final memory set size was reduced to one or three dot locations. Following a delay of 2 s after cue onset, a probe was presented for 0.5 s for the subjects to make a recognition response. The inter-trial interval (ITI) was 1.5 s. Each trial was 7.3 s long. The four task conditions were: (1) *Low-Load*, two dots were presented at the study display, and at cue, one dot location was indicated as relevant and the other dot location was deemed as no longer relevant for the later recognition test; (2) *High-Rel*, four dots were presented at the study display, and at cue, three dot locations were indicated as relevant and the other one dot location was deemed as no longer relevant for the later recognition test; (3) *High-Irrel*, four dots were presented at the study display, and at cue, one dot location was indicated as relevant and the other three dot locations were deemed as no longer relevant for the later recognition test; and (4) *High-Load*, six dots were presented at the study display, and at cue, three dot locations were indicated as relevant and the other three dot locations were deemed as no longer relevant for the later recognition test.

In response to the probe, subjects made button presses to indicate whether the probe matched one of the locations in the final memory set. There were three response conditions: (1) *match* (Yes), the probe matched one of the cued dot locations; (2) *high familiarity non-match* (No-HF), the probe matched one of the non-cued or to-be-ignored dot locations; and (3) *low familiarity non-match* (No-LF), the probe was in a new location, which was not in the initial memory set. The chance of match and non-match probes was equal. Half of non-match probes were "No-HF" probes and the other half were "No-LF" probes. To reduce the effect of trial history, the design ensured that the probe of the current trial did not appear in the preceding two trials. The combinations of the study and probe locations were presented psuedorandomly without repetition. The different types of cue and probe were also selected psuedorandomly and counterbalanced across runs.

A total of 520 trials (512 experimental trials and 8 catch trials) were divided into 8 runs. Each run has four blocks [17 trials in the first block (1 catch trials followed by 16 experimental trials) and 16 trials in the following three blocks] and a resting break (10 s) was inserted in between two blocks.

Visual Stimuli, apparatus and general procedures

To estimate the effect of individual differences in spatial working memory capacity on the behavioral and neural responses to the task manipulations, the same conventional spatial delayed task with set sizes of 1, 2, 4, 6, and 7 as in Experiment 1 (*Figure* 2) was used. One minor change was that the dots were presented on an 8x8 grid to match with the design of the main task. The same procedure and analysis of the *k*-score were used as in Experiment 1.

Visual Stimuli, apparatus and general procedures

For the main task, an 8x8 grid with a visual angle of 10.67° x 10.67° was used. Otherwise, details of the visual stimuli, apparatus, and general procedures were the same as in Experiment 1.

EEG Recording

The EEG recording was the same as in Experiment 1 but with two changes to accommodate the focus of this experiment in examining the post-cue sustained neural activity. First, all electrode impedances were kept below 2kΩ. Second, the EEG and EOG signals were amplified with a DC to 30 Hz bandpass filter, and digitized at 1000 Hz.

Data Analysis

For the behavioral data, trials with response time exceeding 2.5 standard deviations (SDs) from the mean of a given condition of a given subject were removed from the analyses. Accuracy and response time of conditions and probe types were analyzed using the repeated-measures analysis of variances (ANOVAs). Paired *t*-tests were used to test for the facilitation and PI effects.

For the EEG data, preprocessing was conducted using the EEGLab toolbox (Delmore, & Makeig, 2004) in MATLAB (The Mathworks, version 2008a). The EEG data was down sampled to 250 Hz. The data was then digitally filtered with 0.1 to 30 Hz bandpass on the transient neural activity (within the first 1000 ms of EEG data after cue onset) to parallel with the analysis conducted in Experiment 1, and was digitally filtered with 30 Hz lowpass only on the sustained neural activity (at 1000-2500 ms of EEG data after cue onset). Stimulus-locked averages were constructed for correct trials. Incorrect trials were excluded from analysis. Single epochs were baseline-corrected using 100 ms pre-stimulus onset, and ended till the end of the delay interval (2500 ms after cue onset). Eye blinks artifacts were corrected offline by Ocular Artifact Reduction (Semlitsch, Anderer, Schuster, & Presslich, 1986). Eye movement artifacts and body movement artifacts were removed from the averaged ERP waveforms using the moving window peak-to-peak threshold (with a threshold of 100 uV) in the ERPLab toolbox (www.erpinfo.org/erplab) and by visual inspection. Each individual datasets included a minimum of 60% usable trials per condition. All EEG data was re-referenced to the average of the 64 electrodes.

For statistical tests, ERP signals at several electrodes were quantified as the area under the curve within the selected time windows. ERPs elicited by the cue presentation were averaged separately according to the task condition (Low-Load, High-Rel, High-Irrel, and High-Load). To compare and contrast the transient cue-related ERPs with Experiment 1, the first second of the cue- and post-cue period was divided into four time windows after cue onset: 140-200 ms, 250-350 ms, 380-500 ms, and 500-700 ms. A 100 ms pre-cue baseline was used in this set of analysis. To measure the changes in the sustained memory-related neural activity following cue presentation, the post-cue period was divided into three time bins, each bin with 500 ms data points: 1000-1500 ms, 1500-2000 ms and 2000-2500 ms after cue onset. A 100 ms pre-study baseline was used in this set of analysis. ERPs of the High-Load condition were not included in the analyses of the cue stage (see Result for details). Repeated-measures ANOVAs were used to test for the statistical significance of the main effects and interactions. For the transient neural activity, to parallel with the analysis in Experiment 1, ERP data from four midline electrodes were used: Fz, Cz, Pz, and POz. For the sustained neural activity, ERP data (averaged across the three electrodes within a region) from six topographical regions were used (*Figure* 8): Left frontal: F5, FC5, and C5; Right frontal: F6, FC6, and C6; Fronto-Central midline: Fz, FCz, and

Cz; Left parietal: CP5, P5, and PO5; Right parietal: CP6, P6, PO6; Parietal-Posterior-Parietal midline: CPz, Pz, and POz.

For all ANOVAs, the Greenhouse-Geisser correction was used to correct for sphericity violations. The corrected probability values and degrees of freedom are used in this report. Bonferroni correction and false-discovery rate (fdr) were applied to adjust for multiple comparisons for the transient- and sustained-related neural activity, respectively.

3.3. Results

Behavioral data

We conducted separate one-way ANOVAs to test for the effects of relevant and irrelevant load on recognition responses to the probes (combining the results from the "Yes" and "No" probes). The results showed significant differences among the four conditions in mean accuracy and response time to the probes [$F(2.20, 68.25) = 52.35$, $p<.001$, and $F(1.54, 47.63) = 161.57$, $p<.001$, respectively; see *Table* 5]. Paired *t*-tests revealed significantly higher accuracy and faster responses to the Low-Load condition in comparison to the High-Rel and High-Load conditions (*p*s<.001), but not to the High-Irrel condition ($p=.54$). Responses were also more accurate and faster in the High-Irrel than in the High-Rel and High-Load conditions (*p*s<.001), and in the High-Rel condition than in the High-Load conditions (*p*s<.001). Similar results on response accuracy and response time were observed for the "Yes" probes [accuracy: $F(2.38, 73.81) = 39.16$, $p<.001$, and response time: $F(2.02, 62.56) = 112.86$, $p<.001$], "No-HF" probes [accuracy: $F(2.18, 67.47) = 10.57$, $p<.001$, and response time: $F(2.42, 75.08) = 75.42$, $p<.001$], and "No-LF" probes [response accuracy: $F(2.10, 65.04) = 12.74$, $p<.001$, and response time: $F(1.67, 51.67) = 56.77$, $p<.001$]. This indicated that the lower the relevant load, the more accurate and faster the responses were.

To further understand the effects of relevant and irrelevant load on recognition performance, we compared the response accuracy and response time between the relevant load and irrelevant load effects. As in Oberauer's (2001) study, the relevant load effect was measured by contrasting High-Rel and Low-Load condition, and the irrelevant load effect was measured by contrasting the High-Irrel and Low-Load[4]. Significant results for response accuracy and response

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[4] Data from the High-Load condition was not included in the analyses of the relevant and irrelevant load effects. The median estimated *k*-score was 4.08, which indicated that subjects were not able to hold 6 or 7 dot locations.

time were obtained for the relevant load effect, in which responses to the High-Rel condition were less accurate and slower in comparison to the responses to the Low-Load condition [response accuracy: -6.5%, $t(31) = -7.40$, $p<.001$, and response time: 113.58 ms, $t(31) = 13.91$, $p<.001$, respectively; see *Table* 6]. No significant effects were observed for the irrelevant load effect [response accuracy: -1.5%, $t(31) = -1.75$, $p=.09$, and response time: 8.85 ms, $t(31) = -0.46$, $p=.65$, respectively; see *Table* 6]. The results suggested that only the high amount of relevant information has significant influence on recognition behavioral performance, while high amount of no longer relevant information has no effect.

To estimate the PI effect from the no longer relevant dot locations on recognition performance, we calculated the response accuracy and response time differences between the "No-HF" and No-LF" probes across the four conditions. No significant results were observed [response accuracy: $F(2.52, 78.19) = .97$, $p=.399$, and response time: $F(2.54, 78.88) = 1.39$, $p=.254$]. We have also examined the PI effect of each condition separately. Response time differences between the "No-HF" and "No-LF" probes of the Low-Load condition was the only observed significant effect [$t(31) = -2.39$, $p<.05$]. In particular, the responses to the "No-HF" probes were faster relative to the "No-LF" probes ("No-HF" vs. "No-LF": 506.44 ms vs. 523. 13 ms). Thus, this significant difference was not a PI effect. The PI effect is usually small in spatial working memory as compared with verbal working memory. Previous studies found that the no longer relevant spatial information could still influence recognition behavior (e.g., Leung & Zhang, 2004; Oberauer & Kliegl, 2006; Yi et al., 2009; Experiment 1). The reason that we did not observe significant difference could due to the increased number of comparisons, which further diluted this weak effect.

Effects of individual difference on behavioral performance

Furthermore, we examined whether the high and low working memory capacity individuals showed different behavioral performance in the main task across the four task conditions (Low-Load, High-Rel, High-Irrel, and High-Load; *Table* 7). The estimated *k*-score ranged from 1.38 to 5.50. Using the median *k*-score (4.08), subjects were divided into two groups: a high working memory capacity group (mean $k= 4.71$) and a low working memory capacity group (mean $k= 2.94$). We conducted mixed-effects analysis with group as the between-group factor and conditions as the within-group factor. Analyses were combined for the "Yes" and “No” probes. Response accuracy and response time data revealed no significant main effect of group [response accuracy: *F*(1, 30) = 3.10, *p*=.089, and response time: *F*(1, 30) = 3.33, *p*=.078; *Table* 7]. Significant group by condition interaction was observed for the response accuracy data [*F*(2.24, 67.18) = 4.21, *p*<.05], in which the high performers responded more accurately than the low performers in the High-Rel and High-Load conditions [*t*(30) = -2.57, *p*<.05, and *t*(30) = -2.19, *p*<.05, respectively], but not in the Low-Load and High-Irrel conditions (*p*s>.05). No significant group by condition interaction was observed for the response time data though [*F*(1.46, 43.89) = 2.13, *p*=.143].

For the relevant load effect (High-Rel minus Low-Load), analyses on the response accuracy and response time data showed no main effect of group [response accuracy: *F*(1, 30) = 2.31, *p*=.139, and response time: *F*(1, 30) = 2.80, *p*=.105]. However, we observed significant group by relevant load interaction on the response accuracy and response time data [*F*(1, 30) = 11.66, *p*<.01, and *F*(1, 30) = 4.51, *p*<.05, respectively]. Post-hoc *t*-tests showed that high, relative to low, performers showed a smaller difference on accuracy and response time data between the High-Rel and Low-Load conditions [Response accuracy – high vs. low performers: -2.89% vs. -6.69%, *t*(30) = -3.41, *p*<.01, and response time – high vs. low performers: 103.88 ms vs. 77.62 ms, *t*(30) = -2.12, *p*<.05]. It may suggest a speed accuracy trade-off between the two groups. Hence, high performers were more accurate but slower, while low performers were less accurate but faster,

For the irrelevant load effect (High-Rel minus Low-Load), analyses on the response accuracy and response time data also showed no main effect of group [Response accuracy: *F*(1, 30) = 0.46, *p*=.505, and response time: *F*(1, 30) = 3.19, *p*=.084]. No significant group by irrelevant load interaction on response accuracy was observed (*p*=.269), while a significant interaction was observed for the response time data [*F*(1, 30) = 16.41, *p*<.01]. Post-hoc *t*-test revealed that the high performers showed a positive difference between High-Irrel and Low-load conditions (i.e., slower response time to the High-Irrel than Low-Load conditions), while the low performers showed a reverse pattern [i.e., faster response time to the High-Irrel and Low-Load conditions; high vs. low performers: 10.21 ms vs. -13.52 ms, *t*(30) = -4.05, *p*<.001]. This result suggested the high performers might show interference by the higher amount of no longer relevant information at recognition.

For the PI effect across the four conditions, results from the response accuracy and response time data revealed no main effect of group [accuracy: $F(1, 30) = 2.94$, $p=.097$, and response time: $F(1, 30) = 1.00$, $p=.327$], nor significant interaction between group and PI [accuracy: $F(2.42,72.63) = 1.65$, $p=.194$, and response time: $F(2.49,74.66) = 1.54$, $p=.216$]. We have also conducted *t*-tests to examine the PI effect (as measured by response accuracy and response time) separately for each condition between the high and low performers. No significant results were observed for the response accuracy and response time data for all comparisons as well (*p*s>.05).

Effects of sex on behavioral performance

We have also examined whether male and female differed in their behavioral performance to the four conditions. We conducted mixed-effects analysis with sex as the between-group factor and conditions (Low-Load, High-Rel, High-Irrel, and High-Load) as the within-group factor to examine whether the male and female showed differential behavioral performance and ERPs during the main task. Analyses were combined for the "Yes" and "No" probes. For the response accuracy data, no significant main effect of sex nor interaction effect between sex and condition was observed [$F(1, 30) = 0.06$, $p=.806$, and $F(2.23, 66.75) = 1.80$, $p=.169$, respectively]. However, a significant difference between sex was observed for the response time data, while the interaction between sex and condition was marginally significant [$F(1,30) = 5.38$, $p<.05$, and $F(1.60, 47.97) = 3.28$, $p=.057$, respectively; *Table* 8]. Paired *t*-test showed that male responded faster than female subjects (male vs. female: 489.894 ms vs. 554.389 ms).

For the relevant load effect (High-Rel minus Low-Load), results from the response accuracy and response time data revealed no main effect of sex [response accuracy: $F(1, 30) = 0.10$, $p=.751$, and response time: $F(1, 30) = 3.17$, $p=.085$]. No significant interaction effect between group and sex was observed for response accuracy and response time data as well [response accuracy: $F(1, 30) = 0.19$, $p=.67$, and response time: $F(1, 30) = 1.68$, $p=.205$]. Similarly, for the irrelevant load effect (High-Irrel minus Low-Load), results from the response accuracy and response time data revealed no main effect of sex [response accuracy: $F(1, 30) = 0.59$, $p=.447$, and response time: $F(1, 30) = 2.74$, $p=.108$]. No significant interaction effect between group and sex was observed for response accuracy and response time data as well [response accuracy: $F(1, 30) = 0.35$, $p=.557$, and response time: $F(1, 30) = .79$, $p=.382$].

For the PI effect across the four conditions, results from the response accuracy data revealed a significant main effect of sex but not a significant interaction effect between sex and condition [$F(1, 30) = 4.48$, $p<.05$, and $F(2.59, 77.62) = 1.80$, $p=.162$, respectively]. Paired *t*-tests showed that female, in comparison to male, subjects were less accurate in rejecting the "No-HF" probes than the "No-LF" probes. The PI effect of female was -1.8%, while male subjects did not show any PI effect (2.3%). For the response time data, no main effect of sex was observed [$F(1, 30) = 2.80$, $p=.105$, and $F(2.48, 74.41) = 1.18$, $p=.319$, respectively]. We have also conducted *t*-tests to examine the PI effect (as measured by response accuracy and response time) separately for each condition between male and female subjects. No significant results were observed for the response accuracy and response time data for all comparisons as well (*p*s>.05). In sum, the behavioral data revealed that, irrespective of conditions, male subjects responded faster than female subjects. Female, but not male, subjects were less accurate in correctly rejecting the "No-HF" than the "No-LF" probes.

<u>ERP data</u>

Effects of relevant and no longer relevant spatial information during transient cue-related neural activity

Figure 9 showed the whole trial waveforms for the four conditions, in which a 100 ms pre-study baseline was used. To understand whether different amount of relevant and irrelevant information would modulate the updating neural processes observed in Experiment 1, we conducted repeated measures ANOVAs using conditions (without the High-Load condition[5]) and electrodes as the within-subject factors on the first second after cue onset (Figure 10a for cue-elicited averaged waveforms for the three conditions and 10b for topographical maps) for the time windows used in Experiment 1: 140-200 ms, 250-350 ms, 380-500 ms, and 500-700 ms after cue onset.

As previously reported in Experiment 1, the neural activity observed during 140-200 ms after cue onset reflected early processing of cue meaning. Since there was only one type of cue

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[5] The estimate of the working memory capacity showed that half of the subjects were not able to retain six dot locations simultaneously. Hence, the data of the High-Load condition was not included in the analyses, and the data of the Low-Load condition was served as a control. With regard to this, the relevant load effect was measured by contrasting the ERPs between the High-Rel and Low-Load conditions, and the irrelevant load effect was measured by contrasting the ERPs between the High-Irrel and Low-Load conditions.

(an updating cue) involved in this current experiment, our results were as expected that no significant main effect of condition or condition by electrode interaction were observed [$F(2, 62) = 1.00$, p=.375, and $F(2.74, 84.91) = 2.08$, p=.114, respectively; see *Figure* 10a].

During 250-350 ms after cue onset, no main effect of condition was observed [$F(2, 62) = .38$, p=.680; see *Figure* 10b]. A significant condition by electrode interaction was found [$F(2.65, 82.04) = 3.87$, $p<.05$]. However, paired *t*-tests did not show any significant result across all comparisons and at all electrode sites (*p*s>.05). It is possible that the differences between the pairs of conditions in comparisons were small. And the ERPs went in opposite directions between the pair of frontal-/central-midline electrodes and the pair of parietal-/posterior-parietal-midline electrodes. Together, these two factors might contribute to the null results. Otherwise, the observed neural activity could potentially reflect an early part of the selective retrieval process, such as rapid re-focusing to the task relevant information (Fukuda & Vogel, 2009).

During 380-500 ms after cue onset, the main effect of condition was not significant [$F(2, 62) = 0.67$, p=.514; see *Figure* 10c]. However, we observed a significant condition by electrode interaction [$F(2.38, 73.90) = 7.23$, $p<.001$]. Paired *t*-tests showed that the ERPs were more positive in the High-Rel than High-Irrel conditions at the frontal-midline electrode ($p<.001$). However, no significant results were observed at the other electrode sites for the High-Rel and High-Irrel comparisons, or for the Low-Load and High-Rel/Irrel comparisons at all electrode sites (*p*s>.05). According to Experiment 1, neural activity obtained at the frontal-midline electrode during this time window was related to selective retrieval. Hence, the current result in this experiment reflected that more items were being selectively retrieved in the High-Rel than High-Irrel conditions.

During 500-700 ms after cue onset, the main effect of condition was not significant [$F(2, 62) = 0.00$, p=1.00; see *Figure* 10d]. However, we observed a significant condition by electrode interaction [$F(3.32, 102.99) = 3.75$, $p<.01$]. Paired *t*-tests showed that the ERPs were less positive in the High-Rel than High-Irrel conditions at the parietal-midline electrode ($p<.05$). However, no significant results were observed when the comparisons were between the high and low amount of relevant information (Low-Load versus High-Rel at all electrode sites; *p*s>.05) or between the high and low amount of irrelevant information (Low-Load versus High-Irrel at all electrode sites; *p*s>.05).

Early separation of task relevant and no longer relevant spatial information

Analyses on the transient cue-related ERPs seemed to show dissociation of neural activity in response to the relevant and no longer relevant spatial information starting around 250 ms after cue onset. To specifically examine the timing at which the neural representations began to separately code for task relevant and no longer relevant spatial information, we divided the first 1-second of the cue and post-cue delay into ten 100 ms time bins. *T*-tests were conducted to compare the ERPs between the relevant load effect and irrelevant load effects at the frontal-, central-, parietal-, and posterior-parietal-midline electrodes. Results showed that neural activity at the frontal- and central-midline electrode sites started to represent the relevant and no longer relevant spatial information separately at 300-400 ms after cue onset [Fz: $t(31) = 3.29$, $p<.01$, and Cz: $t(31) = 2.10$, $p<.05$; *Figure* 11]. Significant difference between the relevant and irrelevant load effects was observed later at 600-700 ms at the parietal-midline electrode site [$t(31) = -2.84$, $p<.01$; *Figure* 11]. However, no separation between the relevant and irrelevant load effects was observed at the posterior-parietal-midline electrode throughout the 1-second period (*p*s>.05).

Effects of task relevant and no longer relevant spatial information on sustained memory-related neural activity

The sustained ERPs associated with the relevant and irrelevant load effects were examined using three 500-ms bins between 1000 and 2500 ms after cue onset across six electrode clusters.

Sustained and widespread effects of relevant spatial information

To examine whether the post-cue ERPs were modulated by the amount of relevant information (High-Rel versus Low-Load), repeated measures ANOVAs were conducted using the relevant load effect and time as the within-subject factors (*Figure* 12 and *Supplementary Figure* 2). A main effect of relevant load was observed at the left frontal, fronto-central-midline and left parietal regions [$F(1, 31) = 6.57$, $p<.05$, $F(1, 31) = 17.92$, $p<.001$, and $F(1, 31) = 5.87$, $p<.05$, respectively; the parietal-posterior-parietal midline region was approaching significance, $F(1, 31) = 3.04$, $p=.091$]. Paired *t*-tests revealed that ERPs of the High-Rel condition in comparison to the Low-Load condition were more positive at the left-frontal and fronto-central-midline regions, and more negative at the left parietal region. A main effect of time was consistently observed across all six brain regions (*p*s<.001). A marginally significant load by time interaction was observed at the left parietal region [*F*(2, 62) = 3.06, *p*=.054]. Paired *t*-tests revealed that effect of high amount of relevant information on neural activity at the left parietal region was observed between 1000 and 2000 ms after cue onset, but the effect was not significant for the remaining 500 ms of the delay period (*p*=.10). At 2000-2500 ms in the post-cue delay period, the averaged waveforms elicited by the High-Rel and Low-Load conditions were still above baseline, especially at the P5 and PO5 electrode sites. The difference between the averaged waveforms elicited by the High-Rel and Low-Load conditions became smaller, which could contribute to the null result for this period of time. So, it was likely that the high amount of relevant information still have an effect on neural activity during the last 500 ms of the post-cue delay period, albeit to a lesser degree.

In sum, the results suggested that high, in comparison to low, amount of relevant information exerted strong and widespread effects on the memory-related sustained neural activity. This effect was consistent over time at the left frontal, fronto-central-midline, and left parietal regions. Previous studies have only examined the changes in memory- or rehearsal-related neural activity during initial encoding of different amount of information (e.g., Mecklinger & Pfeifer, 1996; Ruchkin et al., 1990, 1992, 1995). Here, we extended from previous research and showed that besides representing memory load, the sustained neural activity could also be used to measure the changes in neural activity of other cognitive processes in response to working memory updating (e.g., the load effect related to memory selection). Hence, different topographical distributions of the slow wave could reflect the involvement of different cognitive or memory processes. Previous neuroimaging studies have shown that the prefrontal cortex is involved in selective information processing and selective maintenance of task relevant information (e.g., Miller et al., 1996; Rainer et al., 1998). Hence, it is possible that the neural activity observed at the left frontal and fronto-central-midline regions could reflect cognitive processes related to working memory updating, while the neural activity at the left parietal region could reflect memory load of the updated memoranda.

Sustained but restricted effects of the irrelevant spatial information

To examine whether the post-cue ERPs were modulated by the amount of irrelevant information (High-Irrel versus Low-Load), repeated measures ANOVAs were conducted using irrelevant load and time as the within-subject factors (*Figure* 12 and *Supplementary Figure* 3). The effects of irrelevant information on the post-cue-related ERPs seemed to be weaker and more restricted than that of the relevant load. A main effect of irrelevant load was only observed at the left frontal region [$F(1, 31) = 5.64$, $p<.05$]. Paired *t*-tests revealed that at the left frontal region, ERPs of the High-Irrel condition was more positive than that of the Low-Load condition. A main effect of time was consistently observed across all six brain regions (*p*s<.001), such that the amplitudes of the ERPs of both conditions became larger over time at the frontal regions, and became smaller over time at the parietal regions. However, repeated-measures ANOVA revealed no significant interaction between irrelevant load and time. In sum, high, in comparison to low, amount of irrelevant information exerted stronger modulation at the left frontal region on the sustained memory-related neural activity.

Effects of individual differences on neural activity

We have also examined whether the amount of relevant and no longer relevant task information would affect the cue- and post-cue related neural activity in high and low working memory capacity individuals differently. We divided the subjects into two groups according to their estimated working memory capacity (high vs. low working memory capacity, see *Behavioral* results), and conducted mixed-effects analyses on the time windows following that of the whole group. No significant main effects of groups (*p*s>.05), nor interaction effects on group by electrode for the analysis on the transient ERP data (*F*s<1). For the analyses on the sustained ERP data, only the main effect of group for the relevant load and the irrelevant load effects at the parietal-posterior-parietal midline region were significant [Relevant load effect: $F(1, 30) = 4.86$, $p<.05$, and irrelevant load effect: $F(1, 30) = 6.96$, $p<.05$; *Figure* 13a and b]. At the parietal-posterior-parietal midline electrode cluster, the high performers showed a positive relevant load effect (i.e., ERPs in response to the High-Rel condition were greater than that of the Low-Load condition), while low performers showed a negative relevant load effect (i.e, ERPs in response to the High-Rel condition were smaller than that of the Low-Load condition). The same pattern was observed for the irrelevant load effects, in which the high performers showed a positive irrelevant load effect (i.e., ERPs in response to the High-Irrel condition was greater than that of the Low-Load condition), and low performers showed a negative irrelevant load effect (i.e., ERPs in response to the High-Irrel condition was smaller than that of the Low-Load condition).

Correlations between the ERP data and behavioral measures (e.g., *k*-score and PI effect) were also conducted. Only one significant correlation was found. A significant negative correlation was observed at the left frontal region between the PI index (as measured by response time)[6] and ERP differences of the irrelevant load effect for the whole delay period [1000-1500 ms: $r(32) = -0.48$, $p<.01$, 1500-2000 ms: $r(32) = -0.57$, $p<.01$, and 2000-2500 ms: $r(32) = -0.53$, $p<.01$; see *Figure* 13c-e].

Effects of sex on neural activity

We conducted mixed-effects analysis to examine whether male and female would show different patterns of neural activity. Sex was used as the between-group factor and condition and time were used as the within-group factors. Although we found behavioral differences in response time and PI effect between male and female subjects, no significant main effect of sex nor interaction effects for sex, condition, and time in the neural data were observed across all stages at all electrode clusters (*p*s>.05).

3.4. Discussion

In our first experiment, we demonstrated that different neural processes were involved in memory selection. In this experiment, we further examined the sustained neural activity related to the maintenance of spatial information following updating. We found that neural activity was quickly separated by the amount of task relevant and no longer relevant spatial information starting at 300 ms after cue onset at the frontal- and central-midline electrode sites. Beyond 1 second after cue onset, neural activity at the frontal region appear to represent sustained effects of memory selection and maintenance of relevant and irrelevant information, as we observed significant interaction effects between relevant/irrelevant load by time throughout the delay period. On the other hand, neural activity at the parietal regions might represent a sustained effect of maintaining relevant information, as we only observed a significant interaction effect between relevant load and time throughout the delay period.

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[6] This PI effect as measured by response time was derived from the difference between the PI effect of the High-Irrel condition (response time difference between the “No-HF” and “No-LF” probes) and the PI effect of the Low-Load condition (response time difference between the “No-HF” and “No-LF” probes).

Transient cue-related neural activity

Results from this experiment showed that the updating-related neural processes observed in Experiment 1 could be further modulated by different amount of relevant and no longer relevant information. We suggested in Experiment 1 that the neural activity measured between 140 and 200 ms after cue onset reflected the processing of cue meaning (e.g., Awh et al., 2000; Griffin & Nobre, 2003; Nobre et al., 2004; Simpson et al, 2011). In Experiment 1, we used a selection cue to indicate updating and a non-selection cue to indicate the maintenance of the whole memorandum presented at study. We, thus, observed differences in ERPs associated with the selection and non-selection cues. In contrast, in the current experiment, only one type of cue was used (i.e., selection cue). Hence, our data was as expected that no difference among the conditions were observed.

After processing the meaning of the cue, a significant condition by electrode interaction between 250 and 350 ms after cue onset seemed to suggest re-focusing of attention to the task relevant information (Fukuda & Vogel, 2009). The meaning of the cue indicated the operations needed for the conditions, such as remember one and ignore one dot location in the Low-Load condition, remember three and ignore one dot locations in the High-Rel condition, and remember one and ignore three dot locations in the High-Irrel condition. Therefore, the cognitive demand of re-focusing of attention to the task relevant information was different among the conditions. However, due to small ERP differences among the pairs of comparisons in the statistical analyses, and the opposite directions in ERPs between the pair of frontal-/central-midline electrodes and the pair of parietal-/posterior-parietal-midline electrodes, post-hoc *t*-tests analyses failed to show any significant results. Therefore, we were unable to conclude how different amount of relevant and no long relevant spatial information would modulate this hypothesized re-focusing-related neural activity.

Results from Experiment 1 suggested that the neural activity during 380-500 ms after cue onset reflected selective retrieval or directing attention to task relevant information (e.g., Kuo et al., 2012; McCollough et al., 2007; Vogel & Machizawa, 2004, Vogel et al., 2005). However, from the design of Experiment 1, as well as the results from previous studies, we did not know if this neural component would differ if different amount of task relevant information was involved. Here, we further modulated the demand of selective retrieval as one relevant dot locations in the Low-Load and High-Irrel conditions and three relevant dot locations in the High-

Rel conditions. Results in this experiment expanded the findings in Experiment 1 and showed an enhanced selective retrieval component in situation where the demand of selective retrieval was high (High-Rel versus High-Irrel conditions). However, no differences in ERPs related to selective retrieval were observed when comparisons were made between a high load versus a low load of relevant (High-Rel versus Low-Load conditions) or no longer relevant information (High-Irrel versus Low-Load conditions). Together, the results suggest that selective retrieval might not be a simple reflection of selectively retrieving task relevant information, but it might reflect interplay between selecting relevant and de-selecting no longer relevant information.

In Experiment 1, we suggested that the neural activity observed between 500 and 700 ms after cue onset was related to re-organization or evaluation of the working memory content. However, results from this current experiment seemed to reflect storage of relevant information. Therefore, the ERPs of the High-Rel condition was more negative (indicating an increase in memory load) than the ERPs of the High-Irrel condition. It is important to note that the experimental designs were different between Experiment 1 and 2. As mentioned previously, Experiment 2 involved memory selection conditions only, while Experiment 1 involved both memory selection and non-selection conditions. Results from this current experiment reflected the neural activity differences within the memory selection condition, and hence, that might reflect a storage difference rather than an organization or evaluation difference. Having that said, without a control condition where no memory selection is required (similar as the NS condition in Experiment 1), it is inconclusive to explain the cognitive process(es) that this neural component represents.

Transient and quick separation of relevant and no longer relevant information by the frontal electrode sites

The prefrontal cortex (specifically, the dorsolateral prefrontal cortex) has been shown to involve in selection and maintenance of task relevant information (e.g., Desimone & Duncan, 1995; Miller et al., 1996; Rainer et al., 1998; Rao et al., 1997; Sakai & Passingham, 2003; see review by Postle, 2006). Evidence from single-unit recordings revealed that prefrontal neurons are selective to task relevant information in the existence of distracting information (Miller et al., 1996). Miller and colleagues (1996) used a delayed-matched-to-sample task to record neuronal activity in the prefrontal and inferior temporal cortices in two rhesus monkeys. Results showed that, among the recorded populations of prefrontal neurons, a majority of neurons coded for task relevant information, while a few coded for task irrelevant information (Miller et al., 1996). This suggested that the prefrontal neurons are responsible for selecting task relevant information among distracting information (Miller et al., 1996). In our experiment, we found cue-related transient neural activity differentiating the High-Rel and High-Irrel conditions at the frontal regions at 380-500 ms after cue onset. Our result corroborate with previous findings in supporting that the frontal region is responsible for selecting information that is relevant to the task goals.

In addition, we observed quick separation of task relevant and no longer relevant spatial information at about 300 ms after cue onset at the frontal- and central-midline electrode sites, while the separation was observed at about 600 ms after cue onset at the parietal-midline electrode site. The timing of separating task information seems to be domain-specific. Previous studies on single-unit recordings showed that separation of relevant and irrelevant spatial information occurred within the first 500 ms after the beginning of the selection process (Hasegawa et al., 2004; Rainer et al., 1998). Rainer and colleagues (1998) recorded the neural activity of two adult rhesus monkeys from a group of neurons in the lateral prefrontal cortex while the monkeys performed a delayed-matching-to-sample task. The monkeys were instructed to encode an item at the cued location. After a 1.5 s delay, the monkeys were tested by judging whether or not the probe was presented at the target location. The results demonstrated that the neural representations of the target locations in the recorded populations of prefrontal neurons occurred as early as 140 ms after array onset. Another study using an oculomotor version of the delayed-matching-to-sample task found that separation of relevant and irrelevant spatial information by some prefrontal neurons occurred within the first 500 ms after the sample display onset (Hasegawa et al., 2004).

In contrast, separation of non-spatial information seems to take longer time than that for spatial information. A behavioral study showed that separation of relevant and no longer relevant information took about 1 second since cue onset in verbal working memory (Oberauer, 2001), Similarly, separation of object information in working memory took about the same time (Xu, 2010). This difference in timing could be due to the involvement of different neural pathways between the two types of information. Neuroimaging and animal studies suggested that working memory functions for spatial and non-spatial information are subserved by different neural pathways between the frontal and parietal cortices (Goldman-Rakic, 1996; Smith, Jonides, & Koeppe, 1996; Ungerleider & Mishkin, 1982; see review by Levy & Goldman-Rakic, 2000). In particular, the dorsal frontal-parietal pathway was proposed to mediate location-based "where" information, while the ventral frontal-parietal pathway was proposed to mediate non-spatial-based (e.g., verbal and object information) "what" information (see review by Levy & Goldman-Rakic, 2000). Taken together, the current and previous' findings revealed dissociation between processing of spatial versus non-spatial content in working memory updating, such that the frontal region showed transient and quicker effect in selecting task relevant spatial information than non-spatial information.

Strong and widespread sustained representations of relevant spatial information

Besides a selection-related transient activity, our data also revealed a memory-related sustained effect of task relevant information at the left and fronto-central regions and left parietal region (although the result was only marginally significant for the last 500 ms of the delay period). The prefrontal cortex has been suggested to provide sustained maintenance effect of spatial and object information (Courtney et al., 1997; Levy & Goldman-Rakic, 2001). Such sustained maintenance effect enabled the prefrontal cortex to play a role in recovering task relevant information after interference by exerting top-down modulation signals to the storage-related brain regions (Miller & Cohen, 2001; Miller at al., 1996, Tomita, Ohbayashi, Nakahara, Hasegawa, & Miyashita, 1999). As previously discussed, Miller and colleagues (1996) showed that neural representation of task relevant information by the prefrontal neurons was not disrupted by the presence of distractors. In contrast, neural representation of task relevant information by the neurons in the inferior temporal cortex was disrupted by distractors (Miller et al., 1996). More importantly, prefrontal neurons have been demonstrated to maintain task relevant information during the presence of distractors, and re-activate the neural representations of task relevant information at the inferior temporal cortex when the distractors were gone (e.g., Miller et al., 1996; Tomita et al., 1999).

An ERP study also showed memory-related sustained neural activity by the prefrontal cortex (Kessler & Keifer, 2005). In this ERP experiment, subjects first encoded either two or four objects, followed by a retention interval. During the retention interval, an interfering distractor was presented in half of the trials and was absent in the other half of the trials. It was then followed by a recovery interval, and then the probe test, in which subjects have to judge if the probe was of the same or different size as in the original display. Results showed that task information was maintained by the frontal region during the presence of interference at retention, and when the distractor disappeared, the frontal region site showed transient and quick effect in initiating the recovery process in the occipital-temporal region (Kessler & Keifer, 2005). Although our task design was different from the above mentioned studies, our results were comparable to theirs. We found that neural activity at the left frontal and fronto-central midline electrode clusters showed a transient and quick selection effect on task relevant information as in Kessler and Keifer's study (2005). The top-down modulation signals were then exerted by the prefrontal cortex onto the parietal cortex for storage of relevant spatial information (Miller & Cohen, 2001).

The posterior association areas (in particular, the parietal cortex) have been shown to associate with maintenance of task relevant information (e.g., Leung et al., 2004; Passingham & Sakai, 2004; Todd & Marois, 2004; Xu & Chun, 2006). By parametrically varying the memory load of visual stimuli in a delayed-matched-to-sample task, Todd and Marios (2004) showed that the neural activity at the posterior parietal cortex was highly correlated with the number of items stored in visual short-term memory (as estimated by the *k*-score). In ERP studies, the NSW has been shown to reflect the number of items maintained in memory (Mecklinger & Pfeifer, 1996), and the cognitive load in rehearsing the memory content (e.g., Ruchkin et al., 1990, 1992, 1995). An increase in memory load would elicit a more negative slow wave. Some studies have shown that spatial information elicited maximum amplitude of NSW at the parietal brain regions (e.g., Mecklinger & Pfeifer, 1996; Rolke et al., 2000). Since our data at the left parietal region showed differences in ERPs between high and low load of relevant spatial information (High-Rel versus Low-Load conditions), but not between high and low load of no longer relevant spatial information (High-Irrel versus Low-Load conditions), it suggested that neural activity at the left parietal region might reflect storage of task relevant information. Although our statistical analysis showed a lack of sustained activity for this parietal effect at the last 500 ms of the delay period, the two memory loads were still different number-wise, and were above baseline. Therefore, a sustained effect was likely, but it was not strong enough to reach statistical significance.

Sustained representation, rather than elimination, of no longer relevant spatial information

The neural representation of irrelevant object information was suggested to be transient, and was observed at the lateral occipital complex (Xu, 2010). In Xu's study (2010), subjects were asked to remember the colors but ignore the shapes of the objects. Neural activity observed at the lateral occipital complex revealed a transient representation of the task irrelevant shape information (which only lasted till the end of the encoding period) when the encoding demand of task relevant color information was low (Xu, 2010). In contrast, we found sustained neural representations of maintaining no longer relevant spatial information at the left frontal region throughout the delay period. This result was similar to the findings by Hasegawa and colleagues (2004), who demonstrated that sustained neuronal firing by the prefrontal cortex neurons represented task irrelevant spatial information. Taken together, differences between transient and sustained representations of irrelevant/no longer relevant information might suggest that our working memory system handles spatial versus non-spatial information differently, such that the maintenance effect observed at the frontal region lasted longer for the irrelevant/no longer relevant spatial information than the non-spatial information.

Furthermore, having neural representations of no longer relevant spatial information that did not diminish in magnitude throughout the delay period might contribute to a stronger PI effect in the High-Irrel condition than the Low-Load condition as observed at the left frontal region. It is important to note that this PI effect was not a straight forward calculation as in Oberauer's (2001) and Yi and colleagues' (2009) study (i.e., response time to the intrusion probes minus the response time to the non-intrusion/negative probes). The PI effect in this experiment was measured as the difference between the PI effect of the High-Irrel condition (involving three no longer relevant dot locations) and the PI effect of the Low-Load condition (involving one no longer relevant dot location). We observed a negative correlation between the PI effect (as measured by response time) and ERP differences of the irrelevant load effect throughout the whole delay period. This indicated that when the no longer relevant information was still being kept in active representation throughout the delay period at the left frontal region, the residual memory from the High-Irrel condition has a stronger intrusion effect than that of the Low-Load condition at recognition. Yi and colleagues (2009) used a delay-recognition paradigm with digits as stimuli and found that the PI effect was observed even when the delay period was extended from 0.1 seconds to 9 seconds. Furthermore, their results showed a negative correlation between the PI effect and the neural correlates of memory selection in the left inferior parietal lobe, the precuneus and the dorsolateral middle frontal gyrus (Yi et al., 2009). Hence, our results were similar to the previous study, and yet, we further showed that the PI effect could be modulated by different amount of no longer relevant information.

The effect of individual differences in working memory capacity on working memory performance

In sum, the results on the cue stage showed that working memory capacity modulated sustained memory-related neural activity rather than transient cue-related neural activity. The modulation was mainly observed at the parietal-posterior-parietal midline region on high, relative to low, amount of relevant and no longer relevant dot locations. The posterior association areas are postulated for storage of task relevant information (e.g., Leung et al., 2004, 2007; Passingham & Sakai, 2004; Todd & Marois, 2004). It is important to note that no difference in ERPs between the high and low performers was observed at the study stage (analyses not shown). This suggested that both groups of performers have encoded the dot locations equally well. Hence, differences observed at the memory-related sustained neural activity at the cue stage might suggest that high and low performers differed in their ability to recover from the interference caused by the no longer relevant information (Kessler & Kiefer, 2005).

Furthermore, for the memory-related sustained activity, we observed various significant correlations between the ERPs of the relevant/irrelevant load effect and working memory capacity or PI effect at the frontal and parietal electrode sites. The prefrontal cortex has been suggested to play a role in selection and maintenance of task relevant information (e.g., Desimone & Duncan, 1995; Miller et al,, 1996; Rainer et al., 1998; Rao et al., 1997; Sakai & Passingham, 2003; see review by Postle, 2006). Negative correlations at the fronto-central-midline and left frontal regions between the ERPs of the relevant/irrelevant load effect and PI effect (as measured by response time) suggested that subjects who experienced smaller differences in selection and/or maintenance of high, relative to low, amount of relevant/irrelevant information was more prone to a stronger PI effect. On the other hand, correlations between the sustained ERPs and working memory capacity or PI effect at the parietal regions suggested that subjects who showed a smaller difference in the memory-related sustained activity were more likely to have a larger capacity or experienced a weaker PI effect (e.g., Yi et al., 2009).

The effect of sex on working memory performance

Similar to the findings in Experiment 1, male subjects responded faster than female subjects. In this experiment, we also found a small PI effect for female but not for male subjects. Female subjects were less accurate in responding to the "No-HF" probes than to the "No-LF" probes, while results of the male subjects showed a reverse pattern. The results could be due to the differences in the use of strategy to complete the task. As reveled by the post-test interview, male subjects tended to group the dots of the same color to form shapes or patterns at the initial encoding stage, while female subjects tended to remember the details of the exact locations of each studied dot. As reported in Experiment 1, various studies have shown strategic differences between male and female human and rat subjects (e.g., Lawton, 1994; Williams et al., 1990). Male subjects tended more to use geometric or configurational cues and to form spatial relationships among objects, while female subjects tended more to use landmarks, features of spatial objects. Together, the use of different strategies could contribute to faster responses by the male subjects than the female subjects.

As revealed by the post-test interview, strategic difference in selecting task relevant information was also observed after the presentation of the updating cue. After seeing the cue, male subjects tended to retrieve all presented studied dots and then added tags to indicate which dots were relevant or no longer relevant. In contrast, female subjects claimed that they tended to just remember the dot locations which were indicated as relevant by the cue. Silverman and Eals (1992) have shown that females were better in remembering both the object identity and the locations of objects than males. In the study, subjects were presented with a random array of lines during the study display for 1 minute, which was then followed by a recognition test in the object identity memory task. After completing the task, subjects were presented with another array, in which some of the lines from the original study array were moved and some were not. Subjects were asked to identify the moved and unmoved lines in the object location memory task. Silverman and Eals (1992) found that females were more accurate than males in both memory tasks. Since response time was not measured in this study, it is not clear if the results were cue to speed-accuracy tradeoff. Furthermore, since no manipulation on the level of familiarity of the probes were made, it is not clear if higher accuracy of females observed in Silverman and Eals' (1992) study would contribute to a PI effect at recognition.

4. General Discussion

This dissertation characterized the neural processes in association with updating and maintenance of spatial information in working memory using ERP. Two ERP experiments were conducted. We characterized the neural correlates of working memory updating of spatial information, and its effect on the subsequent recognition behavior in Experiment 1. We revealed the timing to select relevant and no longer relevant spatial information in memory, and their effects on the subsequent memory-related sustained neural activity in Experiment 2.

Selective encoding and selective maintenance have been shown to recruit similar neural processes in supporting working memory updating of verbal and visual working memory (Nee & Jonides, 2009; see review by Lepsien & Nobre, 2006). Directing attention or selective attention to task relevant information has been proposed as such neural process (e.g., Awh et al., 2000; Griffin & Nobre, 2003). However, it is unclear if the same neural processes were involved in updating spatial information. Further, most of the previous research has focused on examining the neural processes involved in selecting task relevant information among other task irrelevant information or distractors. However, little is known about whether selecting task relevant information among no longer relevant information, which was relevant previously, would yield similar or different neural responses. In light of this, Experiment 1 was designed to characterize the neural processes in correspondence to selective maintenance of relevant spatial information among no longer relevant information. To achieve this goal, a memory selection cue was inserted during the retention interval in a delayed-recognition paradigm to indicate memory updating. Results from Experiment 1 showed that memory selection of spatial information was not a single neural event. Rather, the temporal dynamics revealed an early ERP component associated with processing of cue meaning, an early to intermediate component associated with re-focusing of attention to task relevant information, an intermediate component associated with selective retrieval, and a late component associated with content re-organization or evaluation according to the task goals. Memory updating also influenced probe-elicited ERPs and behavioral performance during probe recognition. Memory selection facilitates recognition performance, as observed in both behavioral and ERP results.

In Experiment 2, we further examined the neural processes involved in memory updating of spatial information over a longer period of time. By reviewing previous studies (e.g., Hasegawa et al., 2004; Oberauer, 2001; Xu, 2010), the findings seem to suggest that the time it took for the updating processes to begin was domain-specific, in which the duration was shorter for updating spatial (e.g., Hasegawa et al., 2004) than verbal (e.g., Oberauer, 2001) information. Our results from Experiment 2 showed that the neural representations of relevant and no longer relevant spatial information separated quickly (about 300 ms after cue onset at the frontal- and central-midline electrode sites) as in other studies on spatial working memory (e.g., Hasegawa et al., 2004; Rainer et al., 1998). In contrast, selecting and updating of relevant verbal information among other no longer relevant information has been suggested to take about 1 second since cue onset (Oberauer, 2001). Hence, our findings provided further support for our speculation of a domain-specificity phenomenon in updating spatial versus non-spatial working memory content.

Furthermore, different patterns of sustained neural representations for relevant and no longer relevant information were observed in different electrode clusters. In particular, sustained representations of relevant information were observed at the left frontal and fronto-central midline electrode clusters, while representations of relevant information at the left parietal electrode clusters were found to diminish over time. A sustained but weaker modulation by the no longer relevant spatial information was observed at the left frontal electrode clusters. Previous findings on the neural representations of irrelevant information were mixed. Representation of irrelevant visual information was found to be represented by the transient, but not sustained, neural activity (Xu, 2010). In contrast, representation of irrelevant spatial information was found to be represented by the sustained, but not transient, neural activity (Hasegawa et al., 2004). Taken together, our results suggest that different neural processes might be involved in updating spatial versus non-spatial working memory content.

The effects of individual differences in working memory capacity on the ERP data were also examined in the two experiments. Our findings suggested a potential recruitment of different brain regions or mechanisms by the high and low working memory capacity individuals at initial encoding and updating. Results from Experiment 1 showed that the low, relative to high, working memory capacity individuals recruited the frontal regions in addition to the parietal regions at initial encoding. Results from Experiment 2 showed that the low working memory capacity individuals were worse than the high working memory capacity individuals in maintaining separable memory traces of relevant and no longer relevant information in the posterior brain regions. Results from the two experiments reflected both qualitative and quantitative differences between high and low working memory capacity individuals in the recruitment of brain regions or mechanisms in updating and maintaining spatial working memory.

Sex, on the other hand, showed little effect on the neural processes of updating and maintenance. Male and female subjects only showed a behavioral difference in response time in both experiments. Male subjects responded faster than female subjects. This difference was likely to be caused by the use of different strategies in encoding and selecting dot locations. Male subjects were more likely to remember the gist of the dot locations and add tags as an extra heuristic during the selection process. In contrast, female subjects tended to remember the exact locations in initial encoding and updating. These differences in strategies could contribute to the timing difference at decision making. Decision making became more difficult in Experiment 2 as varied amounts of relevant and no longer relevant information were involved, the use of strategy could further hurt the female subjects' performance, as shown by the significant PI effect in female subjects but not male subjects.

This dissertation revealed both cue-related transient and memory-related sustained neural activities in response to updating and maintenance of spatial working memory. However, the experimental design was not sensitive enough to demonstrate whether the updating process was due to enhancement of task relevant information or suppression of no longer relevant information. Enhancing the neural representations of task relevant information and suppressing the neural representations of task irrelevant information are both essential in achieving optimal working memory performance (Zanto & Gazzaley, 2009). Results from Experiment 2 seem to suggest an enhancement effect on the relevant information, and a possible suppression effect on the no longer relevant information (as reflected by the significant difference in ERPs between the High-Rel and High-Irrel conditions at selective retrieval). Therefore, future studies are needed to further investigate the contribution of the enhancement and suppression mechanisms on selective information processing.

5. Conclusion

Memory selection was used to examine working memory updating and maintenance of spatial information. We used an ERP approach to dissociate the neural processes involved in updating and maintenance. Based on the present findings, we concluded that updating spatial information involved different neural processes or mechanisms than updating non-spatial information. Qualitative and quantitative differences between high and low working memory capacity individuals in the recruitment of brain regions or mechanisms in updating and maintenance of spatial working memory were also observed. However, little effect on updating and maintenance of spatial working memory was found between male and female.

References

Anllo-Vento, L., & Hillyard, S.A. (1996). Selective attention to the color and direction of moving stimuli: Electrophsyological correlates of hierarchical feature selection. *Perception & Psychophysics, 58*(2), 191-206.

Awh, E., Anllo-Vento, L., & Hillyard, S.A. (2000). The role of spatial selective attention in working memory for locations: evidence from event-related potentials. *Journal of Cognitive Neuroscience, 12* (5), 840-847. doi:10.1162/089892900562444

Awh, E., & Jonides, J. (1998). Spatial selective attention and spatial working memory. In R. Parasuraman (Ed.), *The attentive brain*. Cambridge: MIT Press.

Awh, E., Jonides, J., & Reuter-Lorenz, P.A. (1998). Rehearsal in spatial working memory. *Journal of Experimental Psychology: Human Perception and Performance, 24*(3), 780-90.

Awh, E., Smith, E.E., & Jonides, J. (1995). Human rehearsal processes and the frontal lobes: PET evidence. *Annals of New York Academy of Sciences, 769* (Structure and Functions of the Human Prefrontal Cortex), 97-118. doi:10.1111/j.1749-6632.1995.tb38134.x

Baddeley, A.D. (1986). *Working memory*. New York, NY, US: Clarendon Press/Oxford University Press.

Baddeley, A. (1992). Working memory. *Science, 255*(5044), 556-559.

Baddeley, A.D. & Hitch, G.J. (1974). Working Memory. In G. H. Bower (Ed.), *The psychology of learning and motivation* (Vol. 8, pp. 47-89). New York: Academic Press.

Barrett, S.E., & Rugg, M.D. (1989). Event-related potentials and the semantic matching of faces. *Neuropsychologia*, *27*(7), 913–22.

Birbaumer, N., Elbert, T., Canavan, A.G.M., & Rockstroh, B. (1990). Slow potentials of the cerebral cortex and behaviour. *Physiological Reviews, 70*(1), 1- 41.

Bledowski, C., Rahm, B., & Rowe, J.B. (2009). What "works" in working memory? Separate systems for selection and updating of critical information. *The Journal of Neuroscience, 29*(43), 13735-13741. doi:10.1523/JNEUROSCI.2547-09.2009

Brookhuis, K.A., Mulder, G., Mulder, L.J.M., Gloerich, A.B.M., van Dellen, H.H., van der Meere, J.J., & Ellermann, H. (1981). Late positive components and stimulus evaluation time. *Biological Psychology, 13*, 107-123.

Brown, J. (1954). The nature of set-to-learn and of intra-material interference in immediate memory. *Quarterly Journal of Experimental Psychology, 6*(4), 141-148.

Bunge, S.A., Hazeltine, E., Scanlon, M.D., Rosen, A.C., & Gabrieli, J.D.E. (2002). Dissociable Contributions of Prefrontal and Parietal Cortices to Response Selection. *NeuroImage*, *17*(3), 1562–1571. doi:10.1006/nimg.2002.1252

Casey, M.B., & Brabeck, M.M. (1990). Women who excel on a spatial task: Proposed genetic and environmental factors. *Brain and Cognition*, 12, 73-84.

Chafee, M.V., & Goldman-Rakic, P.S. (1998). Matching patterns of activity in primate prefrontal area 8a and parietal area 7ip neurons during a spatial working memory task. *Journal of Neurophysiology, 79*(6), 2919-2940.

Courtney, S.M. (2004). Attention and cognitive control as emergent properties of information representation in working memory. *Cognitive, Affective & Behavioral Neuroscience*, *4*(4), 501-16.

Courtney, S.M., Petit, L., Maisog, J.M., Ungerleider, L.G., & Haxby, J.V. (1998). An area specialized for spatial working memory in human frontal cortex. *Science, 279*(5355), 1347–51.

Courtney, S.M., Ungerleider, L.G., Keil, K., & Haxby, J.V. (1996). Object and spatial visual working memory activate separate neural systems in human cortex. *Cerebral cortex, 6*(1), 39–49.

Courtney, S.M., Ungerleider, L.G., Keli, K., & Haxby, J.V. (1997). Transient and sustained activity in a distributed neural system for human working memory. *Nature*, 386, 608-611.

Cowan, N. (1995). *Attention and memory: An integrated framework.* Oxford Psychology Series, No. 26. Oxford University Press.

Cowan, N. (2001). The magical number 4 in short-term memory: A reconsideration of mental storage capacity. *Behavioral and Brain Sciences, 24*, 87-114. doi: 10.1017/S0140525X01003922

D'Esposito, M., Aguirre, G.K., Zarahn, E., Ballard, D., Shin, R.K., & Lease, J. (1998). Functional MRI studies of spatial and nonspatial working memory. *Cognitive Brain Research*, *7*(1), 1-13.

Deco, G., & Rolls, E.T. (2005). Attention, short-term memory, and action selection: a unifying theory. *Progress in Neurobiology*, *76*(4), 236-56. doi:10.1016/j.pneurobio.2005.08.004

Delmore, A., & Makeig, S. (2004). EEGLAB: An open source toolbox for analysis of single-trial EEG dynamics. *Journal of Neuroscience Methods, 134*, 9-21.

Desimone, R., & Duncan, J. (1995). Neural mechanisms of selective visual attention. *Annual Review of Neurosicence,* 18(1), 193-222.

Donchin, E. (1981). Surprise!...Surprise? *Psychophysiology, 18*(5), 493-513.

Donchin, E., & Coles, M.G.H. (1988). Is the P300 component a manifestation of context updating? *Behavioral and Brain Sciences, 11*, 357-374.

Donchin, E., Kramer, A.F., & Wickens, C.D. (1986). Applications of brain event-related potentials to problems in engineering psychology. In M.G.H. Coles, E. Donchin, & S.W. Porges (Eds.), *Psycholphysiology: Systems, processes, and applications* (pp. 702–718). New York: Guilford Press.

Drew, T., & Vogel, E.K. (2009). Working Memory, Capacity Limitations. In: L. Squire (Ed.), *The New Encyclopedia of Neuroscience* (Vol.10, pp. 523-531). Amsterdam: Elsevier.

Du, Y., Xiao, Z., Song, Y., Fan, S., Wu, R., & Zhang, J.X. (2008). An electrophysiological signature for proactive interference resolution in working memory. *International Journal of Psychophysiology, 69*, 107-111. doi:10.1016/j.ijpsycho.2008.03.007

Duncan, J., Humphreys, G., & Ward, R. (1997). Competitive brain activity in visual attention. *Current Opinion in Neurobiology*, *7*(2), 255–61.

Ecker, U.K.H., Lewandowsky, S., Oberauer, K., & Chee, A.E.H. (2010). The components of working memory updating: an experimental decomposition and individual differences. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *36*(1), 170-89. doi:10.1037/a0017891

Eimer, M. (1993). Spatial cueing, sensory gating and selective response preparation: An ERP study on visuo-spatial orienting. *Electroencephalography and Clinical Neurophysiology, 88*(5), 408-20.

Eimer, M. (1995). Event-related potential correlates of transient attention shifts to color and location. *Biological Psychology, 41*, 167-182.

Friedman, N.P., & Miyake, A. (2004). The relations among inhibition and interference control functions: a latent-variable analysis. *Journal of Experimental Psychology. General*, *133*(1), 101–35. doi:10.1037/0096-3445.133.1.101

Frye, C.A. (1994). Estrus-associated decrements in a water maze task are limited to acquisition. *Physiology & Behavior,* 57, 5–14.

Fukuda, K., & Vogel, E.K. (2009). Human variation in overriding attentional capture. *The*

Journal of Neuroscience, *29*(27), 8726–33. doi:10.1523/JNEUROSCI.2145-09.2009

Funahashi S., Bruce C.J., & Goldman-Rakic P.S. (1990) Visuospatial coding in primate prefrontal neurons revealed by oculomotor paradigms. *Journal of Neurophysiology, 63*(4), 814–831.

Funahashi S., Bruce C.J., & Goldman-Rakic P.S. (1991) Neuronal activity related to saccadic eye movements in the monkey's dorsolateral prefrontal cortex. *Journal of Neurophysiology, 65*(6), 1464–1483.

Fuster, J. M. (1990). Inferotemporal units in selective visual attention and short-term memory. *Journal of Neurophysiology, 64*(3), 681–697

Fuster, J.M. (2001). The prefrontal cortex – an update: Time is of the essence. *Neuron*, 30, 319-333. doi:10.1016/S0896-6273(01)00285-9

Fuster, J.M., & Alexander, G.E. (1971). Neuron activity related to short-term memory. *Science, 173*(3997), 652–654.

Garavan, H. (1998). Serial attention within working memory. *Memory & Cognition, 26*(2), 263-276.

Gazzaley, A., Cooney, J.W., McEvoy, K., Knight, R.T., & D'Esposito, M. (2005). Top-down enhancement and suppression of the magnitude and speed of neural activity. *Journal of Cognitive Neuroscience*, *17*(3), 507–17. doi:10.1162/0898929053279522

Goldman-Rakic, P.S. (1987). Circuitry of primate prefrontal cortex and regulation of behavior by representational memory. In V.B. Mountcastle & F. Plum (Eds.), *Handbook of physiology: The nervous system, higher functions of the brain* (vol. 5, pp. 373–417). Bethesda, MD: American Physiological Society.

Goldman-Rakic, P.S. (1995). Cellular basis of working memory. *Neuron*, 14, 477-485.

Goldman-Rakic, P.S. (1996). Regional and cellular fractionation of working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *93*(24), 13473-80.

Gomer, R.J., Spicuzza, R.J., & O'Donnell, R.D. (1976). Evoked potential correlates of visual item recognition during memory-scanning tasks. *Physiological Psychology, 4*, 61-65.

Gorgoraptis, N., Catalao, R.F.G., Bays, P.M., & Husain, M. (2011). Dynamic updating of working memory resources for visual objects. *The Journal of Neuroscience, 31*(23), 8502-8511. DOI:10.1523/JNEUROSCI.0208-11.2011

Griffin, I.C., & Nobre, A.C. (2003). Orienting attention to locations in internal representations. *Journal of Cognitive Neuroscience, 15*(8), 1176-1194. doi:10.1162/089892903322598139

Hampson, E. (1990). Variations in sex-related cognitive-abilities across the menstrual-cycle. *Brain and Cognition,* 14, 26–43.

Handy, T.C., & Mangun, G.R. (2000). Attention and spatial selection: Electrophysiological evidence for modulation by perceptual load. *Perception & Psychophysics, 62*(1), 175-86.

Harris, L.J. (1981). Sex-related variations in spatial skills. In L.S. Liben, A.H. Patterson, & N. Newcombe (Eds.), *Spatial representation and behavior across the life span*. New York: Academic Press.

Hasegawa, R.P., Peterson, B.W., & Goldberg, M.E. (2004). Prefrontal neurons coding suppression of specific saccades. *Neuron*, *43*(3), 415–25. doi:10.1016/j.neuron.2004.07.013

Healy, S.D., Braham, S.R., & Braithwaite, V.A. (1999). Spatial working memory in rats: No differences between the sexes. *Proceedings of the Royal Society of London B,* 266, 2303–2308.

Heslenfeld, D.J., Kenemans, J.L., Kok, A., & Molenaar, P.C.M. (1997). Feature processing and attention in the human visual system: an overview. *Biological Psychology, 45*, 183-215.

Hillyard, S.A., & Anllo-Vento, L. (1998). Event-related brain potentials in the study of visual selective attention. *Proceedings of the National Academy of Sciences of the United States of America, 95*(3), 781–787.

Hillyard, S.A., Vogel, E.K., & Luck, S.J. (1998). Sensory gain control (amplification) as a mechanism of selective attention: electrophysiological and neuroimaging evidence. *Philosophical Transactions of the Royal Society B: Biological Sciences, 353*(1373), 1257–1270.

Jiang. Y., Olson, I.R., & Chun, M.M. (2000). Organization of visual short-term memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 26*(3), 683-702. doi: 1O.1O37W0278-7393.26.3.683

Johannes, S., Munte, T.F., Heinze, H.J., & Mangun, G.R. (2003). Luminance and spatial attention effects on early visual processing. *Cognitive Brain Research, 2*(3), 189-205.

Johnson, R., Jr. (1988). The amplitude of the P300 component of the event-related potential: Review and synthesis. In P.K. Ackles, J.R. Jennings, & M.G.H. Coles (Eds.), *Advances in psychophysiology*, (Vol. III, pp. 69-137). Greenwich, CT: Jai Press.

Johnson, R. Jr. & Donchin, E. (1982). Sequential expectancies and decision making in a changing environment: An electrophysiological approach. *Psychophysiology, 19*(2)*,* 183-200.

Johnson, M.R., Mitchell, K.J., Raye, C.L., D'Esposito, M., & Johnson, M.K. (2007). A brief thought can modulate activity in extrastriate visual areas: Top-down effects of refreshing just-seen visual stimuli. *NeuroImage, 37*, 290-299. doi:10.1016/j.neuroimage.2007.05.017

Johnson, M.K., Raye, C.L., Mitchell, K.J., Greene, E.J., & Anderson, A.W. (2003) fMRI evidence for an organization of prefrontal cortex by both type of process and type of information. *Cerebral Cortex, 13*(3), 256-273. doi: 10.1093/cercor/13.3.265

Johnson, M.K., Raye, C.L., Mitchell, K.J., Greene, E.J., Cunningham, W.A., & Sanislow, C.A. (2005). Using fMRI to investigate a component process of reflection: Prefrontal correlates of refreshing a just-activation representation. *Cognitive, Affective, & Behavioral Neuroscience, 5*(3), 339-361.

Jonides, J., Sylvester, C.C., Lacey, S.C., Wager, T.D., Nichols, T.E., & Awh, E. (2003). Modules of working memory. In. R. H. Kluwe, G. Lüer, & F. Rösler (Eds.), Principles of learning and memory (pp. 113–134). Cambridge, MA: Birkhäuser.

Kelley, W.M., Miezin, F.M., McDermott, K.B., Buckner, R.L., Raichle, M.E., Cohen, N.J., Ollinger, J.M., et al. (1998). Hemispheric specialization in human dorsal frontal cortex and medial temporal lobe for verbal and nonverbal memory encoding. *Neuron*, *20*(5), 927–36.

Kessler, K., & Kiefer, M. (2005). Disturbing visual working memory: electrophysiological evidence for a role of the prefrontal cortex in recovery from interference. *Cerebral Cortex, 15*(7), 1075–87. doi:10.1093/cercor/bhh208

Kiss, I., Pazderka-Robinson, H., & Floden, D. (2001). Event-related brain potential and central executive function: Further evidence for Baddeley's model. *Journal of Psychophysiology, 15*(1), 1-13. doi: 10.1027//0269-8803.15.1.1

Kiss, I., Pisio, C. Francois, A., & Schopflocher, D. (1998). Central executive function in working memory: Event-related potential studies. *Brain Research, 6*(4), 235-247.

Kok, A. (1997). Event-related (ERP) reflections of mental resources: A review and synthesis. *Biological Psychology, 45*, 19-56.

Kok, A. (2001). On the utility of P3 amplitude as a measure of processing capacity. *Psychophysiology, 38*, 557-577.

Kotchoubey, B., Jordan, J.S., Grözinger, B., Westphal, K., & Kornhuber, H. (1996). Event-related brain potentials in a varied-set memory search task: A reconsideration. *Psychophysiology, 33*, 530-540

Kuo, B.-C., Stokes, M., & Nobre, A.C. (2012). Attention modulates maintenance of representations in visual short-term memory. *Journal of Cognitive Neuroscience, 24*(1), 51-60. doi:10.1162/jocn_a_00087

Lang, W., Starr, A., Lang, V., Lindinger, G., & Deecke, L. (1992). Cortical DC potential shifts accompanying auditory and visual short-term memory. *Electroencephalography and Clinical Neurophysiology*, *82*(4), 285–295.

Landman, R., Spekreijse, H., & Lamme, V.A.F. (2003). Large capacity storage of integrated objects before change blindness. *Vision Research, 43*(2), 149-164.

Lawton, C.A. (1994). Gender differences n way-finding strategies: Relationship to spatial ability and spatial anxiety. *Sex Roles*, 30 (11/12), 765-779.

Lehto, J. (1996). Working memory capacity and summarizing skills in ninth-graders. *Scandinavian Journal of Psychology, 37*, 84-92.

Lenartowicz, A., Escobedo-Quiroz, R., & Cohen, J.D. (2010). Updating of context in working memory: An event related potential study. *Cognitive, Affective, & Behavioral Neuroscience, 10*(2), 298-315. doi:10.3758/CABN.10.2.298.

Lepsien, J., Griffin, I.C., Devlin, J.T., & Nobre, A.C. (2005). Directing spatial attention in mental representations: Interactions between attentional orienting and working-memory load. *NeuroImage, 26*, 733-743. doi:10.1016/j.neuroimage.2005.02.026

Lepsien, J., & Nobre, A.C. (2006). Cognitive control of attention in the human brain: Insights from orienting attention to mental representations. *Brain Research, 1105*, 20-31. doi:10.1016/j.brainres.2006.03.033

Leung, H.-C., Gore, J.C., & Goldman-Rakic, P.S. (2002). Sustained mnemonic response in the human middle frontal gyrus during on-line storage of spatial memoranda. *Journal of Cognitive Neuroscience*, *14*(4), 659–71. doi:10.1162/08989290260045882

Leung, H.-C., Oh, H., Ferri, J., & Yi, J. (2007). Load response functions in the human spatial working memory circuit during location memory updating. *Neuroimage, 35*(1), 368-377. doi:10.1016/j.neuroimage.2006.12.012

Leung, H.-C., Seelig, D., & Gore, J. C. (2004). The effect of memory load on cortical activity in the spatial working memory circuit. *Cognitive, Affective & Behavioral Neuroscience*, *4*(4), 553–63.

Leung, H.-C., & Zhang, J. (2004). Interference resolution in spatial working memory. *NeuroImage, 23*(3), 1013-1019. doi:10.1016/j.neuroimage.2004.07.053

Levy, R., & Goldman-Rakic, P.S. (2000). Segregation of working memory functions within the dorsolateral prefrontal cortex. *Experimental Brain Research*, *133*(1), 23-32.

Linn, M.C., & Petersen, A.C. (1985). Emergence and characterization of sex differences in spatial ability: A meta-analysis. *Child Development*, 56, 1479-1498.

Luck, S.J., & Hillyard, S.A. (2000). The operation of selective attention at multiple stages of processing: evidence from human and monkey electrophysiology. In: Gazzaniga MS, ed. *The new cognitive neurosciences* (pp. 687–700). Cambridge, MA: MIT Press.

Luck, S.J., Hillyard, S.A., Mouloua, M., Woldorff, M.G., Clark, V.P., & Hawkins, H.L. (1994). Effects of spatial cuing on luminance detectability: Psychophysical and electrophysiological evidence for early selection. *Journal of Experimental Psychology: Human Perception and Performance, 20,* 887-904.

Luria, A.R. (1966). *Higher cortical functions in man*. New York: Basic Books.

Mangun, G.R., Hopfinger, J.B., Kussmaul, C.L., Fletcher, E.M., & Heinze, H.J. (1997). Covariations in ERP and PET measures of spatial selective attention in human extrastriate visual cortex. *Human brain mapping*, *5*(4), 273–9. doi:10.1002/(SICI)1097-0193(1997)5:4<273::AID-HBM12>3.0.CO;2-F

Makovski, T., & Jiang, Y.V. (2007). Distributing versus focusing attention in visual short-term memory. *Psychonomic Bulletin & Review, 14*, 1072-1078.

Makovski, T., Sussman, R., & Jiang, Y.V. (2008). Orienting attention in visual working memory reduces interference from memory probes. *Journal of Experimental Psychology. Learning, Memory, and Cognition*, *34*(2), 369-80. doi:10.1037/0278-7393.34.2.369

Markowitz, D.A., Shewcraft, R.A., Wong, Y.T., & Pesaran, B. (2011). Competition for visual selection in the oculomotor system. *The Journal of Neuroscience, 31*(25), 9298-9306. doi:10.1523/JNEUROSCI.0908-11.2011

Martinovic, J., Mordal, J., & Wuerger, S.M. (2011). Event-related potentials reveal an early advantage for luminance contours in the processing of objects. *Journal of Vision, 11*(7), 1-15. doi:10.1167/11.7.1

McCollough, A.W., Machizawa, M.G., & Vogel, E.K. (1997). Electrophysiological measures of maintaining representations in visual working memory. *Cortex, 43*(1), 77-94.

McElree, B., & Dosher, B.A. (1989). Serial position and set size in short-term memory: the time course of recognition. *Journal of Experimental Psychology: General, 118*(4), 346-373.

Mecklinger, A., & Pfeifer, E. (1996). Event-related potentials reveal topographical and temporal distinct neuronal activation patterns for spatial and object working memory. *Cognitive Brain Research, 4*, 211-224.

Miller, E.K., & Cohen, J.D. (2001). An integrative theory of prefrontal cortex function. *Annual Review of Neuroscience*, *24*, 167-202. doi:10.1146/annurev.neuro.24.1.167

Miller, E.K., Erickson, C.A., & Desimone, R. (1996). Neural mechanisms of visual working memory in prefrontal cortex of the macaque. *The Journal of Neuroscience*, *16*(16), 5154-67.

Miyake, A., Friedman, N.P., Emerson, M.J., Witzki, A.H., Howerter, A., & Wager, T.D. (2000). The unity and diversity of executive functions and their contributions to complex “Frontal Lobe” tasks: a latent variable analysis. *Cognitive Psychology*, *41*(1), 49-100. doi:10.1006/cogp.1999.0734

Monsell, S. (1996). Control of mental processes. In B. Vicki (Ed.), *Unsolved mysteries of the mind: Tutorial essays in cognition* (pp. 93-148). Oxford, England: Erlbaum (UK) Taylor & Francis.

Morris, N. & Jones, D.M. (1990). Memory updating in working memory: The role of the central executive. *British Journal of Psychology, 81*, 111-121. doi:10.111/j.2044-8295.1990.tb02349.x

Morgan, H.M., Jackson, M.C., Klein, C., Mohr, H., Shapiro, K.L., & Linden, D.E.J. (2010). Neural signatures of stimulus features in visual working memory--a spatiotemporal approach. *Cerebral Cortex, 20*(1), 187-97. doi:10.1093/cercor/bhp094

Nagel, I.E., Preuschhof, C., Li, S.-C., Nyberg, L., Bäckman, L., Lindenberger, U., & Heekeren, H.R. (2009). Performance level modulates adult age differences in brain activation during spatial working memory. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(52), 22552–7. doi:10.1073/pnas.0908238106

Nee, D.E., Brown, J.W., Askren, M.K., Berman, M.G., Demiralp, E., Krawitz, A., & Jonides, J. (2012). A Meta-analysis of Executive Components of Working Memory. *Cerebral Cortex.* Advance online publication. doi:10.1093/cercor/bhs007

Nee, D.E., & Jonides, J. (2009). Common and distinct neural correlates of perceptual and memorial selection. *NeuroImage*, *45*(3), 963-975. doi:10.1016/j.neuroimage.2009.01.005

Nee, D.E., Wager, T.D., & Jonides, J. (2007). Interference resolution: insights from a meta-analysis of neuroimaging tasks. *Cognitive, Affective & Behavioral Neuroscience*, *7*(1), 1–17.

Nobre, A.C., Coull, J.T., Maquet, P., Frith, C.D., Vandenberghe, R., & Mesulam, M.M., (2004). Orienting attention to locations in perceptual versus mental representations. *Journal of Cognitive Neuroscience, 16*(3), 363– 373. doi: 10.1162/089892904322926700

Nobre, A.C., Griffin, I.C., & Rao, A. (2008). Spatial attention can bias search in visual short-term memory. *Frontiers in Human Neuroscience, 1*(4), 1-9. doi: 10.3389/neuro.09.004.2007

Oberauer, K. (2001). Removing irrelevant information from working memory: A cognitive aging study with the modified Sternberg task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *27*(4), 948-957. doi:10.1037//0278-7393.27.4.948

Oberauer, K. (2002). Access to information in working memory: Exploring the focus of attention. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *28*(3), 411–421. doi:10.1037//0278-7393.28.3.411

Oberauer, K., & Kliegl, R. (2006). A formal model of capacity limits in working memory. *Journal of Memory and Language, 55*, 601-626. doi:10.1016/j.jml.2006.08.009

Pashler, H. (1998). Familiarity and visual change detection. *Perception and Psychophysics*, *44*(4), 369-378. doi: 10.3758/BF03210419

Passingham, D., & Sakai, K. (2004). The prefrontal cortex and working memory: physiology and brain imaging. *Current Opinion in Neurobiology*, *14*(2), 163–8. doi:10.1016/j.conb.2004.03.003

Picton, T.W. (1992). The P300 wave of the human event-related potential. *Journal of Clinical Neurophysiology, 9*, 456-479.

Postle, B.R. (2006). Working memory as an emergent property of the mind and brain. *Neuroscience*, *139*(1), 23–38. doi:10.1016/j.neuroscience.2005.06.005

Pritchard, W.S. (1981). Psychophysiology of P300. *Psychological Bulletin, 89*, 506-540.

Rainer, G., Asaad, W.F., & Miller, E.K. (1998). Selective representation of relevant information by neurons in the primate prefrontal cortex. *Nature*, *393*(6685), 577-9. doi:10.1038/31235

Rao, S.C., Rainer, G., & Miller, E.K. (1997). Integration of what and where in the primate prefrontal cortex. *Science, 276*(5313), 821–824.

Rolke, B., Heil, M., Hennighausen, E., Häussler, C., & Rösler, F. (2000). Topography of brain electrical activity dissociates the sequential order transformation of verbal versus spatial information in humans. *Neuroscience Letters, 1-2*, 81-84.

Rowe, J., Hughes, L., Eckstein, D., & Owen, A.M. (2008). Rule-selection and action-selection have a shared neuroanatomical basis in the human prefrontal and parietal cortex. *Cerebral cortex, 18*(10), 2275-2285. doi:10.1093/cercor/bhm249

Rowe, J.B., & Passingham, R.E. (2001). Working memory for location and time: Activity in prefrontal area 46 relates to selection rather than maintenance in memory. *NeuroImage, 14,* 77-86. doi:10.1006/nimg.2001.0784

Ruchkin, D.S., Canoune, H.L., Johnson, R., & Ritter, W. (1995). Working memory and preparation elicit different patterns of slow wave event-related brain potentials. *Psychophysiology*, *32*(4), 399-410.

Ruchkin, D.S., Johnson, R., Canoune, H.L., & Ritter, W. (1990). Short-term memory storage and retention: An event-related brain potential study. *Electroencephalography and Clinical Neurophysiology, 76*, 419-439.

Ruchkin, D.S., Johnson, R., Grafman, J., Canoune, H.L., & Ritter, W. (1992). Distinctions and similarities among working memory processes: An event-related potential study. *Cognitive Brain Research, 1,* 53-66.

Rugg, M.D., & Coles, M.G.H. (1995). eds. *Electrophysiology of mind.* Oxford: Oxford University Press.

Sakai, K., & Passingham, R.E. (2003). Prefrontal interactions reflect future task operations. *Nature neuroscience*, *6*(1), 75–81. doi:10.1038/nn987.

Semlitsch, H.V., Anderer, P., Schuster, P., & Presslich, O. (1986). A solution for reliable and valid reduction of ocular artifacts, applied to the P300 ERP. *Psychophysiology, 23*(6), 695–703.

Sherry, D. F., & Hampson, E. (1997). Evolution and the hormonal control of sexually-dimorphic spatial abilities in humans. *Trends in Cognitive Sciences,* 1, 50–56.

Silverman, I., & Eals, M. (1992). Sex differences in spatial abilities: Evolutionary theory and data. In J. Barkow, L. Cosmides, & J. Tooby (Eds.), *The adapted mind: Evolutionary psychology and the generation of culture* (pp. 533–549). Oxford, UK: Oxford University Press.

Shucard, J.L., Tekok-Kilic, A., Shiels, K., & Shucard, D.W. (2009). Stage and load effects on ERP topography during verbal and spatial working memory. *Brain research*, *1254*, 49–62. doi:10.1016/j.brainres.2008.11.063

Simpson, G.V., Weber, D.L., Dale, C.L., Pantazis, D., Bressler, S.L., Leahy, R.M., & Luks, T.L. (2011). Dynamic activation of frontal, parietal, and sensory regions underlying anticipatory visual spatial attention. *The Journal of Neuroscience, 31*(39), 13880-13889. doi:10.1523/JNEUROSCI.1519-10.2011

Sligte, I.G., Scholte, H.S., & Lamme, V.A.F. (2008). Are there multiple visual short-term memory stores? *PLoS One, 3*(2), e1699. doi:10.1371/journal.pone.0001699

Smith, E.E. & Jonides, J. (1999). Storage and Executive Processes in the Frontal Lobes. *Science, 283*(5408), 1657-1661.

Smith, E.E., Jonides, J., & Koeppe, R.A. (1996). Dissociating verbal and spatial working memory using PET. *Cerebral Cortex, 6*(1), 11-20.

Smyth, M.M., & Scholey, K.A. (1992). Determining spatial span: the role of movement time and articulation rate. *The Quarterly Journal of Experimental Psychology, 45A*(3), 479-501

Squires, K.C., Donchin, E., Herning, R.I., & McCarthy, G. (1977). On the influence of task relevance and stimulus probability on event-related-potential components. *Electroencephalography and Clinical Neurophysiology, 42*, 1-14.

Sutton, S., Tueting, P., Zubin, J., & John, E.R. (1967). Information delivery and the sensory evoked potential. *Science, 155*(3768), 1436-1439.

Tays, W.J., Dywan, J., Mathewson, K.J., & Segalowitz, S.J. (2008). Age differences in target detection and interference resolution in working memory: An event-related potential study. *Journal of Cognitive Neuroscience, 20*(12), 2250-2262.

Tays, W.J., Dywan, J., & Segalowitz, S.J. (2009). General proactive interference and the N450 response. *Neuroscience Letters, 462*, 239-243. doi:10.1016/j.neulet.2009.07.025

Theeuwes, J. (2010). Top-down and bottom-up control of visual selection. *Acta Psychologica*, *135,* 77-99. doi:10.1016/j.actpsy.2010.02.006

Todd, J.J., & Marois, R. (2004). Capacity limit of visual short-term memory in human posterior parietal cortex. *Nature*, *428*(6984), 751–4. doi:10.1038/nature02466

Tomida, H., Ohbayashi, M., Nakahara, K., Hasegawa, I., & Miyashita, Y. (1999). Top-down signal from prefrontal cortex in executive control of memory retrieval. *Nature, 401*(6754), 699-703.

Underwood, B.J. (1957). Interference and forgetting. *Psychological Review, 64,* 49-60.

Ungerleider, L.G. & Mishkin, M. (1982). Two cortical visual systems. In *Analysis of visual behavior* (ed. D. J. Ingle, R.J. W. Mansfield & M. A. Goodale), pp. 549-586. Cambridge, Mass.: M.I.T. Press

Vogel, E.K., & Awh, E. (2008). How to Exploit Diversity for Scientific Gain: Using Individual Differences to Constrain Cognitive Theory. *Current Directions in Psychological Science, 17*(2), 171–176. doi:10.1111/j.1467-8721.2008.00569.x

Vogel, E.K. & Machizawa, M.G. (2004). Neural activity predicts individual differences in visual working memory capacity. *Nature, 428*, 748-751.

Vogel, E.K., & McCollough, A.W., & Machizawa, M.G. (2005). Neural measures reveal individual differences in controlling access to working memory. *Nature, 438,* 500-503. doi:10.1038/nature04171

Voyer, D., Postma, A., Brake, B., & Imperato-McGinley, J. (2007). Gender differences in object location memory: A meta-analysis. *Psychonomic Bulletin & Review*, 14(1), 23-38.

Voyer, D., Voyer, S., & Bryden, M.P. (1995). Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. *Psychological Bulletin*, 117, 250-270.

Williams, C.L., Barnett, A.M., & Meck, W.H. (1990). Organizational effects of early gonadal secretions on sexual differentiation in spatial memory. *Behavioral Neuroscience*, 104, 84-97.

Wilson F.A., O'Scalaidhe S.P., & Goldman-Rakic P.S. (1993) Dissociation of object and spatial processing domains in primate prefrontal cortex. *Science, 260*(5116), 1955–1958.

Xu, Y. (2010). The neural fate of task-irrelevant features in object-based processing. *The Journal of Neuroscience, 30*(42), 14020-8. doi:10.1523/JNEUROSCI.3011-10.2010

Xu, Y., & Chun, M.M. (2006). Dissociable neural mechanisms supporting visual short-term memory for objects. *Nature*, *440*(7080), 91–5. doi:10.1038/nature04262

Yi, Y., Driesen, N., & Leung, H.-C. (2009). Behavioral and neural correlates of memory selection and interference resolution during a digit working memory task. *Cognitive, Affective, & Behavioral Neuroscience, 9*(3), 249-259. doi:10.3758/CABN.9.3.249

Yi, Y., & Friedman, D. (2011). Event-related potential (ERP) measures reveal the timing of memory selection processes and proactive interference resolution in working memory.

Brain Research, 1411, 41-56. doi:10.1016/j.brainres.2011.07.004

Zanto, T.P., & Gazzaley, A. (2009). Neural suppression of irrelevant information underlies optimal working memory performance. *The Journal of Neuroscience, 29*(10), 3059-66. doi:10.1523/JNEUROSCI.4621-08.2009

Zhang, J.X., Leung, H.-C., & Johnson, M.K. (2003). Frontal activation associated with accessing and evaluating information in working memory: an fMRI study. *NeuroImage, 20*, 1531-1539. doi:10.1016/j.neuroimage.2003.07.016

Zhang, J.X., Wu, R., Kong, L., Weng, X., & Du, Y. (2010). Electrophysiological correlates of proactive interference in the 'Recent Probes' verbal working memory task. *Neuropsychologia, 48*(7), 2167-2173.

Table 1. Behavioral results of Experiment 1. Mean accuracy (%) and response time (ms) to Yes and No probes are shown for the three task conditions with standard deviations in parentheses. For parallel comparison with the performance on the No trials of the NS4 and NS2 conditions, only responses to the No-LF probes of the MS condition are used to calculate the mean accuracy and response time. ***, *p*<.001. **, *p*<.01. *, *p*<.05.

Condition	Mean Accuracy (%)		Mean Response Time (ms)	
	Yes	No	Yes	No
MS	90.45 (4.59)	97.59 (2.96)	520.32 (99.91)	547.64 (101.00)
NS4	84.46 (6.43)	93.26 (8.99)	620.63 (133.41)	624.98 (117.63)
NS2	94.74 (5.66)	98.50 (2.18)	522.87 (92.76)	530.96 (90.15)
Response Facilitation:				
MS-NS4	5.99*** (4.07)	4.33* (7.49)	-100.31*** (57.55)	-77.34*** (36.20)
MS-NS2	-4.27*** (4.84)	-0.91 (2.38)	-2.55 (37.78)	16.68* (35.34)

Table 2. Proactive interference (PI) effect of Experiment 1. Mean accuracy (%) and response time (ms) data are shown for the two No probe types of the MS condition with standard deviations in parentheses. ***, *p*<.001. **, *p*<.01. *, *p*<.05.

Probe Type	Mean Accuracy (%)	Mean Response Time (ms)
No-HF	93.43 (6.38)	563.77 (110.74)
No-LF	97.59 (2.96)	547.64 (101.00)
PI	-4.16*** (5.26)	16.13* (33.66)

Table 3. Behavioral results on individual differences in working memory capacity of Experiment 1. Mean accuracy (%) and response time (ms) to the Yes and No probes are shown for the three task conditions with standard deviations in parentheses. For parallel comparison with the performance on the No trials of the NS4 and NS2 conditions, only responses to the No-LF probes of the MS condition are used to calculate the mean accuracy and response time.

Condition	Mean Accuracy (%)				Mean Response Time (ms)			
	Yes		No		Yes		No	
	High	Low	High	Low	High	Low	High	Low
MS	93.30 (3.84)	87.61 (3.42)	98.64 (2.05)	96.54 (3.43)	483.87 (95.54)	556.77 (94.39)	514.91 (96.57)	580.38 (98.69)
NS4	87.50 (4.61)	81.41 (6.73)	97.5 (4.33)	89.01 (10.56)	567.13 (121.30)	674.13 (127.92)	586.65 (118.56)	663.30 (108.48)
NS2	97.05 (3.68)	92.40 (6.47)	98.86 (2.34)	98.13 (2.06)	489.16 (96.33)	556.57 (79.33)	514.44 (102.09)	547.49 (77.74)

Table 4. Behavioral results on sex differences of Experiment 1. Mean accuracy (%) and response time (ms) to the Yes and No probes are shown for the three task conditions with standard deviations in parentheses. For parallel comparison with the performance on the No trials of the NS4 and NS2 conditions, only responses to the No-LF probes of the MS condition are used to calculate the mean accuracy and response time.

Condition	Mean Accuracy (%)				Mean Response Time (ms)			
	Yes		No		Yes		No	
	Male	Female	Male	Female	Male	Female	Male	Female
MS	90.52 (4.14)	90.37 (5.30)	96.20 (3.13)	99.25 (1.69)	478.01 (74.46)	571.09 (106.12)	513.43 (80.08)	588.70 (111.95)
NS4	85.05 (7.35)	83.75 (5.43)	92.01 (10.23)	94.75 (7.50)	567.24 (84.66)	684.71 (156.22)	580.40 (86.95)	678.47 (131.21)
NS2	92.4 (6.08)	97.5 (3.73)	98.29 (2.04)	98.75 (2.43)	483.14 (68.62)	570.53 (98.46)	495.93 (66.19)	573.00 (100.04)

Table 5. Behavioral results of Experiment 2. Mean accuracy (%) and response time (ms) to the Yes and No probes are shown for the four task conditions with standard deviations in parentheses.

Condition	Mean Accuracy (%)				Mean Response Time (ms)			
	Overall	Yes	No-HF	No-LF	Overall	Yes	No-HF	No-LF
Low-Load	95.31 (4.64)	95.16 (5.25)	94.82 (6.42)	96.09 (5.66)	472.43 (73.06)	429.32 (73.92)	506.44 (82.86)	523.12 (81.66)
High-Rel	90.52 (5.13)	88.67 (6.68)	92.87 (5.21)	91.89 (10.61)	563.18 (95.80)	542.90 (104.97)	581.77 (107.9)	587.43 (89.22)
High-Irrel	94.36 (4.98)	93.70 (5.98)	94.82 (5.59)	95.21 (5.61)	470.78 (80.72)	438.18 (91.49)	495.96 (75.81)	507.8 (83.06)
High-Load	86.64 (6.88)	84.86 (9.03)	88.96 (7.93)	87.89 (10.81)	584.59 (109.11)	570.14 (120.56)	601.98 (113.9)	597.22 (102.58)

Table 6. Behavioral Results on the relevant and irrelevant load effect of Experiment 2. Differences in mean accuracy (%) and response time (ms) to the Yes and No probes for the High-Rel minus Low-Load conditions (Relevant Load Effect) and High-Irrel minus Low-Load conditions (Irrelevant Load Effect) and are shown for the four task conditions with standard deviations in parentheses.

Condition	Mean Accuracy Difference (%)				Mean Response Time Difference (ms)			
	Overall	Yes	No-HF	No-LF	Overall	Yes	No-HF	No-LF
Relevant Load Effect	-4.78 (3.65)	-6.49 (5.87)	-1.95 (5.42)	-4.19 (7.67)	90.79 (36.90)	113.57 (52.91)	75.33 (46.82)	64.3 (48.97)
Irrelevant Load Effect	-0.95 (3.07)	-1.46 (3.74)	0.00 (5.66)	-0.87 (5.51)	-1.65 (20.27)	8.85 (34.69)	-10.47 (38.01)	-15.32 (29.9)

Table 7a. Mean accuracy (%) to the Yes and No probes are shown for the four task conditions on individual differences in working memory capacity of Experiment 2. Standard deviations in parentheses.

Condition	Overall		Yes		No-HF		No-LF	
	High	Low	High	Low	High	Low	High	Low
Low-Load	95.56 (5.71)	95.07 (3.44)	95.31 (6.22)	95.02 (4.28)	95.31 (5.82)	94.34 (7.15)	96.29 (5.62)	95.90 (5.90)
High-Rel	92.68 (5.49)	88.38 (3.82)	90.63 (6.51)	86.72 (6.48)	93.75 (6.35)	91.99 (3.78)	95.70 (7.47)	88.09 (12.09)
High-Irrel	95.21 (6.00)	93.51 (3.73)	95.12 (6.82)	92.29 (4.82)	94.34 (6.27)	95.31 (4.97)	96.29 (5.73)	94.14 (5.46)
High-Load	89.16 (7.06)	84.13 (5.89)	87.11 (9.33)	82.62 (8.42)	90.43 (8.73)	87.5 (7.03)	91.99 (7.39)	83.79 (12.30)

Table 7b. Mean response time (ms) to the Yes and No probes are shown for the four task conditions on individual differences in working memory capacity of Experiment 2. Standard deviations in parentheses.

Condition	Overall		Yes		No-HF		No-LF	
	High	Low	High	Low	High	Low	High	Low
Low-Load	489.80	455.08	442.65	416.01	528.74	484.15	544.57	501.69
	(73.75)	(70.36)	(78.87)	(68.54)	(71.73)	(89.37)	(82.38)	(77.56)
High-Rel	593.68	532.70	565.65	520.17	627.43	536.12	614.27	560.59
	(87.65)	(96.44)	(95.16)	(112.32)	(94.81)	(103.09)	(84.02)	(88.64)
High-Irrel	500.01	441.56	468.54	407.83	523.97	467.96	539.02	476.59
	(83.57)	(68.27)	(100.70)	(72.08)	(69.51)	(73.31)	(82.54)	(73.27)
High-Load	616.72	552.47	604.14	536.14	633.38	570.59	625.80	568.64
	(105.50)	(106.18)	(111.28)	(123.25)	(118.99)	(102.73)	(100.09)	(99.94)

Table 8a. Mean accuracy (%) to the Yes and No probes are shown for the four task conditions on sex differences of Experiment 2. Standard deviations in parentheses.

Condition	Overall		Yes		No-HF		No-LF	
	Male	Female	Male	Female	Male	Female	Male	Female
Low-Load	95.57	95.08	95.73	94.67	95.42	94.30	95.42	96.69
	(3.55)	(5.54)	(4.55)	(5.90)	(4.99)	(7.59)	(5.89)	(5.58)
High-Rel	89.79	91.18	88.75	88.60	93.13	92.65	88.54	94.85
	(4.89)	(5.41)	(6.28)	(7.22)	(3.58)	(6.44)	(12.65)	(7.65)
High-Irrel	94.95	93.84	94.69	92.83	95.21	94.49	95.21	95.22
	(4.32)	(5.59)	(4.49)	(7.08)	(4.70)	(6.40)	(5.89)	(5.54)
High-Load	85.63	87.55	84.58	85.11	88.96	88.97	84.38	90.99
	(6.92)	(6.94)	(9.15)	(9.21)	(8.09)	(8.05)	(12.27)	(8.55)

Table 8b. Mean response time (ms) to the Yes and No probes are shown for the four task conditions on sex differences of Experiment 2. Standard deviations in parentheses.

Condition	Overall		Yes		No-HF		No-LF	
	Male	Female	Male	Female	Male	Female	Male	Female
Low-Load	445.57	496.14	407.57	448.53	468.75	539.70	496.07	547.01
	(73.87)	(65.53)	(77.58)	(66.99)	(74.64)	(76.96)	(85.17)	(72.68)
High-Rel	523.50	598.21	508.39	573.36	527.67	629.52	553.23	617.62
	(92.50)	(86.70)	(100.90)	(101.69)	(102.68)	(90.38)	(88.58)	(80.59)
High-Irrel	440.09	497.86	410.61	462.51	462.45	525.54	473.29	538.26
	(83.49)	(69.74)	(95.78)	(82.78)	(75.46)	(64.59)	(83.49)	(71.89)
High-Load	538.41	625.34	522.02	612.60	555.26	643.21	554.40	635.01
	(99.18)	(103.42)	(106.97)	(118.59)	(99.62)	(112.26)	(97.57)	(93.92)

Figure captions

Figure 1. A schematic diagram of the spatial working memory task with an informative cue used in Experiment 1. Two or four dots were presented in different locations as the initial memory set on each trial followed by a delay and then a color cue. According to the cue, either the whole (non-selection, NS) or half (memory selection, MS) of the original memory set remained relevant. After another delay, a probe was presented for a recognition response. There were three types of probes: “Yes” probe (probe location matched one of the cued dot locations), “No-LF” probe (probe location not shown in the original memory set), and “No-HF” probe (probe location matched with one of the non-cued dot locations; MS condition only). The selection cue was in blue/orange color and the non-selection cue was a blue-orange pattern.

Figure 2. A schematic diagram of the conventional spatial delayed recognition task. In two versions of the recognition tasks, 1, 2, 4, 5, and 7 or 1, 2, 4, 6, and 7 dots were presented, respectively. The dots were presented in different locations as the memory set on each trial followed by a delay. After the delay, a probe was presented for a recognition response. There were two types of probes: “Yes” probe (probe location matched one of the study display dot locations, and “No” probes (probe location not shown in the study display).

Figure 3. Study-elicited ERPs in correspondence to the memory load during initial encoding and maintenance prior to cue presentation of Experiment 1. Grand-averaged waveforms for the MS (black solid), NS4 (gray solid), and NS2 (black dotted) conditions during the study display and initial delay period are shown for the frontal (F5, Fz and F6), central (C5, Cz and C6), parietal (P5, Pz and P6) and parietal-occipital (PO5, POz, and PO6) electrodes. The analysis time windows are shaded in gray.

Figure 4. (A) Cue-elicited ERPs of Experiment 1. Grand-averaged waveforms for the cue and post-cue delay period are shown for the MS (black solid), NS4 (gray solid), and NS2 (black dotted) conditions at the frontal (F5, Fz and F6), central (C5, Cz and C6), parietal (P5, Pz and P6) and parietal-occipital (PO5, POz, and PO6) electrodes. Differential ERPs between the conditions are divided into four time windows starting from cue onset: 140-200 ms, 250-350 ms, 380-500 ms, and 500-700 ms. The analysis time windows are shaded in gray. **(B)** Topographical contrast maps for the mid and late time windows after cue onset. Note that NS4 elicited a greater frontal positivity in comparison to MS and NS2 during 380-500 ms, whereas MS elicited a greater central and parietal positivity in comparison to NS2 and NS4 500-700 ms.

Figure 5. (A) Probe-elicited ERPs of Experiment 1. Grand-averaged waveforms for the probe period are shown for the MS (black solid), NS4 (gray solid), and NS2 (black dotted) conditions at the frontal (F5, Fz and F6), central (C5, Cz and C6), parietal (P5, Pz and P6) and parietal-occipital (PO5, POz, and PO6) electrodes. The analysis time windows are shaded in gray. **(B)** Topographical contrast maps for the early (250-450 ms) and late (450-650 ms) time windows after probe onset. Note that neural activity during the probe stage of the MS condition is similar to that of the NS2 condition, and both differ from the NS4 condition. **(C)** Grand-averaged waveforms for the "No-HF"(black solid) and "No-LF" (black dotted) probe types of the MS condition at the frontal-midline electrode (Fz). **(D)** Topographical map is shown for the contrast between the two MS-No probe conditions for the 450-650 ms interval after probe onset.

Figure 6. ERPs and individual differences in working memory capacity of Experiment 1. Correlations between ERP amplitude differences between conditions of different memory load and working memory capacity (indexed by *k*-scores) across subjects are shown for **(A)** the frontal-midline electrodes (Fz) between 380-530 ms after study onset, and **(B)** the frontal-midline electrodes (Fz) between 500-750 ms after study onset. Correlations between probe-related ERP amplitude and PI index (measured in accuracy) across subjects are shown for **(C)** the central-midline (Cz) and **(D)** parietal-midline (Pz) electrodes for the MS condition between 250-450 ms after probe onset.

Figure 7. A schematic diagram of the spatial working memory task with an informative cue used in Experiment 2. Two, four, or six dots were presented in different locations as the initial memory set on each trial followed by a delay and then a color cue. According to the cue, either one (Low-Load and High-Irrel conditions) or three (High-Load and High-Rel conditions) dot locations of the original memory set remained relevant. After another delay, a probe was presented for a recognition response. There were three types of probes: "Yes" probe (probe location matched one of the cued locations), "No-LF" probe (probe location not shown in the original memory set), and "No-HF" probe (probe location matched with one of the non-cued locations).

Figure 8. Approximate positions of the electrode clusters. The electrode montage shows the electrode clusters used for analysis of the post-cue sustained neural activity. The left frontal cluster included the F5, FC5, and C5 electrodes (top left). The fronto-central midline cluster included Fz, FCz, and Cz electrodes (top middle). The right frontal cluster included the F6, FC6,

and C6 electrodes (top right). The left parietal cluster included the CP5, P5, and PO5 electrodes (bottom left). The parietal-posterior-parietal midline cluster included the CPz, Pz, and POz electrodes (bottom middle). The right parietal cluster included the CP6, P6 and PO6 electrodes (bottom right).

Figure 9. Whole trial averaged waveforms for all four conditions of Experiment 2. Grand-averaged waveforms for the whole trial are shown for the Low-Load (cyan), High-Rel (magenta), High-Irrel (blue) and High-Load (red) conditions at the left frontal (F5, FC5, and C5), fronto-central midline (Fz, FCz, and Cz), right frontal (F6, FC6, and C6), right parietal (CP5, P5, and PO5), parietal-posterior-parietal midline (CPz, Pz, and POz) and left parietal (CP6, P6, and PO6) electrodes. A 100 ms pre-study baseline was used.

Figure 10. Averaged waveforms and topographical maps of the transient cue-related neural activity of Experiment 2. **(A)** Cue-elicited ERPs in response to the High-Rel, High-Irrel and Low-Load conditions of Experiment 2. Grand-averaged waveforms for the first second of the cue and post-cue delay period are shown for the High-Rel (magenta), High-Irrel (blue) and Low-Load (cyan) conditions at the left frontal (F5, FC5, and C5), fronto-central midline (Fz, FCz, and Cz), right frontal (F6, FC6, and C6), right parietal (CP5, P5, and PO5), parietal-posterior-parietal midline (CPz, Pz, and POz) and left parietal (CP6, P6, and PO6) electrodes. A 100 ms pre-cue baseline was used. **(B)** Topographical maps are shown for the contrasts of High-Rel and Low-Load, High-Irrel and Low-Load, and High-Rel and High-Irrel at the following time windows after cue onset: 140-200 ms, 250-350 ms, 380-500 ms, and 500-700 ms.

Figure 11. Difference waveforms between the transient cue-related relevant and irrelevant load effects of Experiment 2. Difference waveforms between the relevant and irrelevant load effects for the cue and post-cue delay period are shown for the relevant load effect (red) and irrelevant load effect (blue) at the left frontal (F5, FC5, and C5), fronto-central midline (Fz, FCz, and Cz), right frontal (F6, FC6, and C6), right parietal (CP5, P5, and PO5), parietal-posterior-parietal midline (CPz, Pz, and POz) and left parietal (CP6, P6, and PO6) electrodes. A 100 ms pre-cue baseline was used.

Figure 12. Difference waveforms for the memory-related relevant and irrelevant load effects of Experiment 2. Difference waveforms between the relevant and irrelevant load effects for the last 1.5 second of the post-cue delay period are shown for the relevant load effect (red) and irrelevant load effect (blue) at the left frontal (F5, FC5, and C5), fronto-central midline (Fz, FCz, and Cz),

right frontal (F6, FC6, and C6), right parietal (CP5, P5, and PO5), parietal-posterior-parietal midline (CPz, Pz, and POz) and left parietal (CP6, P6, and PO6) electrodes. A 100 ms pre-study baseline was used.

Figure 13. Group effects and correlations between sustained neural activity and individual differences in working memory capacity or PI effect of Experiment 2. Bar graphs for the group effect during the cue and post-cue delay period are shown for the **(A)** relevant load effect, and **(B)** irrelevant load effect at the posterior-parietal midline electrodes. Correlations between ERP amplitude of the irrelevant load effect and PI index (measured in response time) across subjects are shown for the left frontal electrodes at the following time windows after cue onset: **(C)** 1000-1500 ms, **(D)** 1500-2000 ms, and **(E)** 2000-2500 ms.

Supplementary figure 1. Whole trials ERPs of Experiment 1. Grand-averaged waveforms for the MS (black solid), NS4 (gray solid), and NS2 (black dotted) conditions for the whole trial are shown for the frontal (F5, Fz and F6), central (C5, Cz and C6), parietal (P5, Pz and P6) and parietal-occipital (PO5, POz, and PO6) electrodes.

Supplementary figure 2. Cue-elicited ERPs showing the relevant load effect of Experiment 2. Grand-averaged waveforms for the cue and post-cue delay period are shown for the High-Rel (magenta) and Low-Load (cyan) conditions at the left frontal (F5, FC5, and C5), fronto-central midline (Fz, FCz, and Cz), right frontal (F6, FC6, and C6), right parietal (CP5, P5, and PO5), parietal-posterior-parietal midline (CPz, Pz, and POz) and left parietal (CP6, P6, and PO6) electrodes. A 100 ms pre-cue baseline was used.

Supplementary figure 3. Cue-elicited ERPs showing the irrelevant load effect of Experiment 2. Grand-averaged waveforms for the cue and post-cue delay period are shown for the High-Irrel (blue) and Low-Load (cyan) conditions at the left frontal (F5, FC5, and C5), fronto-central midline (Fz, FCz, and Cz), right frontal (F6, FC6, and C6), right parietal (CP5, P5, and PO5), parietal-posterior-parietal midline (CPz, Pz, and POz) and left parietal (CP6, P6, and PO6) electrodes. A 100 ms pre-cue baseline was used.