EFFECTS OF WORKING MEMORY CAPACITY ON WORKLOAD AND TASK PERFORMANCE

by

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DEDICATION

This is dedicated to the memory of my father. I am grateful to him for sharing his love, time, and knowledge.

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I would like to thank my advisor and committee chair, Dr. Matthew S. Peterson, for his inspiration and guidance. His efforts have greatly helped my academic and professional development. I would also like to thank Dr. Carryl Baldwin and Dr. Aimee Flannery who have been instrumental in the completion of this work. Without the support, guidance, and love of my family, friends, and dogs, I would not be where I am today. I especially want to thank Hubert Hwang for his moral support, patience, and witty repartee.

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ABSTRACT

EFFECTS OF WORKING MEMORY CAPACITY ON WORKLOAD AND TASK PERFORMANCE

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Working memory capacity (WMC) is generally referred to as a quantitative measure of the ability to maintain relevant information while performing unrelated tasks (Delaney & Sahakyan, 2007). Studies have shown that WMC can vary by individual, with high WMC individuals generally exhibiting better performance on attentional tasks than low WMC individuals. Current research is inconclusive as to how an individual's WMC affects performance on tasks of varying workload. Kane, Poole, Tuholski, & Engle (2006) tested the relationship between WMC and executive attentional control and found no relationship between individual differences in WMC and performance on basic visual search tasks. Other studies, however, have found that loading working memory interferes with search (Peterson, Beck, & Wong, 2008; Han & Kim, 2004). This dissertation determined if low- and high-WMC individuals perform differently when engaged in complex tasks that tax attentional control and limit automatic forms of information processing, specifically on visual search and navigational driving. The first study tested

whether there is a relationship between WMC and visual search performance on visual search tasks that are more complex than the ones used in Kane and colleagues' 2006 study. The second study explored this relationship in the context of a dynamic driving environment, which has not previously been examined in depth.

An attentional battery measuring WMC, selective attention, and other related measures such as visuo-spatial ability was given to each participant in both studies to assess perceptual and cognitive differences. The results of the battery were compared to performance on tasks in both studies.

The results showed that WMC did not directly impact primary performance in either of the studies, but differences were found in the secondary loading tasks. In each study, high-WMC individuals responded faster than low-WMC individuals to the loading task. Though their performance was equivalent in the primary task, the two studies presented showed that there were attentional control differences between low- and high-WMC individuals in their ability to multitask. As in the visual search studies of Kane and colleagues (2006) and driving studies of Radeborg and Hedman (1999), low- and high-WMC individuals demonstrated equivalent performance.

The implications of this dissertation are useful for understanding tasks that require effortful control. For example, differences between low- and high-WMC individuals may not be apparent under safe driving conditions, but could manifest in decreased response times to hazards on the road when drivers interact with additional tasks created by in-vehicle technologies.

INTRODUCTION

Working memory (WM) refers to a cognitive system responsible for temporarily storing, maintaining, and manipulating information during cognitive activity. Many studies have shown that task performance benefits and disadvantages are related to an individual's working memory capacity (WMC), which is a measure of WM ability and attentional control (Cowan, 2005; Oberauer, Süß, Wilhelm, & Sander, 2007). This dissertation investigates visual search task performance in static and dynamic environments to determine if patterns that emerge are based on the limitations of WMC.

Kane, Poole, Tuholski, & Engle (2006) found no relationship between individual differences in WMC and performance on static feature-absent, conjunction, and spatial configuration visual search tasks. While Kane and colleagues did not find WMC effects in basic visual search tasks, other studies have found a detrimental effect when working memory is loaded (Peterson, Beck, & Wong, 2008; Han & Kim, 2004). These studies found that active working memory manipulation is needed to influence search efficiency and concluded that the basic visual search tasks used in Kane and colleagues' study were too simple.

The first study of this dissertation tested whether the use of a complex visual search task demonstrated a relationship between WMC and visual search performance.

Eye movements were used as a complementary measure to examine how individual differences in WMC affected visual search patterns.

The second study of the dissertation explored visual search in a dynamic driving environment. Numerous studies have shown that cognitively demanding secondary tasks have a negative impact on driving performance (Lee, Lee, & Boyle, 2009; Drews, Pasupathi, & Strayer, 2008; Crundall, Underwood, & Chapman, 2002), but few studies have explored whether individual differences in WMC are a factor affecting driving performance. Working memory processes are essential for driving; drivers are constantly engaged in monitoring the environment while navigating to their destination, which requires situational awareness and attentional control. For example, Johannsdottir and Herdman (2010) found that the driver's situational awareness for surrounding vehicles in the driving environment was disrupted by concurrent performance on secondary tasks. However, the role of WMC on driving and secondary task performance in the literature is unclear and will be tested in the following studies.

In addition, an attentional battery measuring WMC and other facets of attention, such as spatial attention and the ability to divide attention, was administered in the present studies to examine the role of perceptual and cognitive abilities and their potential relationship to the primary and secondary tasks utilized.

Study Purpose & Research Hypotheses

The purpose of the dissertation studies was to examine the effects of individual differences in working memory capacity in situations where participants are engaging effortful control of attention. The studies tested whether variation in WMC predicts the ability to use executive control to block sources of interference such as distractor processing during search for multiple targets among non-targets appearing at various locations. Kane and colleagues (2006) found that WMC does not predict visual search performance in several simple visual search tasks, which other researchers have theorized is because the tasks allowed for automatic processing (Poole & Kane, 2009). Therefore, WMC is predicted to be evident for visual search tasks that constrain attentional resources where attention must be maintained over a brief period of time.

The following studies are hypothesized to confirm the consequences of WMC on diverse tasks, such as in static and dynamic task environments. It is hypothesized in the first study that high-WMC individuals will perform better than low-WMC individuals in a visual search task aimed at engaging the control of attention and limiting automatic forms of information processing. For the second study, individual differences in WMC are hypothesized to affect their driving and secondary task performance.

LITERATURE REVIEW

Working Memory

WM is generally defined as a system of operational resources that utilize short-term memories and attention (Turner & Engle, 1989). This system is responsible for the active maintenance of information despite concurrent processing and distraction (Conway et al., 2005), which is necessary in order to perform any sort of task.

An explicit description of WM was provided by Baddeley and colleagues (Baddeley, 2000; Baddeley & Logie, 1999; Baddeley & Hitch, 1974), whereas researchers like Cowan (2005; 2001) presented a more unspecified description of WM. Baddeley & Hitch (1974) were the first researchers to suggest that WM is not just for storage but an active processing area. Their multi-component model of WM proposes that two slave systems, the phonological loop and visuo-spatial sketchpad, are responsible for short-term maintenance of information. A third component called the central executive is responsible for directing and integrating the information, as well as coordinating the slave systems. The model was extended in 2000 to include a fourth component, the episodic buffer, to account for representations that integrate phonological, visual, and spatial information with episodic information. In contrast, Cowan (2005) described WM representations as two embedded levels in long-term memory (LTM): an activated, unlimited LTM representation and a limited capacity of around four activated representations that are the attended items of WM. Regardless of interpretation, researchers agree that WM consists of mechanisms or processes involved in controlling, regulating, and actively maintaining task-relevant information. Consequently, researchers often examine limits in WM ability by testing working memory capacity.

Working Memory Capacity

Working memory is considered to be limited in capacity (Miller, 1956), with processes competing for shared resources. Cowan (2001) proposed that WM has a capacity of about four chunks in young adults and fewer for children and older adults. A broad definition of working memory capacity (WMC) is the ability to remember things in an immediate memory task (Cowan, 2005). A narrower definition is the amount of information that an individual can hold at one time.

Similar to Cowan’s analyses (2005), Engle and his colleagues (1991; 2001) view working memory as a highly activated subset of long-term memory. They specify that the processes involved in finding and maintaining information are dependent on executive attention to maintain task goals, process current and relevant information, and block external distractions. They believe that individual differences in WMC are due to variations in the ability to control attention and that affects higher-order cognition (Engle & Kane, 2004). Regardless of interpretation, WMC research consistently shows that the ability to control attention, especially when faced with competing demands, is a determinant of performance on working memory tasks (Barrett, Tugade, & Engle, 2004; Engle, 2002). Furthermore, individual differences in the ability to control attention are especially pronounced when WM demands are high.

Individual Differences in Working Memory Capacity

WMC is generally tested by measuring performance on a dual-task paradigm that combines a memory span measure with a concurrent processing task. Dual-task paradigms are used to test the limit of holding unrelated pieces of information simultaneously. Much research has sought to explain why there is such great variability in the limits exhibited by different individuals. One possibility is that individuals that test lower in span have difficulty encoding information, which could be due to forming unreliable bindings that make representations vulnerable to interference (Oberaurer, 2005). Another reason could be that lower scores reflect the inability to focus and maintain attention along with the efficiency of executive functions (Kane & Engle, 2002). The first WMC measure was Daneman and Carpenter's reading span (1980) where subjects read two to six sentences and tried to remember the last word of each sentence. At the end of the list of sentences, subjects repeated back the last words in order. Individuals who differ in their ability to control attention may be dissociated using a variety of paradigms such as the operation span (OSPAN) task (Turner & Engle, 1989): a task similar to Daneman and Carpenter's reading span task, in which subjects are tested on math equations instead of sentences. Turner and Engle found that OSPAN scores were highly correlated with performance on tasks involving memory and attention.

Many have noted that measures of WMC are strongly related to performance on complex cognitive tasks such as reading comprehension, problem solving, and measures of intelligence (Conway et al., 2005; Conway, Kane, & Engle, 2003). For example, subject performance on dichotic listening and divided-attention tasks was correlated with

WMC (Conway, Cowan, & Bunting, 2001; Kane & Engle, 2000). One possible explanation for this is the Strategic Allocation hypothesis (Engle, Cantor, Carullo, 1992), which suggests that some individuals are simply better at multitasking because they strategically allocate resources toward the primary and secondary task components. For example, performing a dual task requires additional attentional processing and potentially extra load on working memory. High-WMC individuals may have more strategic ability than low-WMC individuals during complex cognitive tasks to actively control and maintain relevant information. If this hypothesis is true, higher OSPAN scores or other effective WMC tests should also be related to task performance.

Another explanation of individual differences in WMC and reasoning is that these differences are largely determined by variations in controlled attention (Engle et al., 1999; Kane & Engle, 2002). In a study where subjects were prompted to report their thoughts as they went about their daily routines, Kane et al. (2007) found that subjects with low WMC reported more moments of mind wandering than subjects with high WMC at the highest levels of self-reported concentration. However, high-WMC subjects were more likely to mind-wander than low-WMC subjects at the lowest levels of self-reported concentration. This mind-wandering may have been due to the inability to inhibit irrelevant information, which is reflected in poor attentional control.

In another example, Schmiedek and colleagues (2007) modeled data from eight WM experiments performed by Oberauer, Süß, Wilhelm, & Wittman (2003). They examined the response distribution of accurate and error-related response times and found that slower response times (tails of the distribution) were correlated more with intelligence than faster response times. Explanations of this phenomenon were based on the idea that poor working memory and lapses of attention lead to longer response times, in which individuals with higher intelligence have better attentional control capacity and are better able to control lapses. They concluded that these results reflected variations in controlled attention.

Engle (2002) found that individual differences in working memory were reflected in attentional tasks such as proactive interference, anti-saccade, Stroop, and dichotic-listening. Tasks like the Stroop or the anti-saccade task require maintenance of a single crucial goal. In the Stroop task, participants are shown color words and are required to name the color of the ink the word is printed. Trials can be congruent by having the color word printed in a matching ink color, or be incongruent by having a word printed in a different ink color. Performance on the Stroop task should rely on executive attention to maintain the goal of naming the colors despite trials in which there may be a response tendency to say the written word (e.g. saying the word "green" when the word "green" is written in blue ink). They found that there were no differences between low- and high-WMC individuals on zero percent or 50 percent congruent trials, but when the trials were 75 percent congruent, low-WMC individuals made twice as many errors compared to high-WMC individuals. In general, low-span individuals typically performed worse in most tasks compared to high-span individuals, which reflected their difficulty in maintaining and inhibiting information. However, there were exceptions such as when high-span individuals and low-span individuals had equivalent performance under cognitive load during the proactive interference task.

The General Capacity Model (Conway & Engle, 1996) supports the theory that individual differences in WMC correspond to differences in controlled attention. These differences are revealed in tasks that force the subject to engage in controlled effortful processing. One way to distinguish between tasks that require controlled effortful processing and tasks that are automatic is to examine whether tasks require implicit learning compared to intentional learning (Unsworth & Engle, 2005). A hallmark of implicit learning is that a person is generally unaware of the learning. Intentional learning occurs when a person is actively engaged, requiring some form of cognitive control rather than automatic processing. Unsworth and Engle found evidence from a serial reaction time task that WMC differences only emerged from intentional but not implicit (or incidental) learning. Thus, tasks in which individuals are engaged in intentional learning can be utilized to differentiate individual differences in WMC.

Some studies that examined individual differences in WMC have found general task performance differences between high- and low-WMC. For example, high-WMC individuals perform better on tasks involving controlled effortful processing such as solving difficult math problems (Conway & Engle, 1996). High-WMC individuals are also associated with greater forgetting following a context-change and are better able to intentionally forget items compared to low-WMC individuals, which may indicate that high-WMC individuals are more context-dependent than low-WMC individuals (Delaney & Sahakyan, 2007). However, Delaney & Sahakyan found that having high-WMC may not always be advantageous when trying to resist forgetting during an interruption.

Studies have also shown that in high-pressure situations, high-WMC individuals have no advantage over low-WMC individuals on task performance (Beilock & Carr, 2005).

Across these studies, a clear pattern shows that high-WMC individuals exhibit greater selective attention that manifests when tasks are demanding (Colflesh & Conway, 2007; Brumback, Low, Gratton, & Fabiani, 2003). Furthermore, they can distribute their attention with more flexibly whereas low-WMC individuals are only able to distribute their attention in a spotlight (Bleckley, Durso, & Crutchfield, 2003). Cowan (2005) suggested that individuals differ in their ability to adapt the spotlight, or focus of attention, to task goals. Unsworth and Engle (2007) argued that individual differences in WMC arise from differences in the ability to actively maintain information and the ability to retrieve task relevant information in the presence of irrelevant information. They found that low-WMC individuals recalled fewer items than high-WMC individuals in a complex search task and were slower to recall items because low-WMC individuals had to search through more information than high-WMC individuals during retrieval. Unsworth and Engle also compared results across various studies and found that individual differences in WMC occurred only in situations that required active maintenance or controlled search. It may be likely that WMC is multi-faceted, reflecting active maintenance abilities, strategic planning, and retrieval abilities (Unsworth, 2009; Unsworth & Engle, 2007; Cowan et al., 2003).

In basic visual search studies, finding targets among distracters in a visual environment is often the primary goal, and it may be necessary to engage in strategic planning. Aside from visual search being pervasive in everyday function, investigating and determining the impact of WMC on visual search has merit for critical tasks such as when air traffic controllers interact with visual displays to manage automation systems. This is especially the case if WMC may affect individual performance on attentional tasks ranging from everyday driving to specialized tasks performed by air traffic controllers.

Working Memory Capacity in Visual Search

Visual search incorporates bottom-up and top-down processes. Bottom-up theories of search assume that attentional scanning is guided by activation of a salience map that represents points of interest determined by unique features within a visual scene (Itti & Koch, 2000; Wolfe, 1994). Top-down processes can affect search by modulating the activation within the maps by amplifying signals related to known target properties.

Kane and colleagues (2006) tested the relationship between WMC and executive attention control by comparing individual differences in WMC and performance on visual search tasks; namely, feature-absence, conjunction, and spatial configuration search tasks. They used simple visual search tasks to determine if the results would be similar to past simple attention tasks such as the Stroop task (Kane & Engle, 2003), dichotic listening, and visual flanker tests (Conway et al., 2001; Heitz & Engle, 2006) in which high-span individuals performed better than low-span individuals. Kane and colleagues found no differences between low- and high-WMC subjects when they examined reaction times by display array size and concluded that WMC was unrelated to search efficiency. The lack of relationship found in this study brings to question if WMC resources were tapped when performing visual search and if more complex visual search tasks could reveal a difference. It is possible that the simple visual search tasks used by Kane and colleagues (2006) did not show a difference between low- and high-WMC individuals because relatively automatic forms of information processing were engaged (e.g. selecting objects that stand out during a search task).

While Kane et al. examined the direct relationship between WMC with simple visual search tasks, Han and Kim (2004) tested WM through a series of dual-task paradigms where participants performed visual search while manipulating or maintaining information held in WM. They found that tasks involving WM manipulation influenced the efficiency of visual search. In contrast, simply maintaining information in WM did not change visual search when comparing single and dual-task conditions. They concluded that secondary tasks that included executive processing could interfere with visual search operations.

Peterson, Beck & Wong (2008) found that loading working memory interfered with performance on a tone-counting and search dual-task, in which participants actively counted the number of tones in a sequence, performed a concurrent simple visual search task, and responded with their tone count when prompted by the experiment. Specifically, loading executive working memory during visual search led to increased premature shifts of attention and time needed to identify search items. Sobel, Gerrie, Poole, & Kane (2007), using a conjunction search task that isolated top-down and bottom-up factors, demonstrated that individuals with high-WMC relied more on top-down executive control processes and were better able to override habitual responses than individuals with low-WMC. The participants' performance did not differ when engaged in search in which top-down executive control played a minor role. Therefore,the relationship between WMC and visual search may be better understood through the use of a more complex visual task aimed at engaging the control of attention compared to the tasks used by Kane and colleagues.

Differences in WMC are partially reflected in directed components of the search process, such as in encoding and active maintenance during search (Rosen & Engle, 1997; Unsworth & Engle, 2007). While high-WMC observers are likely to fixate on locations or objects that are highly task relevant and salient, such as traffic lights, compared to those items of little task relevance (McCarley et al., 2004; Theeuwes, 1996), low-WMC individuals are less capable of focusing their search sets, which in turn leads to an increase in the size of their search set. Poole and Kane (2009) compared search latencies when one to eight target locations were monitored alone or with distractors over a long or short delay. They found that WMC affected the ability to maintain constrained focus over time, with low-WMC individuals identifying targets slower than high-WMC individuals in complex visual search tasks only in the presence of distractors and over long fixation delays. Similarly, Oberauer and colleagues (Oberauer, Süß, Wilhelm, & Sander, 2007; Oberauer, 2005) proposed that WMC reflects the ability to create, maintain, and dissolve temporary mental bindings among a limited number of representations such as with binding visual objects to spatial locations. Thus, complex tasks are required in order to distinguish WMC differences.

One application that requires this ability is in aviation, in which air traffic controllers and personnel are involved with performing tactical operations that can be limited by WMC. Furthermore, air traffic controllers typically use visual displays to interact with automated systems, which require them to integrate complex information from these displays in a timely and effective manner.

Working Memory Capacity in Applied Dynamic Domains

Spatial Awareness in Aviation

An aircrew's attention is needed for perceiving and processing the environment, which may be limited by task complexity and information overload from engaging in multiple tasks. Various factors such as distraction by irrelevant stimuli, task saturation, channelized attention, and preoccupation with a task were cited in incidents involving fighter aircraft pilots as significant causal factors (Kuipers, Kappers, van Holten, van Bergen, & Oosterveld , 1990). In a review of accident investigation reports over a four-year period, Endsley (1995) found that major causal factor underlying aircraft accidents in major US air carriers involved a failure to monitor or observe data. This may manifest in an aircrew's ability to manage or maintain their top-down control when problems occur. Top-down attention-control tasks testing for individual differences have typically shown that high-WMC subjects perform better than low-WMC subjects by ignoring irrelevant distractions and withholding habitual responses (Sobel et al., 2007). In contrast, search task performance that relied primarily on bottom-up mechanisms did not vary with respect to WMC. Situations where task demands exceed WMC impose heavy demands on the pilots and may have detrimental effects on task performance.

Sohn & Doane (2004; 2000) found that spatial WMC was most predictive of situational awareness performance for novices whereas spatial long-term memory performance on control flight elements configurations, such as attitude and power, were most predictive for experts. Spans were assessed using modified procedures from Daneman and Carpenter (1980) and Shah and Miyake's (1996) working memory span tasks. This work extends working memory theories to include long-term working memory (LT-WM) or working memory based on the storage in long-term memory (Ericsson & Kintsch, 1995). In Sohn & Doane's studies (2004; 2000), LT-WM was measured in pilots as knowledge about the aircraft state and instrument patterns. According to the skilled memory theory, acquired memory skill allows for storage in long-term memory that is kept directly accessible by retrieval cues in short-term memory. For experts, LT-WM skills interacted with WMC such that relying on WMC decreased performance for individuals who scored high in recall accuracy between possible and impossible flight situations (high LT-WM). These findings fit with Ackerman's theory (1988, 1992) that the predictor of complex-task performance changes as expertise develops. From Sohn and Doane's findings, it would be expected that WMC would predict performance well during the early phases of learning a complex task, but at later stages, other abilities that measure LT-WM skills would be a better predictor. They suggest that since WMC measures predict novice pilot vulnerability to situational awareness failures, pilot instructors may want to assess the WMC of individuals and cater their training accordingly.

Other aviation studies include using general cognitive ability and WMC to predict situational awareness in complex tasks such as navigation. For example, Gugerty, Brooks, and Treadway (2004) tested US Air Force recruits ranging from zero to 200 aircraft flight hours. Individual differences in navigation ability manifested for US Air Force recruits on a cardinal direction task in which half of the participants averaged 35 percent correct, while the other half averaged 80 percent correct. The authors suggested that this bimodal distribution of accuracy scores on the cardinal direction task was due to individual differences. They tested recruits on attentional tasks like mental rotation and the Armed Services Vocational Aptitude Battery, which included measures of fluid intelligence, crystallized intelligence, clerical speed, and technical knowledge. Overall, performance was predicted by visual-spatial abilities, mental rotation knowledge, and fluid and crystallized intelligence. Other than related to navigational ability, fluid and crystallized intelligence measures have been shown to correlate well with WMC (Engle et al., 1999), which suggests a relationship between working memory, processing speed and intelligence.

Like in aviation, navigational ability and working memory are also utilized in driving tasks as drivers use their attentional resources to navigate new routes between destinations. Because of the immense amount of information that is continuously available in the driving environment, attentional control is key to maintaining driving function. Drivers' WMC may be exceeded, and thus compromise driving safety, if their attentional resources are exhausted.

Individual Differences in Driving

Few studies have explored WMC in the domain of driving. One such study examined left turn performance (decision time and gap choice) in older female drivers. Guerrier, Manivannan, and Nair (1999) found that WMC was related to the selection of appropriate gaps through decision time. They interpreted longer decision times to be due to high-WMC drivers spending more time gathering relevant information or recognizing traffic patterns. They found that decision time had the largest direct effect on gap choice.

In these studies, individual differences in driving are often associated with group differences such as age, education level, and personality traits, whereas perceptual and cognitive abilities may also affect driving and secondary task performance. For example, crash involvement among older drivers is known to be related to perceptual and cognitive abilities such as the ability to divide visual attention over a wide area, which can be measured by the Useful Field of View (UFOV) test (Ball, Owsley, Sloane, Roenker, & Bruni, 1993; Owsley, Ball, Sloane, Roenker, & Bruni, 1991). As another example, Gugerty and Tirre (2000) tested U.S. air force recruits on situational awareness in a visual search task involving both dynamic (e.g. road-sign recognition in a driving simulator) and static (e.g. visual search) processing factors. Visual processing was found to predict situational awareness ability, which correlated with fluid intelligence and working memory abilities. Thus, assessing individual differences in driving should include evaluating perceptual and cognitive factors that may affect performance, such as WMC and spatial ability.

One process that is an important aspect of driving and engages perceptual and cognitive abilities is navigation. In the context of driving, navigation can be considered in terms of a segmented, dynamic visual search task where drivers must find streets or specified landmarks to reach their destination. The task of navigation can be broken into three main subtasks: 1) identifying the current location, 2) identifying the locations of other objects in the environment, such as a destination, and 3) finding a route from the current location to the destination (Wickens, 1999). Patrick and Elias (2009) tested how concurrent conversations about spatial mental navigation or non-spatial semantic distractions affected performance on judgments of automobile proximity. They found that conversations involving spatial navigation slowed response time and decreased accuracy when processing dynamically changing vehicle proximity. Thus, performing concurrent spatial tasks causes interference because of using shared cognitive resources. However, it is unclear whether the decreased performance was due to performing concurrent spatial tasks which prevented forming adequate spatial WM representations, or because there was interference with central executive processing. This example shows that spatial navigation tasks that are often performed when driving can overload working memory resources to the detriment of the driver.

The previous studies mentioned within the dynamic domains of aviation and driving allude to individual differences in task performance that may be related to variation in WMC. However, the few studies listed show the need to further tease apart the effects of individual differences in WMC on complex tasks.

General Rationale & Hypotheses

The purpose of the following dissertation studies was to examine the effects of individual differences in working memory capacity in situations where participants are engaging effortful control of attention. The studies tested whether variation in WMC predicts the ability to use executive control to block sources of interference such as distractor processing during search for multiple targets among non-targets appearing at various locations. Kane and colleagues (2006) found that WMC does not predict visual search performance in several simple visual search tasks, which other researchers have theorized is because the tasks allowed for automatic processing (Poole & Kane, 2009). In contrast, tasks that require controlled processing are mentally demanding and dependent on WMC. Therefore, WMC is predicted to be evident for visual search tasks that constrain attentional resources and where objects or previously searched locations must be maintained over a brief period of time.

Studies have used WMC tasks as a measure of individual differences that can be used to predict performance on a range of tasks. Given these differences, the relationship between WMC and task performance may differ according to the workload of the task. A major goal in WMC literature is to understand the effect of variations in WMC among individuals and how this impacts performance in different situations. General predictions based on the reviewed literature are:

1. Individual differences in WMC can be predictive of performance on different tasks.
2. High-WMC individuals will generally outperform low-WMC individuals.
3. There may be a limited number of performance exceptions to (2) if there are tasks that benefit from having low WMC. An example may be automated tasks or high-pressure tasks where low-WMC participants may perform better (Beilock & Carr, 2005).

The following studies are hypothesized to confirm the consequences of WMC on diverse tasks, such as in static and dynamic task environments. It was hypothesized in the first study that high-WMC individuals compared to low-WMC individuals would perform better in a visual search task aimed at engaging the control of attention and limiting automatic forms of information processing. Individual differences in driving performance in the second study were hypothesized to manifest in low- and high-WMC drivers, demonstrating perceptual and cognitive differences affecting their driving and secondary task performance.

STUDY 1: PHOTO SEARCH

Hypotheses

The first study tested how individual differences in WMC affected visual search task performance that was occasionally interrupted by a loading task. It was hypothesized that high-WMC individuals would be faster and more accurate in identifying the changed targets compared to low-WMC individuals. Participants were told to find as many differences between two photographs (one altered, one original) as possible, requiring an effortful, strategic search to find the multiple changed targets. Prior work suggested that variation in WM is related to the ability to retrieve relevant information in the presence of multiple irrelevant representations (Unsworth & Engle, 2008; 2007). Thus, participants were interrupted at least twice by a number-letter loading task while engaged in the photo search.

The effect of WMC on retrieving information after an interruption and subsequent resumption from a secondary loading task was examined. Participants were judged by their ability to avoid previously selected targets after being interrupted. The loading task was hypothesized to negatively impact low-WMC individuals; low-WMC individuals would take longer to resume the search task after the end of the interruption (as measured by the time of the first click) compared to high-WMC individuals and have more difficulty remembering previously selected targets. Similar generalizations were found in reading studies where low-span readers spent more time engaged in backtracking to unfamiliar and task-relevant text during a reading comprehension task compared to high-span readers. Burton & Daneman (2007) attributed this difference to the disadvantages of a limited temporary storage capacity.

Additional attentional measures were also compared to the visual search task performance, one of which was multiple object tracking (MOT). The MOT task required participants to track two or four objects out of eight objects in a display. In the MOT task, participants with higher WMC were hypothesized to perform better at tracking four objects than participants with lower WMC, but show little-to-no difference for tracking two objects. Green and Bavelier (2005) found that expert action video game players were able to successfully track approximately two more items than non-gamers. Furthermore, the role of attentional distribution and spatial ability was shown to impact tracking performance on the MOT. Drew, McCollough, Horowitz, and Vogel (2009) found that behavioral tracking performance was related to the relative amounts of attention allocated to targets and distractors. In this study, higher WMC individuals were hypothesized to be better at allocating attentional resources to track more objects than individuals with lower WMC. Green & Bavelier suggested that the enhanced abilities of expert video game players were due to changes in visual short-term memory skills, which were perhaps demonstrated in individuals with higher WMC.

The useful-field-of-view (UFOV) task was used to measure spatial attention. This paradigm used detection, localization, and identification of targets to assess an individual’s spatial distribution of attentional resources over a wide field-of-view

(Edwards et al., 2005). Maintaining location information in visual working memory requires sustained spatial attention to the locations of the remembered items (Awh, Barton, & Vogel, 2000). The distribution of spatial attention has been shown to affect visual search (Chan & So, 2007), thus affecting performance on applied tasks like playing action video games (Feng, Spence, & Pratt, 2007) and driving (Ball et al., 1993). Performance on the UFOV task was therefore hypothesized to interact with WMC. Participants with higher WMC may be able to better allocate attentional resources over a wider field-of-view, and perform more accurately on the photo hunt task.

Participants were also tested on several spatial attentional measures, specifically, two short paper tasks called the Mental Rotation Task (MRT) and the Paper Folding Task (PFT), a computer-based spatial span test, and a Sense of Direction questionnaire that assessed preference and use of navigational strategies. Miyake and Shah (1999) suggested that spatial ability is related to the involvement of both visuospatial and executive components of working memory. Just & Carpenter (1986) found in previous studies that low spatial ability subjects had difficulty maintaining a spatial representation while performing transformations. Individual differences in spatial visualization were hypothesized to be linked to WMC.

Another measure was the anti-saccade and pro-saccade task, which tests participants on flexible control over eye behavior. For the antisaccade task, participants are asked to look in the opposite direction of where a stimulus suddenly occurs. To perform this task requires top-down inhibition of a reflexive, automatic saccade. Performance on the anti-saccade and pro-saccade task was hypothesized to align with results similar to Kane, Bleckley, Conway, and Engle‘s (2001) study where they found that high- and low-span participants did not differ in pro-saccade performance, but did differ in latency and error rates for anti-saccade performance. The errors that occurred were fast errors, which they believe were indicative of goal neglect.

Top-down visual search strategies used during the photo hunt task may include: systematically searching from left to right in a spatial pattern, or repeatedly checking areas for existing objects (e.g. face is in first picture, face is also in second picture). The displays used in the task were relatively cluttered, requiring top-down processes for efficient search. The speed with which individuals found their first changed object was hypothesized to be comparable, as that should rely mostly on perceptual processes. However, searching for the remaining changes will rely on top-down strategies where high-span individuals should have an advantage. Top-down control needed to override bottom-up attention should give rise to steeper response time slopes for low-span subjects compared to high-span subjects.

Evidence of top-down control in visual attention can be examined through eye movements. In a same or different scene comparison task, Gajewski and Henderson (2005) found that participants generally used a minimal memory strategy in which they frequently examined one object at a time. Since their scenes only had one change at most, the likelihood of employing a maximum memory strategy, or fixating at near capacity of three to four items, was reduced. In the photo hunt task, it was predicted that individuals with high-WMC were more likely to use a maximum memory strategy by examining more objects, resulting in more fixations than individuals with low WMC.

Visual Search Hypotheses

Four visual search hypotheses, adapted from Peterson, Beck, and Wong (2008) and the last adapted from Peterson, Beck, and Wong (2008) and He and McCarley (2010), were tested as follows:

Memory hypothesis: Executive function in visual search is used to actively keep track of examined locations and is limited by working memory capacity. Low-WMC individuals will be able to keep track of fewer examined locations when loading executive WM with a secondary task, resulting in an increased rate at which items are revisited and less efficient search.

Identification hypothesis: Since WM is used to hold and compare items in memory, low-WMC individuals will need longer to identify the changes in the objects leading to increased gaze durations or unprocessed, overlooked items.

Attentional disengagement hypothesis: Having a higher WMC means there are more free resources and less difficulty controlling the disengagement of attention by inhibiting queued shifts of attention (Kane et al., 2001). This would result in premature shifts of attention, leading to inadequate processing of items for low-WMC individuals.

Saccade-programming hypothesis/Postponement hypothesis: Visual search requires recurring access to a response selection bottleneck. Executive control is used in programming of eye movements, where engaging in a concurrent task interferes with programming for low-WMC individuals, leading to increased saccade latencies and saccade-targeting errors.

Method

WMC Screening

The tasks OSPAN and RSPAN were used to evaluate each participant's WMC. Participants were administered the OSPAN, RSPAN, and additional attentional measures (described below) as a separate session of the study to ensure that enough low- and high-WMC individuals participated in the study. A z-score of the two span tasks was calculated by converting task scores to z-scores and averaging them into a composite score. Quartiles were computed from the averaged distribution.

Automated OSPAN task. In this OSPAN task (Unsworth, Heitz, Schrock, & Engle, 2005), participants were presented with multiple trial blocks where a mathematical operation was followed by a character (e.g., IS 4 / 2 + 1 = 6 ? L). The participant was required to read the mathematical statement aloud, indicate whether the statement was correct, and remember the character for later recall. Blocks consisted of three to seven of these paired events. The individual's WMC score was computed by summing the number of characters the participant recalled in the order the characters were presented. The WMC score can range from 0 to 75, with higher scores reflecting greater span.

Automated RSPAN task. The RSPAN ((Daneman & Carpenter, 1980) is similar to the OSPAN, except that the task involves reading a series of sentence–letter strings (e.g., "On warm sunny afternoons, I like to walk in the park. F). Individuals read the sentence aloud and were asked to verify whether the sentence makes sense. Individuals then read the letter aloud. Participants were then instructed to recall all memorized letters in the correct order and at the end of the series, the participant checked off the sequence of letters from a list presented on the screen. Each series had a randomized length of strings between three and seven. Individuals were tested on three series of each length (12 total). The range of scores is from 0 to 75, scored by the total number of words/letters correctly recalled. Like OSPAN, higher scores reflect a greater span.

Additional Attentional Measures

Useful Field of View (UFOV) task. The UFOV task (Ball et al., 1993) evaluated the participant's useful field-of-view, the area from which one can extract visual information in a glance without head or eye movement. UFOV can be reduced by poor vision, difficulty dividing attention, and slower processing ability. Participants were administered the UFOV as part of a separate session. The standardized PC-based task consisted of tasks such as identifying a target object and also localizing a simultaneously presented target object displayed in the periphery with or without distractors for varying lengths of time. Specifically, Subtest 3 of the computer-based tasks was used to evaluate selective attention. Subtest 3 required participants to identify the centrally presented target and locate a simultaneously-presented peripheral target in a field of distracters (white triangles) in the periphery.

Multiple Object Tracking (MOT) task. This task (Pylyshyn & Storm, 1988) was used to examine how well a participant's visual system tracked multiple moving objects. Eight identical circular objects were displayed per trial on the screen. A subset of 2 or 4 targets were briefly flashed to alert the participants of the targets to track. After the objects stopped flashing, all the objects moved in a random fashion for about 10 seconds.

Afterwards, the motion stops and the participant's task was to locate all the tracked objects by clicking on each one using the mouse attached to the computer.

Pro/Anti-saccade tasks. The anti-saccade and pro-saccade tasks measured a participant's level of flexible control on attention. In the pro-saccade task, the participant was told to look at a visual target that appeared in the peripheral visual field. In the anti-saccade task, the participant must suppress the reflexive urge to look at a visual target that appears in the peripheral visual field and instead look away from the target to the opposite direction. Top-down inhibition of a reflexive, automatic saccade is needed for successful completion of the anti-saccade task (Munoz & Everling, 2004).

Mental rotation task. This MRT paper task (Shepard & Metzler, 1971) tested participant's mental imagery by presenting drawings of three-dimensional, asymmetrical assemblages of cubes. Participants completed 10 problems in three minutes, where each problem had the test assemblage on the left and four possible solutions on the right. The four possible solutions may be rotated at different angles or mirror images of the test object. The objective was to tell which two assemblages depicted were identical.

Paper folding task. Participants were given a paper task (Eckstrom, French, Harman, & Dermen, 1976) where they had to fold a piece of paper mentally, imagine a hole was punched through it, and then determine what the paper would look like when unfolded. The PFT test was composed of 20 items divided into two sections where participants were given three minutes per section. This test also measured spatial visualization ability and was from the ETS Kit of Referenced Tests for Cognitive Factors.

Spatial span task. In this task, participants recall the sequence of flashing blocks in the order they were presented. Participants started at a set size of three and after three sequence errors, the test ended. The score on this task was the number of flashing blocks they remembered correctly in the order they were presented. This task was another measure of visuospatial working memory. This web-based task can be found at: http://www.cambridgebrainsciences.com/browse/memory/test/spatial-span-ladder.

Participants

A total of 74 students from George Mason University (55 females, 19 males; *M* = 24.16 years old, *SD* = 6.48) were recruited from the Psychology department subject pool and given course credit or $10 for their participation. Subjects were at least 18 years of age with normal or corrected-to-normal vision and completed the attentional battery (WMC screening and additional attentional measures) prior to testing. A separate group of 36 students (25 females, 11 males; *M* = 20.50 years old, *SD* = 3.63) were recruited to rate the level of subjective difficulty in finding the changed target objects in the photo search stimuli.

Apparatus

A Mac dual quad-core Intel Xeon equipped with a 20-inch monitor operating at 75 Hz with a resolution of 1600 X 1200 pixels was used. Custom software was used to present the stimuli to control the timing of experimental events and record the participants' response times. Eye-tracking data was collected by an Eyelink II system (SR Research) that sampled at 250 Hz and had a 0.2° spatial resolution on a networked computer. Participants were asked to stabilize their head on a chinrest located 70 cm from the monitor.

Stimuli

The stimuli consisted of photo search stimuli and loading task stimuli. Figure 1 shows an example of the photo search stimuli. The photographs were 785 X 1091 pixels on a black background and were from the Washington Post Magazine’s section called Second Glance (http://www.washingtonpost.com/secondglance/). The top picture was the original photograph and the altered photograph on the bottom contained 12 differences varying in three degrees of difficulty (moderate, advanced, and extreme). The type of changes in the photos included: a feature of an object (such as color or size), an absence of item, or an addition of an item. The loading task stimuli consisted of a number and letter placed at the center of the screen. The characters were displayed on a black background and approximately 0.6 X 0.3 cm in size.

Figure 1. Example of photo search stimuli

Subjective Rating of Photos

The 24 photo stimuli chosen were originally distributed across difficulty levels (easy, medium, hard) from Washington Post's ratings. A separate group of 36 participants rated the level of subjective difficulty on a scale of 1 to 5 (1 = easiest, 5 = hardest) in finding each of the changed target objects in the stimuli. The average rating for each picture was computed by averaging the subjective difficulty ratings of the target objects in each picture and ranged from 3.14 to 4.18. The level of difficulty in half the 24 photo stimuli was re-categorized to reflect the differences in subjective ratings. The level of difficulty was considered was considered “easy” if the average subjective rating was less than 3.5; a “medium” difficulty level was between 3.5 and 3.7, and a “hard” difficulty level was an average rating above 3.7.

Design and Procedure

Subjects were tested individually in two sessions, each session lasting approximately 60 minutes. In the first session, participants completed the WMC and attentional measures. In the second session, participants completed the photo search. The experimenter read aloud the instructions presented onscreen. The photo search consisted of a photo search task and a number-letter loading task.

The photo search task consisted of 24 photo trials and the order of the photographs was counterbalanced across participants. The subject had up to two minutes to complete each photo trial and was allotted up to 12 clicks per photo trial. A timer represented by a shrinking bar on the upper left-hand corner of the screen was displayed during the photo task and counted down from two minutes. A running count of correct items found was displayed on the right-hand side of the screen.

Subjects were trained on three number-letter tasks: even-odd, low-high, and consonant-vowel. Subjects performed one of the three tasks until they were either cued to switch to another task or until the screen resumed to the photo task. The length of the loading task was held constant at eight trials per interruption interval and two task switches occurred during the interval for each photo trial.

For each photo trial, two 8 X 11 cm photographs were presented. Participants were told to click on the items that were different in the bottom (altered) photograph. A green square around the item appeared for 500 ms if the correct location of an item was clicked. For every 2-4 correct item key presses, the subject was interrupted with the loading number-letter task. A blue square around the item appeared for 500 ms if a correct item was repeatedly clicked during the trial, signifying to the participant that they have found the item previously (and that it does not count again towards finding a difference). Practice trials consisted of one photo search trial and one number-letter loading trial.

Data Analyses

The primary dependent variables of interest were photo search accuracy (the number of objects found per trial) and resumption times from the number-letter tasks. Dependent eye measures of interest include fixation duration, fixation count, and the number of revisitations after an interruption.

A mixed model analysis of variance (ANOVA) was used to examine differences between subjects' task performance and composite WMC scores. Response times for the photo search task and the number-letter loading task were measured. The effects of WMC on search efficiency, secondary task performance, and fixation count and duration was analyzed using independent samples t-tests. Pearson's correlations were calculated for the attentional battery measures and WMC span.

Results

Attentional Battery

Span measures. The composite WMC scores ranged from 10.5 to 73.5 (*M* = 51.35, *SD* = 14.45). Eighteen low-WMC individuals (*z*-WMC = -0.47, *SD* = 0.54) and 19 high-WMC individuals (*z*-WMC = 0.60, *SD* = 0.23) were determined by a quartile split of the composite measure.

Pro/Anti-saccade task. Participants performed significantly faster on pro-saccade trials (*M* = 183.10 ms, *SD* = 4.53) compared to anti-saccade trials (*M* = 285.44, *SD* = 16.39), $F(1,21) = 49.26$, $p = 0.0001$. Average accuracy on the pro-saccade trials was 94 percent (*SD* = 0.01) and 80 percent on anti-saccade trials (*SD* = 0.03). However, high- and low-WMC individuals were not significantly different in response times to anti-saccade trials (p = 0.19), though high-WMC individuals responded faster (*M* = 265.70 ms, *SD* = 18.27) than low-WMC individuals (*M* = 311.12, *SD* = 28.32). Equivalent performance was found between low- and high-WMC individuals on the pro-saccade trials.

UFOV task. The average score on the UFOV task was 104.56, indicating normal selective attention ability. A score under 350 is considered normal selective attention ability whereas scores above 350 indicate difficulty with selective attention. Since the population sampled was considered normal, scores above 350 were not expected. However, there was variation in the range of scores that may reflect overall selective attentional ability. Low-WMC individuals scored worse than the average with overall higher scores (*M* = 127.22, SD = 22.41) although the differences were not statistically significant, $t(25) = 1.69$, $p = 0.10$. In contrast, high-WMC individuals had a lower score than average ($M = 86.79$, $SD = 10.64$). UFOV performance correlated significantly with attentional measures, specifically, accuracy on the pro/anti-saccade task, MOT performance, and MRT scores (See Table 1).

MOT task. When participants were tracking two targets, the average accuracy was 85 percent ($SD = 0.02$). When tracking four targets, the average accuracy was expectedly lower at 72 percent ($SD = 0.02$). On average, high-WMC individuals performed significantly better than low-WMC individuals on the MOT task, $F(1,23) = 4.54$, $p = 0.04$. Performance was significantly different when participants tracked two and four targets, $F(1,23) = 57.54$, $p = 0.0001$. MOT task type did not interact with WMC, $F(1,38) = 0.29$, $p = 0.60$. The accuracy for the two target trials was 81 percent ($SD = 0.03$) for low-WMC individuals and 90 percent ($SD = 0.02$) for high-WMC individuals. The accuracy for the four target trials was 69 percent ($SD = 0.03$) for low-WMC individuals and 76 percent ($SD = 0.04$) for high-WMC individuals. MOT performance on four targets correlated with performance on the MRT ($r(25) = 0.51$, $p < 0.01$) and the Spatial Span test, $r(23) = 0.61$, $p < 0.01$ (See Table 1).

Spatial measures. On the MRT, Low-WMC individuals scored an average of 2.06 out of 10 ($SD = 0.54$) compared to 4.41 ($SD = 0.47$) scored by high-WMC individuals. This difference was statistically significant, $t(33) = -3.37$, $p = 0.002$. Overall average score on the MRT was 3.65 ($SD = 0.33$). Similar performance occurred for the PFT and the Spatial Span test, where high-WMC individuals performed significantly better than low-WMC individuals, $t(33) = -3.22$, $p = 0.003$ and $t(33) = -2.44$, $p = 0.021$, respectively.

Specifically, the average score for the PFT was 10.22 ($SD = 0.58$), where low-WMC individuals had an average score of 8.49 ($SD = 1.08$) and high-WMC individuals had an average score of 13.09 ($SD = 0.99$). Thus, WMC span correlated significantly with spatial measures Spatial Span ($r(33) = 0.39$, $p < 0.05$), MRT ($r(35) = 0.39$, $p < 0.05$), and PFT ($r(35) = 0.46$, $p < 0.01$; See Table 1). The average and most frequent score for the Spatial Span test was 6 ($SD = 0.14$), where participants were able to remember up to a sequence of 6 flashing boxes. Low-WMC individuals scored an average of 5.67 ($SD = 0.23$) compared to an average of 6.44 ($SD = 0.23$) by high-WMC individuals.

Table 1

Pearson's Correlation Matrix of Study 1 Attentional Battery Scores and WMC Span

	Spatial Span	UFOV	MRT	PFT	MOT 2 obj	MOT 4 obj	proSacc RT	antiSacc RT	proSacc Acc	antiSacc Acc	WMC Span
Spatial Span		-0.270	0.463**	0.759**	0.617**	0.610**	0.175	0.008	0.518*	0.155	0.388*
UFOV			-0.426*	-0.157	-0.457*	-0.410*	-0.153	0.198	-0.486*	-0.547**	-0.192
MRT				0.376*	0.572**	0.511**	0.192	-0.231	0.258	0.301	0.389*
PFT					0.470*	0.426*	-0.140	-0.144	0.309	0.065	0.459**
MOT 2 obj						0.731**	0.344	-0.222	0.518*	0.376	0.364
MOT 4 obj							0.343	-0.175	0.447*	0.503	0.196
proSacc RT								-0.406	0.447*	0.420*	-0.151
antiSacc RT									.128	0.166	.255
proSacc Acc										0.349	0.120
antiSacc Acc											0.101
WMC Span											

**p < 0.01
*p < 0.05

Photo Search

On average, participants clicked 4.23 times (*SD* = 0.46) per photo trial, and found approximately three out of 12 items (*SD* = 0.32). The participants clicked incorrectly 1.16 times (*SD* = 0.13) and rarely repeated clicks on any item (M = 0.10, SD = 0.01). WMC span did not affect the total number of clicks on the photos, $F(1,35) = 0.09$, $p = 0.77$. Participants clicked on items more frequently for photos with an easy subjective rating (*M* = 5.40, *SD* = 0.59) compared to medium (*M* = 4.33, *SD* = 0.471) and hard photos (*M* = 3.24, *SD* = 0.35), $F(2, 35) = 106.12$, $p = 0.0001$ (see Figure 2). Photo rating difficulty did not interact with WMC span across total clicks, $F(2, 35) = .10$, $p = 0$ .91. The total percentage of correct clicks out of total clicks by participants was significantly correlated with UFOV performance, $t(73) = -0.32$, $p = 0.006$.

More items were correctly found for photos with an easy subjective rating (*M* = 4.06, *SD* = 0.44; See Table 2) compared to medium (*M* = 3.15, *SD* = 0.34) and hard photos (*M* = 1.87, *SD* = 0.20), $F(2, 35) = 230.22$, $p = 0.0001$. There was no WMC span effect on the correct number of items clicked on the photos, $F(1,35) = 1.16$, $p = 0.29$. Photo rating difficulty did not interact with WMC across the average amount of correctly found targets, $F(2, 35) = 0.16$, $p = 0.85$. Average correct and incorrect clicks was significantly correlated with UFOV performance, $t(73) = -0.29$, $p = 0.01$.

Participants' incorrect clicks (clicks on items that did not differ between photos) were affected by photo difficulty, $F(2, 35) = 4.53$, $p = 0.01$. Specifically, incorrect clicks across easy (*M* = 1.13, *SD* = 0.12) and medium (*M* = 1.07, *SD* = 0.11) trials were not significantly different ($F(1, 35) = 0.08$, $p = 0.78$; See Table 2), but participants had more significantly incorrect clicks on hard photo trials (*M* = 1.26, *SD* = 0.14), *F*(1, 35) = 8.98, *p* = 0.004. There was no WMC span effect on the incorrect number of items clicked on the photos, *F*(1,35) = 0.16, *p* = 0.70. Photo rating difficulty did not interact with WMC span across incorrect clicks, (*F*(2, 35) = 1.49, *p* = 0.23). Average incorrect clicks was significantly correlated with UFOV performance, *t*(73) = 0.25, *p* = 0.035.

Table 2
Click Performance by Subjective Rating Difficulty

	Easy	Medium	Hard
Correct Clicks (# items found)	4.06**	3.15**	1.87**
Incorrect Clicks	1.13	1.07	1.26**

**p < 0.01

Response times to resuming the photo trials when interrupted by the number-letter loading task were also measured. Average click resumption was 15.43 seconds (*SD* = 0.72) for low-WMC individuals and 13.37 seconds (*SD* = 0.67) for high-WMC individuals and was significantly different, *t*(30) = 2.07, *p* = 0.047; See Table 3. Resumption errors were calculated as the percentage of incorrect first and second clicks. The average percentage of incorrect first clicks upon resumption was 36 percent while the average percentage of incorrect second clicks to the photo trials was 38 percent. The resumption errors on first clicks and second clicks were not significantly different when comparing low- and high-WMC individuals, *t*(35) = 0.33, *p* = 0.74 and *t*(35) = 0.90, *p* = 0.38, respectively.

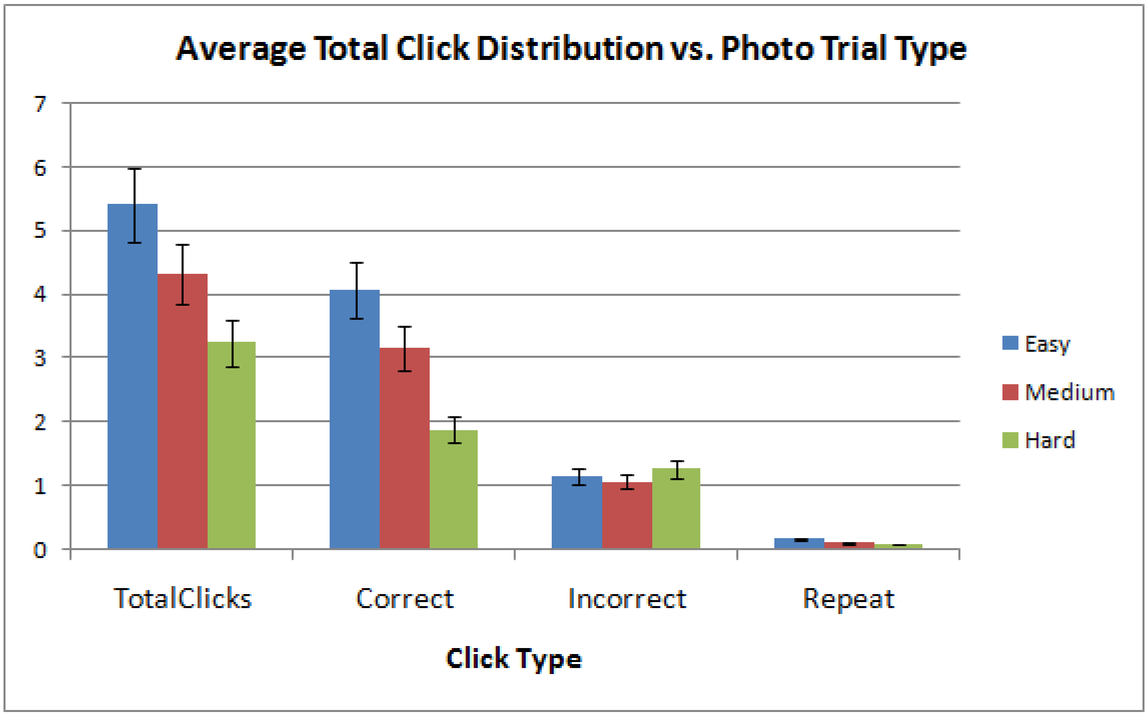

Figure 2. Average total distribution of clicks by subjective rating difficulty.

Number-Letter Loading Task

Overall accuracy on the number-letter loading task was 96 percent (*SD* = 0.03) and was not significantly different across low- and high-WMC individuals, $t(34) = -1.39$, $p = 0.17$. Participants were interrupted up to two times during each photo trial by the number-letter loading task when they found two new changed targets during the photo trials. There was no overall difference between the number of interruptions experienced by low- and high-WMC individuals, $t(35) = -0.66$, $p = 0.52$. Participants were interrupted and performed the number-loading task, on average, 19 initial times (first interruption, *SD* = 3.71) and 9 subsequent times (second interruption, *SD* = 4.17) during the 24 photo trials. The number of first and second interruptions experienced was not significantly different between low- and high-WMC individuals, $t(35) = -0.55$, $p = 0.59$ and $t(35) = -0.68$, $p = 0.50$, respectively.

Average overall response time on the task was 1313.47 ms (*SD* = 154.91). During the loading task, participants had faster response times within trials (*M* = 1154.07 ms, *SD* = 136.01) compared to the resumption trials (*M* = 1709.56, *SD* = 201.47), which were the first subsequent number-letter trials where participants resumed performance on the number-letter task, $F(1, 34) = 53.469$, $p = 0.0001$. Low-WMC individuals were significantly slower to resume the number-letter task (*M* = 1750.91 ms, *SD* = 153.15) compared to high-WMC individuals (*M* = 1327.28, *SD* = 97.11), $t(25) = 2.34$, $p = 0.03$. Low-WMC individuals (*M* = 1180.18 ms, *SD* = 68.97; See Table 3) also had significantly slower response times during within number-letter trials (non-resumption trials) compared to high-WMC individuals (*M* = 1003.73, *SD* = 37.51), $t(25) = 2.25$, $p = 0.03$.

Table 3
Average Response Times by Working Memory Capacity

	Low-WMC	High-WMC
Photo Resumption (sec)	15.43*	13.37*
Number-Letter Task Resumption (sec)	1.75**	1.33**
Within Number-Letter Task trials (sec)	1.18*	1.00*

**p < 0.01, *p < 0.05

Eye Measures

On average, there were roughly 7429 total fixations (*SD* = 171.35) with fixations durations of 321.58 ms (*SD* = 5.13) overall. The number of fixations was not significantly different between low- and high-WMC individuals, $t(35) = 0.51$, $p = 0.61$. However, average fixation duration was significantly longer for high-WMC individuals (*M* = 339.19 ms, *SD* = 9.35) compared to low-WMC individuals (*M* = 313.87 ms, *SD* = 7.91), $t(35) = -2.06$, $p = 0.047$. An average of 15 percent of the total fixations (1126.03 of the total fixations) were on the target items (12 target differences for each of the 24 photo trials) and were not significantly different between low- and high-WMC individuals, $t(28) = -0.19$, $p = 0.85$. Furthermore, participants fixated on all 12 target items 60 percent of the time during the experiment. The percentage of fixations on all target items did not differ for low- and high-WMC individuals, $t(28) = -0.17$, $p = 0.87$.

Discussion

The goal of this study was to explore how WMC affects visual search performance, namely to test whether the use of a complex visual search task could demonstrate a relationship between WMC and visual search performance. Also, the effect of WMC on the battery of attentional tasks was explored. Studies have used WMC tasks as a measure to compare individual differences and predict performance on a range of tasks. Since most of the tasks in previous studies have been basic and static in nature, this study served to advance understanding of the relationship in a complex visual search task.

It was hypothesized that high-WMC individuals would be faster and more accurate in identifying changed targets in the photo hunt task than low-WMC individuals.

However, low- and high-WMC individuals had equivalent performance in finding changed targets during the photo search, on average finding only a fourth of the changed targets per photo. This overall low performance suggests that all participants found the task challenging, particularly on photos with a higher difficulty rating. Participants found fewer objects and had an increased amount of incorrect clicks compared to easy and medium difficulty-rated photos. The photos were challenging enough that participants had overall low performance and were not able to find all the changed objects in each photograph despite numerous fixations on the static images. WMC did not affect the number of correct or incorrect clicks on the photo search. Similar to other visual search studies (Kane et al., 2006; Pool & Kane, 2009), the results of this experiment did not indicate that WMC affected the search processes or executive processes linked to WMC, even with increasing search complexity.

Instead, differences in performance between low- and high-WMC individuals manifested when participants were interrupted with the secondary loading task. Prior work suggests that variation in WMC is related to the ability to retrieve relevant information in the presence of multiple irrelevant representations (Unsworth & Engle, 2007; 2009). Participants in this study had to remember previous locations of identified changed targets after resuming from the number-letter tasks to continue to search for additional changed targets. Interruption from the secondary number-letter loading task was hypothesized to impact low-WMC individuals where the first subsequent click, or time to resumption, would be slower compared to high-WMC individuals. Resumption times followed this prediction and were slower for low-WMC individuals compared to high-WMC individuals when participants resumed to the photo trials and to the secondary number-letter task. Furthermore, low-WMC individuals had slower response times during the number-letter task compared to high-WMC individuals. These differences show that WMC predicted response time interference related to latency in the context of reinforcing and actively maintaining task goals. Low-WMC individuals were also predicted to have more difficulty in retrieving the information needed to continue the multiple target searches, resulting in more errors to previously clicked targets than high-WMC individuals. However, participants rarely repeated clicks to targets and there were no resumption error differences between low- and high-WMC individuals.

Participants with a wider UFOV were hypothesized to have a larger distribution of spatial attention, resulting in better performance on the photo hunt task. While there was no interaction between UFOV performance and WMC, UFOV performance was correlated with correctly finding objects in the photo hunt task and incorrect non-target clicks. Participants with a larger spatial attention distribution, as indicated by UFOV performance, clicked on more target objects and had less incorrect clicks on non-target objects. WMC did not correlate with performance on the MOT or the anti-saccade task, both of which required attentional inhibition. Instead, WMC measures were significantly correlated with visuospatial manipulation measures like spatial span, MRT and the PFT.

Gajewski and Henderson (2005) suggested that there is a general overall bias toward the minimal use of visual working memory in complex visual tasks, usually resulting in one object at a time encoded and maintained in visual working memory for a scene comparison task. If the difference between varying degrees of WMC meant that low-WMC individuals were more likely to employ a minimal memory strategy, and high-WMC individuals were more likely to employ a maximum memory strategy, then there should have been a marked WMC difference on finding target objects in the photo hunt task. It was likely that participants on this complex visual search task were only able to employ the minimal memory strategy during visual search. It was also likely that participants were only able to effectively employ bottom-up search processes for their initial searches and needed more time to actively compare targets as they continued examining the photos. Similar fixation counts and durations were found across low- and high-WMC individuals. While WMC differences were not found during the primary visual search task, differences between low- and high-WMC individuals were evident when resuming tasks and performing the secondary loading task.

Since there was equivalent behavioral and physiological performance on the photo hunt task, the memory hypothesis and the attentional disengagement hypothesis did not hold true in this study. Instead of increased gaze durations by low-WMC individuals proposed by the identification hypothesis, the opposite occurred. High-WMC individuals had longer fixation durations during the photo trials than low-WMC individuals. Evidence of interference between engaging in the photo trials and concurrent loading task was demonstrated by low-WMC individuals having slower resumptions and slower response times during number-letter trials. While this partially supports the saccade-programming or postponement hypothesis, both low- and high-WMC individuals had difficulty finding the correct targets despite actively scanning and fixating on targets in the photos. However, high-WMC individuals had significantly longer fixation durations.

It was hypothesized that the same cognitive functions that are affected by WMC in search are expected to be affected similarly in the more complex environment of driving in the following study.

STUDY 2: NAVIGATIONAL DRIVING

The goal of this study is to move from examining WMC differences when participants perform static visual search tasks such as in Study 1 to examining WMC differences when performing a dynamic visual search task such as when driving. Additionally, a majority of studies have tested WMC differences in static environments. This study used a dynamic driving simulation designed to ensure constant updating and maintenance of information in working memory by the driver. Furthermore, the driving environment has the benefit of being more applicable to potential problems with real world issues such as driver distraction.

Hypotheses

Differences in WMC are apparent when multitasking is demanding on executive function, as evidenced by a variety of attentional tasks (Poole & Kane, 2009; Unsworth & Engle 2008; Colflesh & Conway, 2007). The purpose of the second study presented was to use another challenging task and concurrent loading task that had participants actively taxing their working memory. Similar to Study 1, Study 2 explored the effects of WMC on visual search on encoding, maintenance, and retrieval of information in the display. Study 2 specifically attempted to distinguish the effects of WMC applied to real-world tasks in an effort to understand individual differences, previously found in attentional tasks, which may manifest in driving behavior. Prior studies have identified differences in attentional deployment between novice and experienced drivers, with experienced drivers showing strategic differences in peripheral attention (Crundall, Underwood, & Chapman, 2002) and decision times in choosing gaps to make left-hand turns (Guerrier et al., 1999). Few studies have explored whether individual variability in WMC is a factor affecting driving and wayfinding performance, though tasks varying in working memory load are often used to test the extent of concurrent task difficulty on driving performance (Lee, Lee & Boyle, 2009). Furthermore, gender, computer experience, and spatial skills have been identified as impacting wayfinding, however, much variation in performance is still unaccounted for.

Individual differences in WMC are hypothesized to affect driving and wayfinding performance. Driving and navigating to a location involves storing, retrieving, and making decisions based on constantly changing information from navigating the driving environment; these are all activities that actively engage working memory. For example, the driving task required the use of cognitive abilities such as actively searching in the environment for a target landmark and maintaining route information to reach the destination. Participants were also given a cued-recall navigation task. In this study, participants performed simulated driving routes to four destinations. All drivers were given route guidance to assist them in reaching their destinations. While the locations of the starting point and the destinations were always the same, the order of the four destinations was randomized. As a secondary task, participants were to respond to a peripheral detection task (PDT). This measure is commonly used to assess workload (Jahn et al., 2005).

In the navigation task, participants were given cued wayfinding instructions to each location in the form of visual and auditory cues. WMC was predicted to affect route maintenance and target identification, so that low-WMC individuals were more likely to have trouble recalling a route, or how to get to a location, compared to high-WMC individuals. Low-WMC participants, who are hypothesized to have difficulty reaching their destination, are expected to be slower, more likely to get lost, and less likely to complete their route to the four destinations. At higher driving task difficulty, less attentional resources are available, negatively impacting the performance of low-WMC individuals. High-WMC individuals were hypothesized to have more resources to devote to encoding and maintaining route information, and therefore better performance.

Often in cases of high demand on driving tasks, driving performance suffers, likely because the driver's cognitive limits are exceeded (Drews et al., 2004). The cognitive load from navigating, particularly by having to simultaneously pay attention to the PDT task, is predicted to exacerbate errors in driving performance measures. These measures include lane deviation, speed maintenance, and wayfinding performance (remembering and finding the locations).

Another measure is spatial learning, which is described as progressing through stages of development, mainly by landmark, route, and survey knowledge. Landmark knowledge is a memory for distinctive objects such as a particular building along a road. Route knowledge is the procedural linking of these objects, as well as forming distance and direction estimates. Survey knowledge (Siegel & White, 1975) is the ultimate integration of these landmarks and routes into a cognitive map of the environment. Route guidance systems have been hypothesized to speed up the process of route knowledge (Adler, 2001; Schofer, 1993). The effects of repeated route guidance use on driver behavior is not well understood. As a driver's spatial knowledge of the environment increases, the ability to make route choices and perform high level tasks like linking together landmarked locations can improve. Evidence of spatial learning was assessed in a navigational quiz that was administered after completing the five routes. The quiz assessed landmark knowledge by having participants mark the locations of the targets on a map. Survey knowledge is also demonstrated through questions that ask about the relative cardinal locations of buildings to each other and route knowledge was demonstrated through questions that ask the participant to name what street the buildings are located on. Performance on the navigation quiz is predicted to demonstrate spatial learning ability, particularly for high-WMC individuals who are hypothesized to have better spatial learning ability compared low-WMC individuals.

Peripheral Detection Task (PDT) sensitivity is theorized to be due to general cognitive workload. Previous studies (Engstrom et al., 2005; Olsson, 2000; Martens & van Winsum, 1999) have shown a reduction of target hit rates and reaction time with simultaneous engagement in secondary tasks. The PDT measures the ability to detect visual stimuli presented in the periphery with some temporal and spatial uncertainty. A modified PDT task was used that includes an irrelevant distractor stimulus (a blue dot) that participants are told to ignore. Studies have shown that peripheral detection is sensitive to route demands (Jahn et al., 2005). Low-WMC individuals were predicted to have longer response latencies to the PDT compared to high-WMC individuals due to the navigational demand of the driving task. Lower WMC individuals were also hypothesized to make more errors by responding to irrelevant stimuli (blue dot) more often than higher WMC individuals.

Like in Study 1, performance in Study 2 was compared to performance on an attentional battery of tasks measuring spatial attention, divided attention, and navigational strategy. High-WMC and low-WMC individuals were expected to perform similarly to the Study 1 hypotheses on the UFOV, MOT, and spatial measures. UFOV performance was not hypothesized to interact with WMC. Participants with higher WMC were hypothesized to perform better at tracking two and four objects than participants with lower WMC in the MOT task. The pro/anti-saccade task was not assessed since an eye tracker was not used in this study. Instead, a Sense of Direction (SOD) questionnaire (Kato & Takeuchi, 2003) was added to assess individual differences in strategy use. Baldwin (2009) found that those who scored low on the SOD had more difficulty learning the routes in general and tended to rely more heavily on verbal strategies than visuospatial strategies. The responses from this questionnaire were used to compare the SOD scores reflecting potential strategies used to differences in WMC and navigation performance. It was hypothesized that participants who scored low on the SOD would have difficulty learning the routes and would have lower route completion rates compared to participants who scored high on the SOD.

Method

Participants

A total of 67 students from George Mason University (44 females, 23 males; *M* = 22.55 years old, *SD* = 6.01) were recruited from the Psychology department subject pool and given course credit or $15 for their participation. All eligible subjects were at least 18 years of age with normal or corrected-to-normal vision and held a valid driver's license. Participants completed the attentional battery (WMC screening and additional attentional measures) prior to testing.

Apparatus

A Dell Dimension 2.13 GHz Intel Core 2 DM061 computer running SimCreator software (Realtime Technologies, Inc.) was used to present the driving simulation. The roadway environment and driving tasks were developed in RTI's SimVista authoring tool. The driving task stimuli was presented at 60 Hz on a 20.1" widescreen LCD monitor. The screen resolution was 1680 x 1050. A Logitech Driving Force GT steering wheel and pedals with force feedback was also used for controlling the simulated vehicle. The peripheral detection task stimuli was presented at 60 Hz on a 17" CRT Monitor at a screen resolution of 1024 x 768.

Figure 3. Experiment set-up with PDT task placed to the left of driving display.

Stimuli

The RTI SimVista authoring tool (version 2.24) was used to create the experimental tasks, roadway environment, and scenario elements. Their SimCreator software (version 2.8) was used to run the simulation. The scenarios required participants to drive in a city environment for approximately 50 minutes. There was sparse ambient traffic on the roadway. A light density of residential and commercial buildings was also present along the roadside.

Four landmark destinations were placed in the driving environment because the literature suggests that WMC for objects is around four items. Alvarez and Cavanagh (2004) suggested that visual short-term memory is limited in capacity to an upper bound of approximately four to five objects depending on working memory load and feature complexity. Liu and colleagues (2009) found that the capacity of maintaining multiple moving objects was about three to four items when participants were asked to track the objects and maintain their identities in a MOT paradigm.

Design and Procedure

Similar to Study 1, subjects were tested individually in two sessions, each session lasting approximately 60 minutes. In the first session, participants completed the WMC and attentional measures. The questionnaire, the Sense of Direction (SOD) questionnaire (Kato & Takeuchi, 2003), was also included.

The SOD questionnaire contains 17 statements designed to determine the degree that people believe they can benefit from or remember things such as cardinal directions, maps, and landmarks. The questionnaire is composed of two scales: an awareness of orientation (nine items), and memory for usual spatial behavior (eight items). While the first scale is correlated with pointing accuracy for distant locations, the second scale is significantly correlated with judgments over comparatively short distances like finding the nearest metro station (Takeuchi, 1992). Participants are asked to indicate on a scale of 1-5 how much they strongly agree to strongly disagree with each statement. Responses to this questionnaire were subjected to structural equation modeling, which identified three independent factors: use of cardinal directions, maps, and landmarks. The average of items contributing to each factor was averaged and summed to form composite scores for overall SOD. Previous studies have grouped participants into good and poor categories using the criteria of one standard deviation above and below the mean.

For the second session, the navigation task consisted of the participant driving to specified locations. The task can be broken into three main subtasks: 1) identifying the current location, 2) identifying the locations of other objects in the environment such as a destination, and 3) finding a route from the current location to the destination (Wickens, 1999). Participants may have used landmarks or street signs to identify and encode a specific route.

Each participant completed five driving route tasks among four destinations: Walgreens, KFC, Blockbuster, and SouthTrust Bank. The order of the destinations was randomized for each route. Participants were given up to 10 minutes to complete each driving route task. A compass showing the directional heading (N, S, E, W) of their vehicle was located on the upper left-hand side of the screen. All routes included voice guidance preceding each turn, presented as an audio clip similar to when using a navigation system. In addition to the auditory cue, the directions also appeared at the center of the screen (e.g. “Turn right on A St.”). Figure 4 shows a map of the world where the locations of the buildings are marked. The driving world was created using SimVista. The layout of the driving world was designed in a grid-like pattern, where numbered streets were arranged from North to South and lettered streets were arranged from East to West. The street names were posted on green signs along the roadway such that the driver could always see the street name that they were currently on.

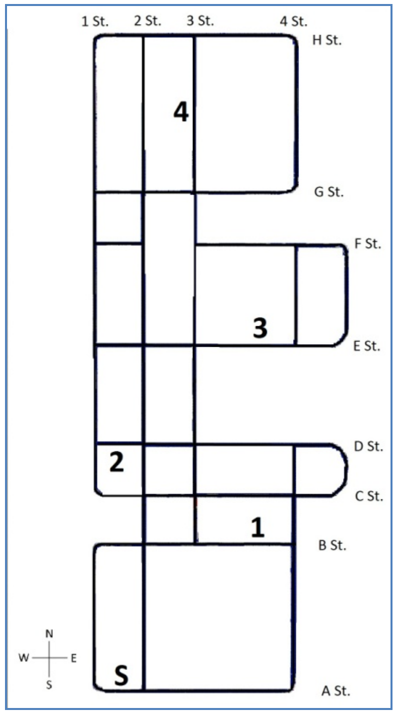

Figure 4. Layout of driving world (S=Start, 1=Walgreens, 2=SouthTrust Bank, 3=Blockbuster, 4=KFC).

The participant responded to a concurrent peripheral detection task while driving. The peripheral detection task (PDT) was developed by van Winsum and colleagues (1999) as a secondary task to measure mental workload and spare attentional capacity. A modified version of the PDT was used that included irrelevant stimuli (blue no-go trials) requiring no response from the participants. The standard task requires a manual response to stimuli presented at eccentricities between 5° and 25° left of the drivers' normal line of sight (van Winsum, Martens, & Herland, 1999). The stimuli in our task consisted of a red dot or blue dot visible for 1-2 seconds presented at an interval of 3-5 seconds. A red dot appeared in 80 percent of the trials. The dot either appeared at a near location of approximately 15° left of the line of sight of the driver or at a far location approximately

21° left of the line of sight of the driver. The participant responded by pressing a button only when a red dot appeared on the screen.

After receiving instructions, participants practiced driving around the world with the secondary PDT task for approximately eight minutes. The participants were also told that the voice guidance system would not recalculate, and to make a u-turn if a turn is missed. The drivers were also instructed that they would be asked about the locations of the destinations after the five routes were completed. The participants were told that the layout of the world was a grid-like design where numbered streets go from North to South and lettered streets go from East to West. They were instructed that they would always start at the same starting point and the locations of the buildings would never change. The order of the four destinations was randomized for each route. Participants were also instructed to obey traffic laws as they would normally drive and to perform the secondary PDT as quickly and accurately as possible.

After completing the driving route tasks, participants were given a paper quiz. In the first part of the quiz, participants were given a map similar to Figure 4 (without the locations 1-4 marked). The participants were told to mark the corresponding numbers for the four destinations on the map, similar to Thorndike & Golding's (1981) location task. Performance on this task was measured by the difference (in millimetres) between the participants' mark and the actual location of the destination on the map. The second part of the quiz asked participants the relative cardinal directions between locations on the map (e.g. Blockbuster is North/South/East/West of Walgreens). The third part of the quiz asked the street names for the four destinations (e.g. KFC is on ____ St.).

Data Analyses

Multiple dependent measures of driving performance were measured to assess the operational, tactical, and strategic levels involved in driving. These measures are often used in driving studies like in the navigation task in Drews, Pasupathi, and Strayer's 2008 study.

Route completion. Since participants were allotted the same amount of time (10 minutes) to complete each route, participants who had instances of getting lost or who overshot their cued directions likely did not complete their routes. Route completion is calculated as a percentage score of number of destinations reached divided by four total destinations.

Vehicle data. Some measures of interest include lane deviation, speed, and vehicle location. A measure of the operational level was lane deviation or how well participants were able to stay in the center of the lane without lateral movements and drifting. Lane deviation was calculated from root mean square error between the center of the road and the center position of the vehicle. Participants, on a tactical level, can vary speed and headway distance from vehicles on the road. Vehicle speed was measured by averaging the speed of the driver for each segment of the task (from landmark to landmark).

Workload. The PDT was used as an objective measure of workload. The percent of missed stimuli, false alarms to blue probes, and reaction time was measured.

A mixed model analysis of variance (ANOVA) was used to examine differences between subjects' driving task performance and composite WMC scores. Response times for the PDT task were also measured. A repeated measures ANOVA was used to analyze

PDT performance and driving performance across routes to see if routes affected PDT. The effects of WMC on route completion and secondary task performance were analyzed using independent samples t-tests. Pearson's correlations were calculated for the attentional battery measures and WMC span.

Results

Attentional Battery

Span measures. The composite WMC scores ranged from 20 to 73.5 (*M* = 51.72, *SD* = 14.95). Twenty-one low-WMC individuals and 28 high-WMC individuals were determined by using the same quartile split from study 1.

UFOV task. The average score on the UFOV task was 96.38, indicating normal selective attention ability. Like study 1, the population sampled was considered normal and were not expected to score above 350. Low-WMC individuals scored significantly worse than high-WMC individual with overall higher scores (*M* = 132.57, SD = 20.57), $t(32) = 2.13$, $p = 0.04$. In contrast, high-WMC individuals had a lower score than average (*M* = 82.59, *SD* = 11.32). Like study 1, performance on the MRT was also correlated with the UFOV ($r(46) = -0.32$, $p = 0.03$), but was uncorrelated with MOT performance (See Table 4).

MOT task. When participants were tracking two targets, the average accuracy was 83 percent (*SD* = 0.02). When tracking four targets, the average accuracy was expectedly lower at 69 percent (*SD* = 0.01). Unlike study 1, low- and high-WMC individuals performed equivalently on the MOT task, $F(1,38) = 0.41$, $p = 0.53$. Performance was significantly different when participants tracked two and four targets, $F(1,38) = 74.17$, *p*

= 0.0001. Type of MOT task did not interact with WMC, $F(1,38) = 1.15$, $p = 0.29$. Like study 1, MOT performance was significantly correlated with performance on the Spatial Span and the MRT, $r(36) = .42$, $p < 0.05$ and $r(39) = .41$, $p < 0.01$, respectively (See Table 4).

Spatial measures. Low-WMC individuals scored significantly lower than high-WMC individuals on the MRT, specifically, an average of 2.40 (*SD* = 0.41) compared to 3.73 (*SD* = 0.39) out of 10, $t(44) = -2.35$, $p = 0.02$. Overall average score on the MRT was 2.98 (*SD* = 0.2). Similarly, high-WMC individuals performed significantly better than low-WMC individuals on the PFT, $t(44) = -2.60$, $p = 0.013$. The average score for the PFT was 9.38 (*SD* = 0.61), where low-WMC individuals had an average score of 7.55 (*SD* = 1.08) and high-WMC individuals had an average score of 11.09 (*SD* = 0.89). The average. PFT performance was significantly correlated with Spatial Span ($r(40) = 0.51$, $p < 0.01$), MRT ($r(46) = 0.33$, $p < 0.05$), and MOT performance on two target objects ($r(39) = 0.37$, $p < 0.05$; See Table 4). The most frequent score for the Spatial Span test was 6 (*SD* = 0.11). Low-WMC individuals scored an average of 6.06 (*SD* = 0.26) compared to an average of 6.42 (*SD* = 0.17) by high-WMC individuals on the Spatial Span. In contrast to study 1, this difference was not statistically significant, $t(41) = -1.23$, $p = 0.228$. However, MRT and PFT were significantly correlated with WMC span, $r(46) = 0.30$, $p < 0.05$ and $r(46) = 0.32$, $p < 0.05$, respectively (See Table 4).

SOD questionnaire. Forty-six total participants who scored above the median of 3.125 were classified as having a good sense of direction (GSD), those who scored below the median were classified as having a poor sense of direction (PSD). Significant individual differences were observed when comparing the averaged composite WMC span score and SOD classification, $t(44) = -2.09$, $p = 0.04$. The average WMC score was lower for the PSD group ($M = 47.70$, $SD = 3.77$) compared to the GSD group ($M = 58.09$, $SD = 3.22$). When comparing SOD classification and WMC classification, 72 percent of participants in the low-WMC group were classified PSD and 64 percent of participants in the high-WMC group were classified GSD.

Table 4
Pearson's Correlation Matrix of Study 2 Attentional Battery Scores and WMC Span

	Spatial Span	UFOV	MRT	PFT	MOT 2 obj	MOT 4 obj	SOD	WMC Span
Spatial Span		-0.283	0.207	0.513**	0.313	0.421*	0.155	0.114
UFOV			-0.315*	-0.243	-0.252	-0.199	-0.132	-0.267
MRT				0.332*	0.393*	0.414**	0.151	0.299*
PFT					0.373*	0.267	0.079	0.320*
MOT 2 obj						0.603**	-0.144	0.085
MOT 4 obj							-0.066	-0.044
SOD								0.208
WMC Span								

**p < 0.01
*p < 0.05

Route Completion

Over half of participants (54 percent) completed all five driving route tasks to the four destinations. In the first driving route task, 63 percent of participants completed the full route, 23 percent of participants completed three out of four destinations, and 15 percent of participants completed half the route (see Table 5). Participants who completed the full route ranged between 87 to 92 percent between the second to the last driving route. The range for participants who completed three out of four destinations was 4 to 13 percent between the second to the last driving route; participants who completed half the route ranged between 0 to 4 percent for the second to the last driving route. Route completion was not affected by WMC span, $t(46) = 0.05$, $p = 0.96$.

Table 5
Driving Route by Percent of Route Completion

Route Completed	1	2	3	4	5
100%	62.5%	91.6%	89.6%	87.5%	87.2%
75%	22.9%	4.2%	8.3%	12.5%	8.5%
50%	14.6%	4.2%	2.1%	0%	4.3%

PDT Performance

Participants' performance on the PDT task across the five routes were not significantly different, $F(4,46) = 0.64$, $p = 0.64$. The average response time to a red dot (target stimuli) in the PDT task was 1333.52 ms ($SD = 352.97$). High-WMC individuals had a significantly faster response time ($M = 1227.77$ ms, $SD = 57.42$) to target stimuli compared to low-WMC individuals ($M = 1444.34$ ms, $SD = 67.41$), $t(46) = 2.46$, $p =$

0.02. Participants rarely responded (*M* = 0.006, *SD* = 0.01) to the blue dot (no-go stimuli). On average, participants missed the red dot 21 percent of the time (*SD*=0.16). PDT target misses significantly differed across the five routes, *F*(4,46) = 7.07, *p* = 0.0001). Specifically, participants performed significantly worse on the first route (*M* = 27.40 percent, *SD* = 0.03) compared to all other subsequent routes (*M* = 22.17 percent, *SD* = 0.01), *F*(1,46) = 24.07, *p* = 0.0001. No WMC differences were found when comparing miss rates to target stimuli, *t*(46) = 0.40, *p* = 0.69.

Driving Performance

Average lane position (*M* = 1.84 meters, *SD* = 0.19) was significantly different across driving routes, *F*(4, 44) = 4.03, *p* = 0.004. Mean lane deviation comparisons of the first route (*M* = 1.79 meters, *SD* = 0.03) was significantly lower compared to subsequent routes route (*M* = 1.85 meters, *SD* = 0.01), *F*(1, 44) = 14.92, *p* = 0.0002. No significant differences were found when comparing lane deviation across low- and high-WMC individuals, *F*(1,43) = 0.79, *p* = 0.38. The interaction between average lane deviation across driving routes and WMC was not significant, *F*(4, 43) = 0.78, *p* = 0.54.

Average speed, however, significantly increased from the first route (*M* = 25.0, *SD* = 0.62) to the third route (*M* = 26.96 mph, *SD* = 0.65) but decreased and stayed steady for the fourth (*M* = 27.89, *SD* = 0.73) and fifth routes (*M* = 27.49, *SD* = 0.89), *F*(4,44) = 12.51, *p* = 0.0001. No significant differences were found when comparing speed across low- and high-WMC individuals, *F*(1,43) = 0.02, *p* = 0.89. The interaction between average speed across driving routes and WMC was also not significant, *F*(4, 43) = 1.07, *p* = 0.37.

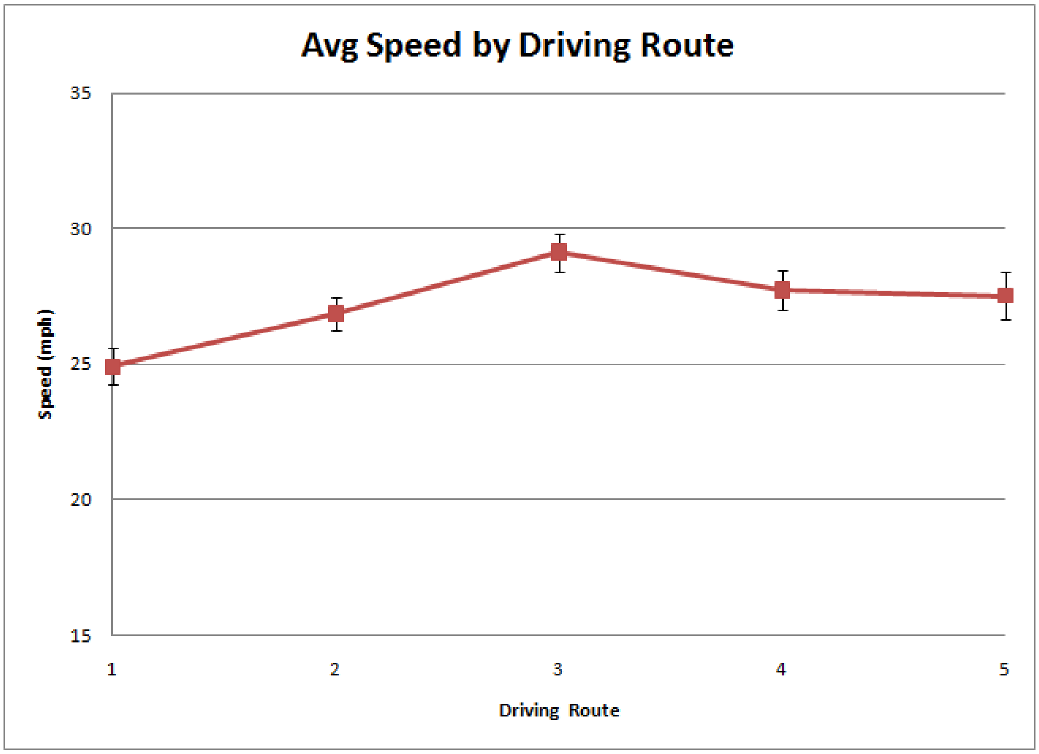

Figure 5. Average speed for each driving route.

Destination Quiz Performance

The first part of the quiz required participants to locate and mark the four destinations on a map of the driving world. The starting point was given as a reference landmark. The streets on the map were also labelled similar to Figure 4. An absolute sum and a relative sum was calculated to identify if they were able to correctly mark the locations and how close they were in marking the actual locations on the map. A score between 0 to 0.5cm was considered correctly identifying the location of the destination. Participants, on average, did not perform well on marking the locations on the map but were able to find 0.84 locations (*SD* = 0.11), marking an average of 2.22 cm (*SD* = 0.54) away from the target locations. On average, the most accurately marked location 1 (i.e.

Walgreens) was 1.87 cm (*SD* = 0.22) away from the actual location. SouthTrust Bank was marked 2.55 cm (*SD* = 0.21) away from the actual location; Blockbuster was marked 1.97 cm (*SD* = 0.15) away from the actual location; KFC was marked the furthest away (M = 2.54 cm, SD = 0.23) from the actual location. Performance on marking the locations on the map was not significantly different between low- and high-WMC individuals, $t(46) = 0.82$, $p = 0.42$.

Participants performed best on the street naming portion of the quiz where over half of the participants (M = 52.94 percent, SD = 0.04) were able to correctly identify all the streets the buildings were located. Performance on this portion of the quiz was not significantly different between low- (M = 52.78 percent, SD = 0.08) and high-WMC (M = 58.33 percent, SD = 0.09) individuals, $t(47) = -0.08$, $p = 0.94$. On average, participants scored 49 percent (SD = 0.03) on the directional portion of the quiz where they were asked about relative cardinal locations of the buildings. However, performance on the directional portion of the quiz was significantly higher for high-WMC individuals compared to low-WMC individuals, $t(47) = -2.25$, $p = 0.03$. SOD did not correlate with the directional portion of the quiz when controlling both for WMC, $r(41) = -0.26$, $p = 0.10$. Only three participants found all the locations on the map and had perfect scores on the second portion, where they were asked about the relative locations of the buildings from each other, and perfect scores on the third portion where they named the streets of where the buildings were located.

Discussion

The goal of this study was to explore WMC differences in a dynamic search task in an effort to understand whether WMC has an impact on a task like driving, where it is often a common occurrence, though not encouraged, to engage in secondary tasks. Individual differences were hypothesized to manifest in low- and high-WMC drivers. Since driving and navigating to locations coupled with secondary tasks have been shown to impair encoding of information (Strayer, Drews, & Johnston, 2003) and affect how drivers distribute their attention (Recarte & Nunes, 2003), this study aimed to test whether WMC and navigation strategies were related to participants' performance on a driving and secondary PDT task. All participants were given wayfinding instructions to each location. Participants with high-WMC and SOD performance were expected to have more attentional resources available, which would be reflected in better primary and secondary task performance and better recall on the navigation quiz.

Like study 1, performance on the primary task of driving, specifically completing the routes, was not significantly different across low- and high-WMC individuals. However, overall lane deviation increased from the first route to the last route, which may reflect difficulty with performing the PDT task and actively remembering the destination locations. Although overall secondary PDT performance stayed consistent from first route to the subsequent routes, the average participants' vehicle speed increased over the first three routes before leveling off. This finding may indicate that the participants were becoming familiar with performing the routes.

Like study 1, differences in WMC were found in the secondary loading task where high-WMC individuals had faster response times compared to low-WMC individuals on the task. As the PDT is often used as a measure of workload demand (Jahn et al., 2005), slower response times by low-WMC individuals indicate that they were more impaired by route demands than high-WMC individuals. Individual differences in driving performance were hypothesized to be evident in low- and high-WMC drivers' primary and secondary performance. This finding was partially supported by the differences found in secondary task performance.

While most participants were able to reach all four destinations, their ability to explicitly recall the destinations on a map was poor. Instead, participants did best on naming the streets where the buildings were located. This finding may indicate that most participants used a visual route-based strategy to navigate between buildings. Thus, one possibility for poor destination recall may be supported by differences in two possible strategies for learning a route proposed by Aginsky and colleagues (1997). The authors suggest that drivers may follow a visually-dominated or spatially-dominated strategy. In a visually-dominated strategy, participants may visually recognize decision points along a route but they are not integrated into a survey representation. In a spatially-dominated strategy, participants represent the environment as a survey map from the start. Scenes and landmarks may be recognized visually but may not be used for navigational purposes. Although all participants received navigational directions during the route, they may have chosen a particular strategy to learn the locations of the destinations. Baldwin & Reagan (2009) also found that individuals with poor SOD relied more heavily on verbal rather than visuospatial WM resources. The relationship between WMC and SOD may indeed be linked, as participants with high-WMC were found to have a higher average SOD score compared to low-WMC individuals.

A previous driving simulator study by Burnett and Lee (2005) found that participants who navigated around a representation of a small town with a route guidance system were less able to remember routes, and developed a poorer mental representation compared to those who used a map to plan their route. This effect was attributed to the level of information processing required of the participants. One possible explanation was that using the map required processing of orientation and directions at a deeper level than the participants who used the route guidance system. This fact is another possible explanation for why participants' performance on the location task (marking location on the map) was worse compared to when they were simply asked to name the streets the buildings were located on.

High-WMC individuals did, however, perform significantly better on the directional portion of the navigation quiz. Additionally, WMC span was correlated with two spatial measures, the MRT and the PFT. The relationship between WMC and navigational ability is not fully understood though there are studies that point to a possible link. For example, some studies suggest that the ability to remember the sequence of landmarks along a route does not share common processes with small-scale spatial cognition, or measures of spatial abilities based on tasks such as the MRT and PFT, but does share the ability to infer the environmental configuration based on the route experience (Allen et al., 1996; Hegarty et al., 2006). While WMC and SOD were not directly related, WMC and small-scale measures of spatial ability may be indirectly related to navigational learning.

In summary, participants engaged in five repeated driving routes to four destinations while performing a secondary PDT task. Route guidance was given to aid all in reaching their destinations. Most of the participants were able to complete each driving route within the allotted time of 10 minutes. Although the drivers had repeated exposures to the locations and routes between the destinations, they had difficulty explicitly marking the locations of the destinations on a map, and therefore had difficulty indicating directional relationship between buildings. The participants performed best at naming the street locations of the buildings. The use of route guidance may suppress cognitive map formation, impacting the ability to process navigation information. Furthermore, the attentional battery given in Study 1 and 2 similarly found showed a correlation between performance on WMC span and the spatial measures of paper-folding (PFT) and mental rotation (MRT). More research is needed to understand the long term use effects of route guidance on vehicle navigation and on the relationship of WMC, spatial ability, and navigational learning.

CONCLUSION

The results of these two experiments highlight the need to understand the effects of individual differences in WMC on complex tasks. Contrary to expectations, WMC did not predict performance on the primary tasks in these studies. Individual differences in WMC have been shown to moderate performance in tasks associated with attentional control and selective focus abilities, but have not been demonstrated in simple, prototypical visual search tasks. Even with complex visual scenes with multiple distracters, low- and high-WMC individuals can perform equivalently. Similar performance is also shown with completing routes and recalling locations of target landmarks on a map. While WMC did not directly impact search performance or driving performance, WMC affected performance on the secondary tasks and the ability to resume tasks. Low-WMC individuals had slower response times compared high-WMC individuals, indicative of strain on attentional resources and an increase in workload demand. This finding demonstrates that low- and high-WMC individuals can, to at a certain extent, perform equivalently, consistent with the results from visual search studies like Kane and colleagues (2006) and driving studies like Radeborg and colleagues (1999); however, performance differences occur when given more cognitive load in the form of secondary tasks. The two studies presented here also showed that there were attentional control differences between low- and high-WMC individuals in their ability to multitask, specifically with performance differences in the secondary loading tasks. In each study, high-WMC individuals responded faster than low-WMC individuals. Though their performance was equivalent in the primary task, low-WMC were affected by the cognitive load of the secondary task, which resulted in slower response times. The results of this study have implications for real world situations where attention is needed for perceiving and processing the environment, such as in air traffic control and driving. Valuable information may be discerned from individual differences in WMC and more research is needed to understand how this variability may relate with performance in other cognitive domains.

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