POOLE, BRADLEY JOHN, Ph.D. Executive Control and Attentional Scope in Visual Search: A Latent Variable Investigation. (2012)
Directed by Dr. Michael J. Kane. 154 pp.

This study uses latent-variable analysis to investigate the roles of control and attentional scope aspects of working memory (WM) on three visual search tasks that the literature indicates involve controlled processing—preview search (Watson & Humphreys, 1997), cued location search (Poole & Kane, 2009) and attention capture search (Lavie & De Fockert, 2005). Latent variable analyses indicate that control and attentional scope aspects of WM are best conceptualized as part of the same unitary WM construct rather than as separate entities. Capture search resulted in an unexpected reverse capture effect with the presence of irrelevant stimuli leading to faster search. Modeling indicated that controlled processes involved in preview search and cued search should be conceptualized as reflecting the same processes rather than separate types of control, in spite of differences in task requirements. After partialling out variability common to traditional search which does not recruit control processes (Kane, Poole, Tuholski & Engle, 2006), the unitary WM factor was related to a latent control factor based on preview search and cued search performance.

EXECUTIVE CONTROL AND ATTENTIONAL SCOPE IN VISUAL SEARCH: A LATENT VARIABLE INVESTIGATION

by

Bradley John Poole

A Dissertation Submitted to
the Faculty of The Graduate School at
The University of North Carolina at Greensboro
in Partial Fulfillment
of the Requirements for the Degree
Doctor of Philosophy

Greensboro
2012

Approved by

____
Committee Chair

A special thanks to all the friends and family who helped me along the way.

This work is as much a product of my labor as is it your love.

APPROVAL PAGE

This dissertation has been approved by the following committee of the Faculty of The Graduate School at the University of North Carolina at Greensboro.

Committee Chair ____

Committee Members ____

____

____

____

____

Date of Acceptance by Committee

____

Date of Final Oral Examination

ACKNOWLEDGMENTS

Many thanks are owed to my advisor, Dr. Michael Kane, for his teaching, guidance, and seemingly boundless patience.

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CHAPTER I

INTRODUCTION

Cronbach (1957) eloquently called for combined use of the experimental and correlational approaches in scientific psychology. Important in his proposal was that by looking at variability among individuals, the non-treatment variance attributed to error by experimentalists could be informative; understanding general, common processes as well as those specific to individuals can be valuable. Underwood (1975) promoted this cause further, and proposed that most theories of mental processes should be tested using individual differences. The reasoning is that if individuals vary on an ability or process, correlations should differ with performance measures manipulated to increase or decrease the involvement of such processes. Therefore the combined use of experimental and individual differences approaches results in a strong tool for theory falsification.

Recent work using an individual-differences approach has been valuable in better characterizing the notion of cognitive or executive control, which is proposed to be necessary in monitoring and troubleshooting tasks which are complex, novel, or require multiple steps (Monsell, 1996). For example, Miyake and colleagues (e.g., Miyake, Friedman, Emerson, Witzki, Howerter, & Wager, 2000) have investigated whether control, or “executive function”, is better characterized as a single, unitary construct or ability, or rather as several separate abilities. They tested how individual differences in performance on tasks purported to tap three theorized control functions — task-set shifting, memory updating, and inhibition of prepotent responses, would relate to performance on several common executive-function tasks (e.g., Wisconsin card sort, random number generation). Factor analysis and structural equation modeling (SEM) indicated the three control function variables were separable, but also moderately correlated (*r*s = .42 to .63), suggesting that while these aspects of control are distinct from one another, they also share some commonality. Further, the three function variables contributed differently to performance on the executive function tasks tested, suggesting that executive control may not be unitary (e.g., the central executive of Baddeley, 1986; the supervisory attention system of Norman & Shallice, 1986; see also Friedman & Miyake, 2004 for an extension of this work to inhibitory functions). Such findings are not restricted to young adults; related research using older adults lead to a similar conclusion – with a fractioning of control into at least two separate functions reflecting the shifting and updating of goal relevant representations as well as the inhibition of proactive interference (Hedden & Yoon, 2006).

The current study uses an individual differences approach to clarify the nature of control. This large-scale study presents a latent-variable analysis of several visual search tasks thought to depend on controlled processes, and their relationship to measurements of different aspects of working memory (WM). Individual differences analyses are underrepresented in the visual search literature and, in addition, this work investigates whether a unitary top-down control system best characterizes performance in these tasks and advances our knowledge regarding how attention control relates to WM.

Individual Differences in Control – Working Memory and Attention

The literature investigating the relationship between the executive control aspect of working memory capacity (WMC) and performance on low-level attention tasks has relied heavily on the individual-differences approach. Complex, dual-task WMC measures require subjects to interleave processing and memory storage, as in the reading span task (RSPAN) where subjects comprehend sentences while remembering unrelated words for later recall (e.g., Conway et al., 2005). The surge of research regarding the WMC-attention relationship is due, in part, to the finding that WMC measures predict performance on higher-order cognitive tasks including intelligence tests, language learning, and others (see, e.g., Ackerman, Beier & Boyle, 2005; Kane, Hambrick, & Conway, 2005; Oberauer, Schulze, Wilhelm, & Süβ, 2005). Theorists have proposed that the reason WMC is so important to performance in these tasks is that they tap into a general attentional component of WM, and that this component is common, and important, to many intellectual activities (e.g. Engle & Kane, 2004; but see also Cowan, 2001; Hasher, Lustig & Zacks, 2007; McNamara & Scott, 2001; Oberauer, 2005, for different views).

WM and Restraining Responses

A number of studies have demonstrated the relationship between WM measures and aspects of attention control. These extreme-groups experiments have shown variability in WMC to predict performance on a variety of tasks that require subjects to withhold a habitual or automatic response. For example, WMC is important in performing the antisaccade task, which presents a salient visual flash on either side of a central fixation point and requires attending to the opposite direction. Subjects with high WMC are better able to withhold the response of looking toward the flash than subjects with low WMC (Kane, Bleckley, Conway & Engle, 2001; Unsworth, Schrock & Engle, 2004). Other research has shown WMC to be important in an individual's susceptibility to the Stroop (1935) effect. On incongruent trials, where the word and the color it is written in conflict, subjects scoring highly on WMC measures were able to report the words much faster or more accurately that were those who scored poorly on WMC measures (Kane & Engle, 2003; Long & Prat, 2002).

WMC And Constraining Conscious Focus

Other research also indicates a relationship between WMC and performance of tasks requiring attentional constraint, here described as the limiting of processing amidst distraction. Research with the dichotic listening task has shown that low WMC subjects commit more errors than do high WMC subjects in repeating an auditory message in one ear when another competing distractor message is also presented in the other ear (Conway, Cowan & Bunting, 2001). Further, when the subject's own name is presented to the ignored ear, low WMC subjects were three times more likely to hear their own name than were high WMC subjects (see also Colflesh & Conway, 2007 for an extension of this work). WMC is also related to visual focus. In a version of Egly and Homa's (1984) visual orienting task, Bleckley, Durso, Crutchfield, Engle and Khanna (2003) had subjects identify a masked letter at fixation and localize another presented on one of several concentric rings surrounding fixation. Some trials verbally cued which ring would contain the second letter (e.g., “middle"). Localization performance did not vary by

WMC on validly cued trials. But on invalid trials, when the letter appeared at a location closer to fixation than the cue indicated, high spans' performance suffered while low spans' performance was unaffected. High spans thus seemed able to constrain their attention to only the cued ring, while not processing the area between that ring and fixation. Low spans, in contrast, distributed their attention more diffusely, perhaps as a spotlight encompassing the entire region contained within the cued areas (e.g., Posner, 1980). Follow-up research supported the notion that distributing attention discontiguously is a controlled process. Bleckley (2001) put subjects under a dual-task load and eliminated this ability in high span subjects—they allocated attention in a spotlight similar to low spans. Further, cueing the target ring exogenously with a flash allowed low WMC subjects to limit attention to the cued ring. WMC was thus important to constraining visual focus only when relying on endogenously generated, controlled processes.

Research using the flanker task (Eriksen & Eriksen, 1974) further supports this relationship between WMC and constraining the focus of visual attention. Heitz and Engle (2007) had subjects identify the central letter of a string while manipulating whether the surrounding letters matched it, as well as the time allowed for response. WMC was unrelated to letter identification when the surrounding letters matched. At short deadlines, high WMC subjects outperformed low WMC subjects on mismatch trials, showing they were able to constrain their visual focus more quickly than their low span counterparts (Heitz & Engle, 2007; Redick & Engle, 2006).

Visual Search: Another Instance of Control?

Since theorists have proposed that the executive attention component of WM is what drives the predictive relationship between WMC measures and higher order cognitive tasks (e.g., Engle & Kane, 2004) a critical question is whether WMC is related broadly to all attention-related tasks or to only tasks that require withholding habitual responses or constraining attention. An attention-demanding task of much interest in the literature is the visual search task. Visual search tasks are ubiquitous in everyday life; we perform such tasks when trying to find a set of car keys on a cluttered desk or when we search through shelves of journals to find the desired volume. In the laboratory, subjects search for a target, for example the letter C, among a display containing distractors, which may be Xs or Os; similarly, the target might be a blue circle among blue squares and red circles, or any other possible combination of attributes. Lead theorists have posited an important role for top-down control in some visual search tasks. The most influential views today, guided search theory (e.g., Wolfe, 1994) and feature integration theory (e.g., Treisman & Sato, 1990), propose that knowledge plays an important role in visual search. Common across these views is that the visual scene is analyzed automatically and in parallel across the visual field based on simple features such as shape or color (though what constitutes a basic feature is not altogether clear; Wolfe, 1998). This early automatic, bottom-up analysis results in a master map with varying levels of activation based on local differences in basic features from the visual display. Top-down knowledge is also critical to search such that it augments activation in areas containing target-characteristics (e.g., a particular color) or decreases activation in other areas (depending on the particular theory). Searches then proceed with attention probabilistically visiting the areas with greatest activation to those with progressively lesser activation until the target item is found.

Some visual search tasks, for example when searching for a blue item among red items, are thought to rely primarily on bottom-up, salience-based factors because such searches are fast and independent of number of distractors present. In these cases the target seems to ‘pop-out’ effortlessly from the visual scene because it is the only unique item present; the target can be located based on the basis of a single feature. However, when the target item shares features with distractors, for example when the target is a blue circle and distractors are blue squares and red circles, searches seem effortful, and reaction times (RTs) increase drastically with more distractors presented (Treisman & Gelade, 1980). These conjunction searches are thought to rely on top-down factors by requiring the focus of attention to serially visit each item in turn, in order to bind its component features together to form a coherent object for identification.

Attentional engagement theory further specifies how top-down control might operate in visual search (see e.g., Duncan & Humphreys, 1989; 1992). According to this view, displays are analyzed early on by a parallel stage of feature-based processing with stimuli chosen for further analysis by two processes. One is via perceptual grouping – similar items are grouped together and enter or are rejected from visual memory. The other is by matching the stimuli to an actively held target template; both of these processes bias a competition for access to visual short-term memory. Attention engagement theory views this template as an active top-down control signal which determines search requirements—simple templates (determined by simple targets) are quick to find while more complex templates and targets take longer to match, due to greater number of elements involved in the comparison. Analogous to feature integration and guided search, the top-down component of attentional engagement theory is crucial since it guides attention when stimulus-driven display characteristics may not single out the target automatically.

Kane, Poole, Tuholski & Engle (2006) investigated whether individual differences in WMC influence performance in a variety of visual search tasks in testing the boundary conditions of the WM–attention relationship. Across several experiments they presented searches of varying difficulty. Some searches defined the target based on the absence of a feature and presented the stimuli in a strict grid-like or less structured arrangement (Experiment 1). Other searches presented relatively unstructured displays and defined targets based on a specific spatial configuration of oriented lines or a conjunction of color and orientation (Experiment 2). Kane et al. found large mean search slopes, indicating inefficient search, but WMC was unrelated to performance. Why were individual differences in WMC unrelated to search, given that WMC is related to performance in so many other attention demanding tasks? Kane et al. proposed that the WMC and visual search tasks studied may have tapped different varieties of controlled processes.

Some recent work supports this notion that visual search tasks are not ‘controlled’ as it is commonly thought of in the executive function or cognitive control literature (e.g., Norman & Shallice, 1986). Smilek, Enns, Eastwood and Merikle (2006) instructed participants to either ‘give up’ active control during search, letting the target passively come to them, or to actively direct attention in order to locate it. Searches were performed *more* efficiently under the passive than active search condition. Further, a secondary memory load did *not* affect ‘easy’ searches (presenting easily distinguishable targets); a load did affect ‘hard’ searches making them more efficient under dual than single task conditions. Smilek and colleagues propose that relying on controlled processing may hinder search efficiency, as rapid automatic processes usually guide attention in visual search. Other research supports this conclusion. Wolfe, Alvarez and Horowitz (2000) compared visual search performance in a typical task to a ‘command’ task in which subjects had to follow a pre-specified search path around the display in order to identify the target. Search rates were much longer in the command task than the traditional search task, which they interpreted as evidence that searches are typically performed in a largely automatic (“anarchic”) fashion. Do any visual search tasks rely primarily on top-down factors related to controlled processes like those related to resisting the influence of habit or constraining focus, as measured in WMC?

This question has been investigated using visual search tasks that manipulate the potential influence of top-down and bottom-up influences. Sobel and Cave (2002) had subjects perform a color-orientation conjunction search (for a red vertical bar) and varied the relative proportions of the distractor types used. When the distractor types were highly discriminable (green vertical and red horizontal bars) searches were limited to the dimension (color or orientation) with fewer distractors. This is attributed mainly to bottom-up salience, as the features of the smaller group are more distinct among the members of the larger group. When the distractors were similar to each other (green vertical bars and red bars tilted 20° from vertical) however, subjects only searched based on color, regardless of whether it was the smaller or larger of distractor groups. Sobel and Cave (2002) interpreted this effect as due to controlled top-down grouping strategies, perhaps based on the perceived difficulty of searching by orientation in the similar condition, as the colors were more easily distinguished from each other than the orientations were.

Sobel, Gerrie, Poole & Kane (2007) used a similar methodology in which they induced a habit (à la the congruency manipulation in Stroop work of Kane & Engle, 2003) to search (for a target red horizontal arrow) by color by presenting many trials in which orientation distractors predominated. Similar to Sobel and Cave (2002) they presented distractors in either distinct (green horizontal and red vertical arrows) or similar orientations (green vertical and red tilted 20° from horizontal). WMC was unrelated to performance in the distinct orientation condition, as search in this context relies primarily on bottom-up factors (Bacon & Egeth, 1997). In the similar orientation condition, however, low WMC subjects performed as well as high WMC subjects except when the number of color-distractors presented in the displays was greater than the number of orientation distractors. High WMC subjects limited searches to the orientation items but low WMC subjects searched through color items even though they had to search through a greater number of items, on average, to find the target. In this situation, when color-based information was most salient (though orientation information most useful to limit search), low WMC subjects were either unwilling or unable to limit search based on the less salient, orientation-based information. Top-down strategic factors related to WMC were important to constraining the search set amidst a context predisposing subjects to search via the salient color dimension; again a search condition relaying on primarily bottom-up influence was unrelated to WMC.

Control processes related to WMC are also important in visual search tasks which pre-cue likely target locations. Poole and Kane (2009) gave subjects central symbolic cues to limit visual attention to a subset of locations in the search display. Subjects searched for a target letter under conditions that either manipulated the amount of distractor noise while keeping the same four potential target locations constant across trials or, in other experiments, presented constant distractor noise while manipulating the number of potential target locations per trial. WMC was unrelated to performance when distractor noise was low, but in the high noise condition, and when having to reconfigure attention to different locations across trials, high WMC subjects searched faster than low WMC subjects. To determine whether this WMC effect was based on the speed with which attention could be configured, their last experiment manipulated how long a fixation screen was presented before the search display. WMC differences only arose at the *long* duration; low WMC subjects seemed to be unable to keep their visual attention limited to the target locations as long as high WMC subjects were able. This work suggests that WMC is important to keeping visual attention limited to locations in high noise contexts, especially when the task requires the frequent reconfiguring of spatial attention.

The review above suggests that controlled processes involved in WMC measures are not related to those involved in typical visual search tasks, as demonstrated by Kane et al. (2006). Further, WMC was also unrelated to ‘command’ search, requiring attention to move through a pre-specified path in the search display, even though this is proposed to be an endogenously controlled task (Kane et al., 2006; Wolfe et al., 2000). WMC is related to restricting conscious focus of attention to cued locations amidst distraction (Bleckley et al., 2003; Heitz & Engle, 2007; Poole & Kane, 2009), especially when the task requires a frequent reconfiguration of such locations. Further, the work of Sobel et al. (2007) demonstrates WMC’s importance in a conjunction search task where task characteristics allow for performance improvements from top-down, strategic factors.

What then can be said regarding the nature of top-down control in visual search? Almost certainly the influence of top-down knowledge of the target’s features is apparent in virtually all the visual search tasks described above. However, empirical results indicate a distinction between different visual search tasks in that only some seem to be related to controlled processes (as involved in WMC). Top-down influence in visual search seems ubiquitous if thought of as dependent on the searcher’s knowledge. However, such knowledge-based influence is seemingly different from executive control. Consider, for example, the experiment involving the “command” search task that requires moving attention around a pre-specified path in the display (Kane et al., 2006). While knowledge of task requirements is crucial to finding the target in this task, due to the specificity of search path, control as measured in WMC tasks plays no role. Tasks requiring controlled processes, like constraining visual attention, demand involvement of processes in addition to the searcher's knowledge-based ones.

Controlled Visual Search Tasks

The current study involves several visual search tasks thought to be related to WM in order to investigate the commonality of control processes among visual search tasks and their relationship to WM measures. Notions of cognitive control and top-down processing are used commonly in this literature, though efforts to determine whether the same processes are involved across tasks are lacking. Studies mentioned above, including Wolfe et al. (2000) and Kane et al. (2006) provide evidence that investigating the involvement of control processes in visual search tasks is not a trivial pursuit; even some long, effortful searches do not involve controlled processes like those related to WM. Although the three types of search tasks in this proposal, preview search, cued search, and attention capture search have different surface characteristics, they all depend on the observer's own goals settings and controlled process available to implement them. The following section describes these tasks in greater detail.

Preview Search

One task of interest here is the preview search task, which presents a target as well as two types of distractors. In contrast to typical search conditions, where the target and all distractors are presented together at the same time, half of the distractors are presented and then, following a delay, the remaining half of the distractors and the target are also presented. RTs are faster in the preview than full (or baseline) search condition.

Further, the time to find the target in preview search is virtually independent of the number of distractors in the old display as evidenced by flat search slopes across distractor-set sizes (Watson & Humphreys, 1997). This has been taken to suggest that ‘old’ distractor items are deprioritized or suppressed as a group as if the observer limited the search to only the new items in the search display (Watson & Humphreys, 1997). The dominant theory attributes the preview benefit to visual marking, an active, top-down controlled process (e.g., Olivers & Humphreys, 2002; Watson & Humphreys, 2000). While this view has been challenged most notably by a proposal claiming that such an effect is based on attentional capture (e.g., Belopolsky, Theeuwes & Kramer, 2005) with the newly presented items capturing attention, other evidence has demonstrated this view to be at least not the complete explanation (Braithwaite, Hulleman, Watson, & Humphreys, 2006; Jiang, Chun & Marks, 2002). For example, Braithwaite et al. (2006) still found a preview benefit even when limiting the possibility of using attention capture to limit searches to the post-preview display by presenting only isoluminant displays to reduce bottom-up effects. Thus the visual marking view, which attributes the preview benefit to top-down controlled suppression of old items is currently the dominant view, though theorists admit some bottom-up factors may also play a limited role in the preview benefit (e.g., Donk & Verburg, 2004; Olivers, Humphreys & Braithwaite, 2006).

Evidence that the preview benefit depends on controlled processing comes from several studies. A secondary task performed while the ‘old’ previewed items are displayed significantly disrupts the preview benefit (Watson & Humphreys, 1997), suggesting that attention processes are required for visual marking. Further, Watson and

Humphreys (2002) presented a preview search task at the end of an RSVP stream and induced an attentional blink to manipulate the availability of attention during preview search and intermittently probed distractor locations. They found that probe identification was greater at distractor locations when the preview display was presented during the blink. The authors proposed that without attention available during the presentation of the distractors that they were unable to be deprioritized, indicating a critical role for attention in producing the preview effect.

Cued Search

Another visual search task involving control processes is the spatial cued search task. A common finding in the literature is that if subjects are cued in advance to where a target will appear, that target identification will be faster than targets appearing at neutral or non-cued locations (e.g., Posner, 1980). The discussion here focuses on the experiments in which the cues are endogenous (or voluntary) as opposed to exogenous (or reflexive) in nature, as endogenous cues are associated with control (see e.g., Lu & Dosher, 2000; Muller & Rabbitt, 1989, for a comparison of these cue types). Typically, subjects are presented with a symbolic cue (e.g. an arrow) at fixation for some duration. The cue indicates where the target will appear with some predetermined validity. The cue benefit is reflected in faster RTs when the target appears in the cued location compared to when it appears elsewhere. Two primary types of theories have been put forth to account for these effects. In resource-allocation models, like signal enhancement (Henderson, 1996), processing resources are limited so that when locations are cued, resources must be allocated away from non-cued and toward cued locations in order to speed identification. The other type, distractor exclusion models, such as biased competition (e.g. Awh, Matsukura & Serences, 2003) propose that attention limits interference from surrounding, non-target areas when likely target locations are cued. Such an effect is accomplished either via direct inhibition of processing (with lowered quality of processing) at non-cued locations, or by attentional gating indirectly blocking information processed (such that the information does not enter awareness) from those locations (see e.g., Verghese, 2001, for a related view based on decision processes). Regardless which type of model is correct, both posit a central role for top-down attention in cued search.

Compelling support for the involvement of top-down attentional control in spatially cued visual search comes from a number of studies by Awh et al (2003). Subjects reported targets which appeared in two spatially separated locations while the frequency with which distractors ("noise") were presented was manipulated across blocks. They cued likely target locations and compared performance on identical trials differing only by how common distractor-laden displays were. Performance differed by cue validity only in the high noise block. In low noise blocks, cueing showed little effect, while high noise blocks showed a large cue benefit. Awh and colleagues interpreted this spatial cue benefit appearing selectively in the high noise block as due to increased distractor exclusion. They offered support for the top-down controlled nature of these processes by demonstrating that the quality of distractor exclusion did not change passively, but rather was modulated strategically following trial by trial cues (Awh et al., 2003, Experiment 5). Further support for the controlled nature of cued search comes from the work of Poole & Kane (2009), described above, who reported WMC effects in several experiments which used endogenous cues to indicate potential target locations in distractor laden displays.

Attention Capture Search

Another visual search task that is thought to rely on top-down control factors is the attention capture task. Subjects search displays for the target item but on some trials a singleton stimulus, which differs in some characteristic from all the other stimuli, is also presented. Early work typically presented the search display and then, after some amount of time had passed, also presented the new singleton item as an onset or new item appearing in a previously unoccupied area (e.g., Yantis & Jonides, 1984). Also common in this research is the use of color singletons, where an item of a different color than the other search items is presented without a delay (e.g., Theeuwes, 1992). Importantly, subjects are instructed to ignore the singleton during search as they are irrelevant to the task and (in most preparations) are never the target item. The capture effect is a disruption or slowing of search on trials when an irrelevant singleton is presented in comparison with baseline trials without singletons (Theeuwes, 1992). To explain this effect some theorists have proposed that the bottom-up activation brought on by the high salience of the singleton forces attention to focus at its spatial location and that top-down control has virtually no effect on attention in this context (Sagi & Julesz, 1985; Theeuwes, 1992, 1994). Support for this view comes from research demonstrating that capture effects occur when using the same singleton over trials and even with extended practice on the task (Theeuwes, 1992).

Other theorists, however, have shown support for a causal role for top-down attention in producing capture. Folk, Remington and Johnston (1992) manipulated the relationship between the characteristic which defined the singleton distractor and that the target – whether each was defined by color or onset status. Onset singletons disrupted search when the target was defined by an onset, but not when it was defined by color. Likewise, capture was greater for a color singleton when the target was defined by color rather than onset, and other work has shown invalid motion cues disrupt search for targets defined by motion, but not color features (Folk, Remington & Wright, 1994). The contingent capture account holds that a combination of both top-down and bottom-up influences produce capture effects. According to this view the occurrence of capture critically depends upon the attentional control settings of the observer, which are largely determined by knowledge of the task requirements. The notion that this effect is based largely on controlled processes is supported by research by Lavie and colleagues. Lavie and De Fockert (2005) reported 3 experiments that presented color singletons and manipulated whether subjects were under a memory load. Visual search was more disrupted by the singleton when under a secondary load, which the authors interpreted as evidence for the involvement of WM in providing goal-directed control of visual attention in the service of minimizing goal-irrelevant distraction (see also Lavie & DeFockert, 2006, regarding overlapping brain regions involved in capture and executive control).

The visual search tasks used here are of interest to the current exploration of the notion of control among visual search tasks as well as their relation to WMC for several reasons. First, while preview search and attention capture search are thought of as dependent on top-down control and are both disrupted by a secondary task (see e.g. Watson & Humphreys, 1997, and Lavie & Defockert, 2005, respectively), their surface task requirements are rather different. In preview search, control limits search to only stimuli appearing in the second (i.e., full) display. Conversely, in attention capture, control keeps attention from the newly appearing item in order to keep search processes focused on the potential target-containing old items. Further, since prior work has shown spatial cueing tasks to be related to WMC (see Bleckley et al., 2003; Poole & Kane, 2009), inclusion of this task serves two purposes. First, control in this task limits attention to a particular, predetermined spatial location or locations on each display, unlike the other two tasks of interest here, in which the relevance of spatial locations is unknown to the subjects. Secondly, finding a relation between WMC and cued search will replicate the previous findings from Poole and Kane (2009) in a new context and be useful as a comparison for WM's relationship to the other controlled visual search tasks.

Individual Differences in Visual Search

In comparison to some other research areas in cognitive psychology, like cognitive control and WM cited above, individual differences research in visual search has been underrepresented. This may be due to assumptions among researchers that such elementary processes vary little, if at all, between people. Of those few studies that have investigated individual differences, several are of interest to the work proposed here.

Wallace and Newman (1998) used an individual-differences approach to test whether the personality trait of neuroticism predicted susceptibility to attention capture in visual search, based on their view proposing that attentional processes affect cognition, which in turn influence affect. Each trial cued subjects as to which letter (of a small pool of letters) would be the target for that set of frames per display. Each of several frames in the search display presented three letters; on some trials an irrelevant stimulus (e.g., an arrow, smiley face, etc.) was also presented. Among the 70 females in their sample, those high on neuroticism on a personality inventory demonstrated a greater capture effect than non-neurotic females. They propose that a disposition to negative affect is associated with disruptions of controlled, self-regulatory processes. Related work with personality variables has shown individual differences in self-rated impulsivity to be related to visual marking, such that a poorer preview benefit was associated with greater impulsivity in a sample of 40 subjects (Mason, Booth & Olivers, 2004).

Though these are not the only visual search studies using an individual-differences approach, such use is uncommon in the literature. Other areas, like the intelligence literature have looked at individual differences in visual search. For example, Ackerman (1988) has shown that fluid intelligence measures are related to an individual's performance on variably-mapped trials (e.g., Schneider & Shiffrin, 1977) where the target changes from trial to trial (r = .64) but are not related to consistently mapped trials where the target remains constant throughout the task.

This work illuminates the fact that visual search performance varies across individuals, with potentially interesting relations with other variables; the current study aims to help remedy the lack of individual differences studies in the visual search literature.

Control and Scope – Aspects of Working Memory

The investigations previously reviewed involving individual differences in WMC and attention control have all used measures of WM which tap the central executive or control aspect of WM. Other measures, described below, purport instead to measure the scope of attentional focus in WM. This section will describe research regarding these scope measures as several of them are used here. It may be that measures primarily tapping the attention scope and control aspects of WM have a different relationship with top-down factors involved in the proposed visual search tasks.

In the view put forth by Cowan (1999, 2001, Cowan et al., 2005) the WM system consists of an active portion of long-term memory, a focus of attention and a central executive controller. According to this view, the focus or scope of attention contains that which is in conscious awareness and the executive component of WM controls this focus. The control component is typically measured by complex dual-tasks (i.e., processing and storage WMC tasks) like operation span (OSPAN), shown to be related to performance of a variety of low-level attention tasks (e.g., Kane et al., 2001). Scope of attention tasks aim to measure *how much* information can be held in an active state; they attempt to exceed the structural storage limitations by overloading the system with information. An example of a scope task is running memory span, which presents a list of words of unpredictable length and requires recall of as many words as possible from the end of the list. Recent work reviewing a wide variety of data indicates the scope of attention is limited to between 3 and 5 chunks of information (Cowan, 2001). Further, Cowan has described the focus of attention as able to be zoomed out in order to apprehend several items or be zoomed in to focus on just one, making its function similar to visual attention models (e.g., Eriksen & St. James, 1986).

According to Cowan's view, scope measures evaluate the structural limitations of the focus of attention. The ability to change the scope of attention – in the sense of focusing tightly on a single goal, or widening it to apprehend multiple objects, may be a function of the control aspect of WM (Cowan et al., 2005). Measures of these two aspects differ in that scope tasks present a lot of information in a small amount of time in an attempt to exceed the scope's limit, while complex span tasks require switching back and forth between processing and storage components. Theorists have also proposed that WMC measures reflect at least in part, cue-based long-term memory retrieval in addition to, or instead of maintenance in active memory (Unsworth & Engle, 2007). An investigation using latent variable analysis and SEM has examined the control and scope aspects of WM. Latent variable analysis takes variability in performance common to several tasks and statistically extracts a more pure measure of the construct of interest so that its relation with other variables can be tested. Cowan, Elliott, Saults, Morey, et al. (2005) derived latent variables based on the control and scope aspects of WM by using several each of the dual-task control and single-task scope tasks, respectively. They found the control and scope constructs were strongly related and that a structural equation model predicting a variety of aptitude tasks with a single latent WM factor fit better than a model with separate scope and control factors. This is not to say, however, that the control and scope measures were the same in all aspects. For example, in accounting for variance in aptitude measures the control tasks tapped task-specific variance beyond that of the scope measures and vice versa, which indicates such measures also pick up on additional specific skills or processes. It is also possible that while control and scope measures of WM account for similar variability in broad aptitude measures, that the same may not be true with other tasks, such as visual search.

Other work using event related potentials (ERP) also suggests a relationship between scope and the ability to control attention. Vogel, McCollough & Machizawa (2005) reported that those subjects who were able to maintain more visual information in memory were also better able to filter out irrelevant visual items from processing. Vogel and colleagues cued subjects to remember items in a visual array and manipulated whether they were presented alone or interspersed with irrelevant distractors. ERP waves reflecting encoding and storage of items produced by subjects able to store a large amount of information were similar when presented with 2 memory and 2 irrelevant items compared to when they were presented with 2 memory items without any distractors. This result indicates that those who were able to store many items were also able to control what information was encoded. ERPs for low capacity subjects were similar when they were presented with 4 visual items, regardless of whether they were all to be remembered or whether only half were relevant, suggesting they were storing irrelevant items along with relevant ones – a lack of control. These results suggest how much visual information can be held in memory is not simply dependent on storage, but rather on how efficiently irrelevant visual information can be filtered out of processing.

Current Study

The current study aims to help clarify the nature of the control construct using an individual-differences approach. Though the phrase ‘top-down control’ is frequently used in the visual search literature, little work has been done to test whether such control is common across different search tasks. This study tests the commonality of top-down control as it is involved in three visual search tasks—preview search, cued search and attention capture search. While each task is purported to depend on top-down control, each varies in its particular implementation, which makes a latent variable analysis an ideal tool for investigation since the bulk of the commonality among them should be the involvement of control. For example control in preview search is in the service of limiting attention to only new items in the display. Conversely, in attention capture search it keeps search limited to the old items in the display and not the irrelevant singleton. Finally, in cued search control limits attention to particular spatial locations. In spite of the disparate characteristics across tasks they are all purported to involve attentional control.

Baseline visual search conditions are included with each of the search tasks, with typical search tasks for preview (i.e., target and distractors presented together at once) and capture search, as well as un-cued search trials in cued search. These serve as baselines, against which the control conditions of interest are measured, and also serve to assure that variance shared with between WM measures and controlled visual search tasks cannot be attributed to traditional visual search performance. Such trials do not involve WMC (Kane et al., 2006) and are performed without involving control (e.g., Wolfe et al, 2000). Additionally, salience of the visual display stimuli will also be manipulated based on research suggesting salience may interact with the visual search effects of interest here. For the preview search some trials present new items as onsets while others remove camouflaged letters to reveal them; a similar manipulation is used to present or reveal the stimuli in cued search. Capture search trials use either a salient onset singleton or less salient color singleton. These manipulations are based on evidence that targets which appear abruptly are identified more efficiently than targets revealed by removing camouflage parts of the display (e.g., Gibson, 1996; Hawkins, Shafto & Richardson, 1988). This effect has been attributed to a higher visual quality of the onset items leading to a more efficient encoding of the items compared to non-onsets (Gibson, 1996). The importance of the interrelation between top-down and bottom up factors has also been demonstrated, such that when targets are less salient that added top-down activation can help to speed search to a greater extent then when targets are more salient, as less room for improvement exists in this latter case (Soto, Humphreys & Heinke, 2006). Thus salience is also manipulated here in order to present contexts with varied opportunities for top-down effects to influence performance.

Further, based on the work of Cowan and colleagues, this study investigates the involvement of attentional scope as well as control aspects of WM in the performance of top-down controlled visual search tasks. Including such measures builds on the previous work demonstrating measures of control to be unrelated to traditional search (e.g. Kane et al., 2006) as well as explores whether the attention scope aspect of WM may be important in performing these tasks.

In summary, this exploratory work expects to unveil a relationship among the controlled visuals search tasks of interest: preview, cued and attention capture search, based on their dependence on attentional control for task performance. Individual differences in WMC are expected to relate to performance on these tasks based on prior work linking WMC with attentional control (e.g., Poole & Kane, 2009) but WMC should show no relationship to baseline visual search trials (Kane et al., 2006). The salience manipulations implemented here should result in a performance advantage for high WMC individuals for the offset trials on both preview and cued search based on prior findings that these manipulations result in greater attentional demands (e.g., Braithwaite et al., 2006). The converse should be true regarding capture search, such that a static color singleton should be an easier distraction to ignore than the abrupt onset of a new visual stimulus (Folk et el., 1992). Finally, in regards to the relationship between control and scope measures of WM, prior work suggests latent analysis here will likely indicate either a close relationship between the measures or a preference for a single WM factor to account for the data (Cowan et al., 2005).

CHAPTER II

METHOD

Subjects

Subjects were 199 undergraduate students from the University of North Carolina at Greensboro who participated in return for partial fulfillment of an introductory psychology course requirement. Subjects were native English speakers between 18 and 35 years old, with normal or corrected-to-normal vision.

Apparatus

All tasks were presented via E-Prime 1.1 (Schneider, Eschman, & Zuccolotto, 2002) on Dell desktop computers equipped with Pentium D or faster processors, and color CRT monitors. Subjects responded by key press on the computer mouse or keyboard for all the tasks.

General Procedure

Subjects were run in groups of up to 6, with the experiment consisting of two sessions. The first session presented subjects with three each of WMC span and scope of attention (WMK[1]) tasks presented in an alternating order; the second session consisted of the visual search tasks; each session lasted approximately 60-90 minutes. Instructions

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[1] This acronym is used to avoid confusion with the common use of WMC as working memory capacity, which here is used to refer to control aspects measured by complex span tasks like OSPAN. The use of WMK refers to Cowan's *K* (e.g., Cowan et al., 2005) a metric of attentional scope in WM.

were presented on the computer screen while accompanied by verbal instructions from the experimenter. Subjects completed the second session a week after the first session.

Working Memory Capacity Screening

Automated versions of the OSPAN, Spatial span (SSPAN) and RSPAN tasks (Unsworth, Heitz, Schrock & Engle, 2005) were used for WMC screening. The OSPAN task first presented a practice block in which subjects saw a series of letters and then recalled them in serial order. Subjects then saw a screen displaying all 12 of the potential to-be-remembered letters and responded by clicking on boxes next to the letters to indicate the order in which they were presented. Feedback was given regarding the number of letters correctly remembered on each trial. Subjects practiced verifying simple math equations (e.g. *IS (6 x 2) – 5 = ?*; [next screen: *7*; click *true* button]), receiving accuracy feedback on each trial. The program computed the mean time to complete the processing items for each subject. These means plus 2.5 standard deviations were then used as a response deadline for the processing components of the practice and experimental trials for each subject. These trials presented subjects with a processing item that remained onscreen until they responded; then they were presented with a to-be-remembered item for 800 ms. If the subject failed to respond to the processing component before the deadline occurred, the task continued and counted that trial as a processing error. After a series of processing–memory string pairs equal to the set size were presented, the recall screen appeared until response (for further details see Unsworth et al., 2005). Subjects completed three trials each of set sizes 3 through 7. The total number of items correctly recalled (out of a maximum 75 possible) was the span score (Conway et al., 2005; Kane, Hambrick, et al., 2004).

SSPAN had subjects first perform recall practice, in which they viewed red squares, presented one at a time for 650 ms each in one of 16 locations on a visible 4 x 4 grid and then indicated on an empty grid the locations of the presented squares with the mouse. Subjects then practiced the processing component, verifying whether black and white patterns within 8 × 8 grids were symmetrical along their vertical axis; accuracy feedback was given in both of these blocks. Practice and experimental trials gave subjects their mean time to judge the pictures plus 2.5 standard deviations as a response deadline. When the appropriate set size was reached, the recall screen appeared until response. Subjects completed four trials each of set sizes 2 through 5 for a maximum absolute span score of 48.

The RSPAN task was very similar to the OSPAN and SSPAN tasks described above, except subjects judged the meaningfulness of unrelated sentences while remembering individual letters, presented for 800 ms, following each sentence (e.g. *Andy was stopped by the policeman because he crossed the yellow heaven ? X*; Kane, Hambrick, et al., 2004). RSPAN presented three trials each of set sizes 3 through 7 for a maximum absolute score of 75.

All WMC span scores were converted to Z-scores based on means and standard deviations from the pool of subjects.

Scope of Attention Tasks

Visual Array Comparison. The first WMK task was a visual array comparison task based on the work of Luck & Vogel (1997) and Cowan et al. (2005). Subjects briefly saw a visual array composed of colored squares and, after a short blank delay, saw another array and decided, via key press, whether the square at the encircled location changed color from the first array. This cued square (and no others) changed to a different color on half of the trials and subjects received accuracy feedback. Trials began with a screen containing a cross at fixation for 1,000 ms followed by the first array of colored squares for 300 ms. Then a blank gray screen was presented for 900 ms. Then a second display was presented with the test square surrounded by a black box outline, until a response was made. Square color was randomly selected on each trial from seven easily discriminable colors (black, white, red, green, yellow, blue and violet; chosen with replacement). After completing a practice block of 6 trials, subjects completed the experimental block consisting of 72 trials total, with 12 trials at each set size of 3, 4, 5, 6, 8, and 10 squares (Cowan et al., 2005), presented in random order. Cowan's *k*, or estimate of capacity, was calculated for each subject using the formula $k = N*(H+CR-1)/CR$, where N is the number of items presented, H is the hit rate and CR is the correct rejection rate (see Appendix A of Cowan et al., 2005).

Running Span. Running span presented subjects with a sequence of 12-20 single digits appearing at fixation on a gray background (Broadway & Engle, 2010). At the end of each trial, 3, 4, 5, 6, or 7 blank spaces cued how many items to report from memory, in forward order, from the last point in the sequence; subjects selected the digits in order from a list using the mouse, guessing if necessary. Trials presented a cross signaling the start of the trial for 500 ms, followed by each to-be-remembered digit for 300 ms. A 200 ms blank screen appeared between the digits and the end of the sequence and was followed by a 300 ms blank screen before the recall screen was presented until a response; another 1,000 ms blank screen preceded the start of the next trial. Presented items were randomized with the constraint that no digit appeared twice in a row. After a brief practice block, subjects completed 25 trials of the running span task, with five repetitions at each of the five set sizes, randomized with overall presented list length. Ten more "catch" trials (2 repetitions x 5 set sizes) presented only the number of digits to be tested, to encourage subjects to remember all items and not just the last few. The absolute number of digits recalled in the correct sequence position (of 175 possible) determined the running span score.

Brief Visual Report. The third scope of attention task was a version of Sperling's (1960) visual report task. Subjects briefly saw a display containing 4, 5, 6, 8 or 10 consonants, appearing randomly in locations in an invisible 4 x 4 grid against a gray background. Trials began with a warning screen containing a cross at fixation for 600 ms followed by the letter array for 50 or 100 ms, determined at random. Then a gray background was presented for 1,000 ms until a recall screen in which subjects typed in as many letters as they could remember from the display, in any order (with a maximum equal to the array size). Consonants were chosen at random, without replacement, for each display. After a practice block of 3 trials, subjects completed an experimental block of 50 (10 at each set size) trials total, with half presenting the display for 50 ms and half for 100 ms.

Visual Search Tasks

Letter stimuli used in all the search tasks were created in Microsoft Paint, using a black Zurich Ex Bt font letter ‘E’ (measuring 11x 15 pixels, or 5 x 7 mm) with the center horizontal bar extended to equal the length of those at the top and bottom (as in Poole & Kane, 2009). All other search stimuli were created from this template: the letter F was made by removing the lowest bar of the E, a horizontally tilted T was made by also removing the top bar. Backward versions of these letter stimuli were made by flipping each stimulus horizontally. In all search tasks subjects responded via key press to whether the target on the trial was an F or backward F. The remaining Es, tilted Ts, and their backward versions served as distractors for all the search tasks.

Preview Search. The search displays in the onset preview task presented stimuli in locations corresponding to an invisible 8 × 8 irregular grid (e.g., Humphreys, Watson & Jolicoeur, 2002). All trials presented stimuli against a white background. In the *full search*, baseline condition, subjects focused on a centrally presented fixation cross for 750 ms, followed by a blank screen for 50 ms, and then the full display of search stimuli until response. Following response, a 400 ms blank white screen preceded the next trial. In the *preview search* condition, subjects were presented with a central fixation cross at the beginning of each trial followed by a blank screen for 50ms. Each trial then presented half of the distractors (either Es and backward Es, or tilted Ts and backward Ts, counterbalanced within the block; Figure 1A) for a variable amount of time before presenting the remaining distractors and target (Figure 1B) until response. The duration for which the first set of distractors remained onscreen varied between 200, 400, 600, 1000 ms and 1200 ms. Again, on these trials a 400 ms blank white screen followed a response. The total number of distractors presented on each trial was 8, 16, or 32; preview displays presented half the distractors before the blank gap and half after. Full and preview search conditions were each performed in a separate block, with 60 full condition trials (3 distractor set sizes x 20 iterations) and 180 preview condition trials (3 distractor set sizes x 5 preview durations x 12 iterations) in the experimental conditions following short practice blocks in each. For the preview search block, subjects were instructed to limit their search to items appearing after the gap (because the target could only appear in this second set of stimuli).

A second, similar preview search task was also used. This task used the same stimuli as described above, but the stimuli were presented as offsets, limiting the amount of bottom-up information that could be used to prioritize search to new items. Each trial began with stimulus locations occupied with block-shaped “8”s (of the same dimension as the search stimuli; see Figure 2A) for 750 ms. After that time, the first half of the stimuli appeared to the subjects, created by removing pieces of this 8 shape (Figure 2B). After the preview duration (again, of 200, 400, 600, 1000 ms and 1200 ms), the other half of the stimuli appeared (Figure 2C). After distractor items were presented in the preview condition they remained onscreen until the end of the trial. In full search the entire array was presented after the 750ms offset display. Like the onset preview task, the offset version also presented 60 full search and 160 preview trials. Each block consisted of the experimental trials followed by full search baseline trials; block order was counterbalanced across participants.

Cued Search. The cued search task presented letter stimuli in 25 locations making up an invisible 5 x 5 grid. Each trial presented a central endogenous (symbolic) cue to indicate which locations could potentially contain the target on that trial (see Figure 3). Subjects were informed that the target would only appear in one of the eight locations surrounding the central location within the central 3 × 3 (of the larger 5 x 5) matrix, and never in the central location or those exterior to the interior matrix. Trials began with a 500 ms blank screen, followed by a cue indicating the potential target location(s) for 500 ms, then a blank screen for 50 ms. Then a fixation display containing dots in all 25 locations was presented onscreen for 500, 1,000, 1,500 or 2,000 ms, followed by a 50 ms blank screen; subjects were instructed to use these dots to focus attention on the target locations. The search display was then presented until response.

The pre-cue indicating potential target locations cued 2 or 4 locations with vertical, horizontal or diagonal lines and "X" shape symbols (Figure 3). Four cues indicating 2 target locations were presented for a total of 128 (4 fixation durations x 4 cue types × 8 locations) 2-location-cue trials. These cues indicated the target locations were directly above and below or to the left and right, or across either of the diagonals, in relation to the central point of the matrix (see Figure 4 for an example of a trial cued indicating a potential target location above and to the left and below and to the right of center; here the target is a backward F). Each trial also presented a target lure (an F or backward F presented in a non-target location) in some non-target location in the central 3 x 3 matrix as well as another lure presented outside the central matrix; all remaining locations were populated with distractor E's, T's, and their tilted versions. The 2 cue types indicating 4 target locations were created similarly, presenting 128 (4 fixation durations × 2 cue types × 8 locations × 2 repetitions) 4-location-cue trials total. For these trials the target never appeared outside the central 3 x 3 matrix. Subjects also performed baseline trials presenting no location cue information. These trials began with a 500 ms blank screen, followed by a dot presented in the center of the screen for 600 ms, then a blank screen for 50 ms before the search display was presented. No lure stimuli were presented on baseline trials because all stimuli locations were possible target locations. There were 64 (8 locations × 8 repetitions) baseline trials randomly presented among the experimental trials.

Subjects also performed a separate cued search block identical to the one described above except the letter stimuli were presented as offsets. After subjects were presented with the cue indicating the potential target locations, the following fixation screen contained block figure "8"s (as in the preview search above), in lieu of fixation dots (Figure 5). Further, after the appropriate fixation duration the search stimuli appeared as portions of the figure 8's being removed. The offset cued search presented 128 (4 fixation durations x 4 cue types × 8 locations) 2-location-cue, 128 (4 fixation durations × 2 cue types × 8 locations × 2 repetitions) 4-location-cue and 64 (8 locations × 8 repetitions) baseline trials.

Attention Capture Search. All details matched those in preview search, with the following exceptions: Baseline trials first presented a cross at fixation, signaling start of the trial, for 750 ms; then after a 50 ms blank screen, 8, 16, or 32 randomly distributed distractors were presented along with the target stimulus and remained onscreen until response. A 400 ms blank screen then preceded the next trial. The static *color singleton* trials and dynamic *onset singleton* trials were identical except for the appearance of the singleton stimuli. In the former condition, a red color singleton was presented as one of the distractors in the display (Figure 6), and in the latter condition, an abrupt onset item (of the same color as the rest of the stimuli) was presented (Figure 7A and Figure 7B); distractor E's T's and their tilted versions appeared as the singleton equally often across displays. The onset singletons appeared pseudo-randomly 150, 300, or 500 ms after the initial display presentation. Each different trial type was presented in a separate block. The experiment presented 60 baseline trials (3 distractor sizes x 20 repetitions) and 180 of each singleton search trial (3 display sizes x 3 time delays [onsets only] x 20 repetitions).

The order of the visual search tasks was counterbalanced across participants in a Latin-square design, with order of salience versions kept constant for each group of subjects (see Table 1).

CHAPTER III

RESULTS

Analyses

Initial data management and analyses were performed using Statistical Analysis Software (SAS) version 8 and Systat 11. The factor analytic and SEM analyses were performed using EQS 6.1 (Multivariate Software, Inc.) and AMOS 5.0 (SPSS, Inc.).

Statistical Procedure

Several fit statistics were used here in determining model fit as is common practice (see, e.g., Raykov and Marcoulides, 2000). Absolute fit statistics include Chi-Square values, Chi-square divided by degrees of freedom (df), and the Root Mean Square Error of Approximation (RMSEA); relative fit values reported are the Standardized Root Mean Residual (SRMR), Comparative Fit Index (CFI) and the Bentler-Bonett Normed Fit Index (NFI). Ideal values for these tests are as follows: Chi-Square – non-significant, Chi-square/degrees of freedom–less than 2, SRMR lower than ~.08, RMSEA lower than ~.05. For the relative fit tests, CFI and NFI, values greater than .90 indicate good fit. Specific instances where the models reported deviate from these guidelines are addressed as they appear.

Results

The results section first presents ANOVA-based analyses which focus on investigating the visual search tasks in detail regarding salience, set size, and fixation duration manipulations. Further, this section also presents analyses aimed at investigating the role of WMC in visual search and how it varies based on these manipulations. The second part of the results section focuses on confirmatory factor analysis and structural equation models. This part looks at the relationship between the control and attentional scope aspects of WM. Then, the shared variance among controlled visual search tasks is examined and finally, the associations between common control processes in visual search tasks and WM is assessed.

Participants

One hundred ninety-nine participants completed the WM sessions of the study. Of these remaining participants, computer errors lead to lost data; further participants were dropped for error rates exceeding 45%[2] on one or more parts of the search tasks. One hundred forty six participants completed the preview search and 12 more were dropped due to errors, leaving one hundred thirty-six participants in the analysis. One hundred eighty four participants had both session 1 and cued search data; 15 were dropped due to errors, leaving one hundred sixty-nine participants in the cued search analyses. On hundred forty-two participants had data for the capture search task; 16 participants were dropped due to errors, leaving one hundred twenty-six participants.

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[2] This error rate was chosen due to a natural break in the data.

WMC Screening

The OSPAN, RSPAN and SSPAN scores were determined by the mean proportion of items recalled correctly across all sets for each span task. The mean performance on these tasks were 0.667 (SD = 0.211), 0.566 (SD = 0.231) and 0.637 (SD = 0.111), respectively. These proportion span scores were converted (separately for each subject and measure) into Z-scores. The Z-scores for each WMC task were then averaged for each participant to create a composite WMC score, which had a normal distribution (skewness = -0.54; kurtosis = -0.23). Membership in WMC group for analyses of variance was based on the highest (High) and lowest (Low) tercile performers from the composite Z-WMC scores.

Visual Search

The alpha level was set at .05 for all analyses. Results of analyses for experimental effects will be reported separately for RTs and errors. All RTs reported are means of individual participants' medians.

Preview Search

Reaction Time. Figure 8A presents mean RTs for preview search by WMC group for onset and baseline trials by distractor set size. Figure 8B presents offset and baseline trial data. WMC was generally unrelated to performance on the baseline and onset preview trials but RTs differed by WMC group for offset preview trials.

A 2 (WMC: High vs. Low) × 3 (Trial Type: Onset vs. Offset vs. Baseline [RTS were nearly identical from baseline trials from both onset and offset blocks and are combined here]) × 3 (Distractor set size: 8 vs. 16 vs. 32) mixed ANOVA was performed with WMC as a between subjects factor. RTs differed by trial type, $F(2,176) = 38.07$, MSE = 53504.70, $p <.001$, $\eta_p^2 = .302$. There was also a significant effect of distractor set size, $F(2,176) = 857.24$, MSE = 73070.47, $p <.001$, $\eta_p^2 = .907$, with RTs increasing with greater number of distractors but this was qualified by an interaction of distractor set size and trial type, $F(4,352) = 44.15$, MSE = 23970.95, $p <.001$, $\eta_p^2 = .334$. RTs appear to be shortest at small distractor set sizes for onset trials followed by offset trials.

High WMC subjects responded faster overall than did Low WMC subjects, $F(1,88) = 6.46$, MSE = 343105.57, $p =.013$, $\eta_p^2 = .068$ and WMC interacted significantly with trial type, $F(2,176) = 8.82$, MSE = 53504.70, $p <.001$, $\eta_p^2 = .091$, but not distractor set size, $F(2,176) = 1.17$, MSE = 73070.47, $p =.331$, $\eta_p^2 = .013$. This was qualified by a three-way interaction among WMC, trial type, and distractor set size, $F(4,352) = 3.85$, MSE = 23970.95, $p =.004$, $\eta_p^2 = .042$. The largest WMC group differences appear in offset trials presenting many distractors.

Separate analyses for onset and offset trials were performed to clarify their effects; remember that while onset trials in the preview search may involve WMC, that offset trials were expected to do so, based on increased attentional demands on offset trials. In order to investigate the effects of onset previews, a 2 (WMC: High vs. Low) × 2 (Trial Type: Onset vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) mixed ANOVA was performed with WMC as a between subjects factor. RTs for onset trials were faster than baseline trials, reflecting a significant preview effect, $F(1,88) = 81.46$, MSE = 44714.10, $\underline{p} <.001$, $\eta_p^2 = .481$. RTs also increased with distractor set size, $F(2,176) =$

800.25, MSE = 56481.37, p <.001, η_p^2 = .901, and there was a significant interaction of distractor set size and trial type, F(2,176) = 65.83, MSE = 24691.23, p <.001, η_p^2 = .428; this appears to be driven by longer RTs for distractor set size 32 on baseline compared to onset trials.

High and Low WMC subjects did not differ in overall RTs on onset trials, F(1,88) = 1.79, MSE = 241997.70, p = 0.185, η_p^2= .020, nor did WMC interact significantly with any of the other variables of interest (all Fs < 1).

The following analyses examined RTs on offset trials. Based on increased attentional demands compared to onset trials, we expected WMC to be related to RTs. A 2 (WMC: High vs. Low) × 2 (Trial Type: Offset vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) mixed ANOVA was performed with WMC as a between subjects factor. RTs increased with greater set size, F(2,176) = 705.15, MSE = 68139.65, p <.001, η_p^2 = .889, but they did not differ by trial type, F(1,88) =2.30, MSE = 64674.19, p =0.133, η_p^2 = .025. This was qualified by the interaction of trial type and distractor size, F(2,176) = 52.91, MSE = 27257.00, p <.001, η_p^2 = .376. The greatest preview benefit appears to occur at distractor size 32.

High WMC subjects had shorter RTs than did Low subjects overall, F(1,88) = 8.00, MSE = 263043.62, p = 0.006, η_p^2 = .083, but WMC did interact with trial type, F(1,88) = 12.08, MSE = 64674.19, p = 0.001, η_p^2 = .121, indicating this was true for offset but not baseline trials (see Figure 8B). This was qualified by a three-way interaction including trial type, distractor set size and WMC, F(2,176) = 6.46, MSE = 27257.00, p =0.006, η_p^2 = .068. It appears that High but not Low WMC subjects were able to use the offset previews to speed their responses in comparison to performance on baseline trials, due to the greater attentional demands on those trials. To test this, analyses were conducted separately for each WMC group. High WMC subjects were tested in a 2 (Trial Type: Offset vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) repeated measures ANOVA. There was a main effect of trial type, indicating a preview benefit overall, $F(1,44) = 23.01$, MSE = 34997.02, $p < .001$, $\eta_p^2 = .343$. The main effect of distractor set size was significant, $F(2,88) = 447.43$, MSE = 50042.89, $p < .001$, $\eta_p^2 = .910$ and it was qualified by an interaction with trial type, $F(2,88) = 99.80$, MSE = 12592.96, $p < .001$, $\eta_p^2 = .694$; the greatest preview benefit of 375 ms occurred at the largest distractor set size, 32. Similarly, Low WMC subjects were tested in a 2 (Trial Type: Offset vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) repeated measures ANOVA. The main effect of trial type was not significant, indicating no preview benefit for Low WMC subjects overall, $F(1,44) = 1.32$, MSE = 94351.35, $p = .257$, $\eta_p^2 = .029$. The main effect of distractor set size was significant, $F(2,88) = 298.50$, MSE = 86236.43, $p < .001$, $\eta_p^2 = .872$ and it was qualified by an interaction with trial type, $F(2,88) = 8.63$, MSE = 41921.03, $p < .001$, $\eta_p^2 = .164$. For Low WMC subjects, RTs increased with distractor set size but, in contrast to the finding with High WMC subjects, RTs were greater on offset than baseline trials. Overall, High WMC showed a preview benefit of 327 ms while Low WMC subjects were actually 129 ms *slower* on preview trials than baseline trials.

The following analyses investigated the effects of the duration manipulation on search. Remember the prediction that longer preview durations might allow more time for attention to limit searches to new items in the display. Figure 9A and Figure 9B present onset and offset trial RTs, respectively, for High and Low WMC groups by distractor set size and duration. Note that baseline trials are not included in this analysis because they did not vary in duration.

A 2 (WMC: High vs. Low) x 2 (Trial Type: Onset vs. Offset) x 3 (Distractor set size: 8 vs. 16 vs. 32) x 5 (Duration: 200ms vs 400ms vs 600ms vs 1,000ms vs 1,200ms) mixed ANOVA was performed with WMC as a between subjects factor. Onset trials had shorter RTs overall than did Offset trials, *F*(1,88) = 38.15, MSE = 272491.06, $p < .001$, $\eta_p^2 = .302$, and RTs decreased with increasing fixation duration, *F*(4,352) = 23.65, MSE = 102609.40, $p < .001$, $\eta_p^2 = .212$, as well as increased with distractor set size, *F*(2,176) = 808.27, MSE = 221388.93, $p < .001$, $\eta_p^2 = .902$. There were significant two-way interactions of trial type and distractor size, *F*(2,176) = 4.90, MSE = 97118.64, $p = 0.009$, $\eta_p^2 = .053$, and distractor set size and duration, *F*(8,704) = 7.93, MSE = 90860.18, $p < .001$, $\eta_p^2 = .083$, but not trial type and duration, *F*(4,352) = 1.58, MSE = 75291.54, $p = 0.178$, $\eta_p^2 = .018$. These were qualified by the three-way interaction of trial type with distractor set size and duration, *F*(8,704) = 2.50, MSE = 75513.09, $p = 0.011$, $\eta_p^2 = .028$. The difference between onset and offset trials seems to be greatest at the largest distractor set size and this difference appears to be more pronounced at longer durations.

High WMC subjects had shorter RTs overall than did Low WMC subjects, *F*(1,88) = 8.72, MSE = 1268194.66, $p = 0.004$, $\eta_p^2 = .090$, and WMC interacted with trial type, *F*(1,88) = 2.46, MSE = 102609.40, $p = 0.048$, $\eta_p^2 = .110$, distractor set size, *F*(2,176) = 3.00, MSE = 221388.93, $p = 0.054$, $\eta_p^2 = .033$, and duration, *F*(4,352) = 2.46, MSE = 102609.40, $p = 0.045$, $\eta_p^2 = .027$. These effects seem to be driven by the large WMC differences appearing on trials presenting 32 distractors with increasing WMC differences with larger durations on offset trials. The three-way interactions of WMC with trial type and duration was not significant, $F(4,352) = 1.86$, MSE = 75291.54, $p = 0.117$, $\eta_p^2 = .021$, nor was the interaction of WMC with distractor set size and duration, $F(8,704) = 1.24$, MSE = 90860.18, $p = 0.271$, $\eta_p^2 = .014$. WMC did interact with trial type and distractor set size, $F(2,176) = 3.76$, MSE = 97118.64, $p = 0.025$, $\eta_p^2 = .041$, reflecting large WMC differences at the largest distractor set size for offset but not onset trials. The interaction of WMC with trial type, distractor set size, and duration was not significant, $F(8,704) = 1.88$, MSE = 75513.09, $p = 0.06$, $\eta_p^2 = .021$. Finally, note that RTs were reliably measured; Cronbach's alpha calculated on subjects' mean RTs across the 3 distractor set sizes (and so, 3 variables) was .88 for onset trials, .92 for offset trials and .84 for the combined baseline trials.

RT analyses indicated that performance on onset and offset preview trials were faster than their baseline comparison trials. Significant WMC related effects appeared on offset but not onset trials, in agreement with the proposal that using offsets would pose greater attentional demands than onsets in order to limit search to new items.

Error Rates. Table 2 presents mean proportion error data by WMC group for onset, offset, and baseline trials by distractor set size. WMC was generally unrelated to errors.

A 2 (WMC: High vs. Low) × 3 (Trial Type: Onset vs. Offset vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) mixed ANOVA was performed with WMC as a between subjects factor. Error rates did not differ by trial type ($F < 1$), but the largest errors appeared on trials for distractor set size 32, *F* (2,176) =16.36, MSE = 0.003, *p* <.001, η_p^2 = .157. Further, the interaction of distractor set size with trial type was significant, *F* (4,352) = 5.53, MSE = 0.001, *p* <.001, η_p^2 = .059, which appears to be driven by lower mean errors for distractor set size 32 for onset trials.

Errors did not differ by WMC (*F* < 1), nor was the interaction of WMC with trial type, *F* (2,176) =1.43, MSE = 0.002, *p* =.241, η_p^2 = .016, nor with distractor set size, significant, *F* (2,176) =2.14, MSE = 0.003, *p* = 0.120, η_p^2 = .023. The three-way interaction of WMC with trial type and distractor size was also not significant (*F* < 1).

Error analyses do not indicate any speed accuracy trade-offs. A lack of WMC related effects in errors does not complicate interpretation of the significant WMC effects in RTs.

Cued Search

Reaction Time. Figure 10 presents mean RTs for cued search by WMC group and locations cue for onset and offset trials. Similar RT values suggest 8-cue trials were performed like 4-cue trials rather than as a baseline measure. High WMC subjects had shorter RTs than did Low WMC subjects for all cuing conditions.

A 2 (WMC: High vs. Low) x 2 (Trial Type: Onset vs. Offset) x 3 (Locations cued: 2 vs. 4 vs. 8) mixed ANOVA was performed with WMC as a between subjects factor. Offset trials had shorter RTs than onset trials, *F* (1,110) = 11.01, MSE = 134146.29, *p* =.001, η_p^2 = .091. There was a main effect of locations cued, *F* (2,220) = 226.99, MSE =50214.47, *p* <.001, η_p^2 = .674, with an advantage for trials cueing the lowest number of locations, but this was qualified by a two-way interaction of locations cued with trial type, *F* (2,220) = 3.53, MSE = 15014.92, *p* =.031, η_p^2 = .031. An inspection of Figure 10 suggests this may be due to having shorter RTs for 2 and 4 location cued trials for offset but not onset trials. High WMC subjects were faster overall than Low WMC subjects, *F* (1,110) = 15.92, MSE =347738.25, *p* <.001, η_p^2 = .126, but WMC did not interact significantly with either trial type (*F* <1) or locations cued, *F* (2,220) =1.29, MSE = 50214.47, *p* =.279, η_p^2 = .012. The three-way interaction of WMC with trial type and locations cued was not significant, *F* (2,220) = 1.89, MSE = 15014.92, *p* =.154, η_p^2 = .017.

Though the main effect of locations cued was significant overall, an inspection of the means indicate the "baseline" 8-location trials were performed at RTs comparable to the 4-location cue trials (for 4 and 8 cue trials, respectively: onset RTs were 1420 ms and 1372 ms; offset RTs were 1291 ms and 1290 ms). In order to test whether the baseline 8-location trials (presenting no cue information, and no lures) were performed differently from trials cueing 4 locations, a 2 (WMC: High vs. Low) x 2 (Locations cued: 4 vs. 8) repeated measures ANOVA was performed with WMC as a between subjects factor; here, separately for onset and offset trials. For onset trials, High WMC subjects had shorter RTs than did Low WMC subjects, *F* (1,110) = 7.45, MSE = 222803.21, *p* =.007, η_p^2 = .064, but RTs did not differ between trials that cued 4 locations or baseline trials which presented no cue information, *F* (1,110) = 2.56, MSE = 51126.23, *p* =.113, η_p^2 = .023. WMC did not interact with locations cued (*F* < 1). For offset trials, a 2 (WMC: High vs. Low) x 2 (locations cued: 4 vs. 8) mixed ANOVA showed again, that High WMC subjects outperformed Low WMC subjects, *F* (1,110) = 7.06, MSE = 204891.92, *p*

<.001, η_p^2 = .106, and trials cueing 4 locations did not differ from baseline trials (*F* <1). The interaction of locations and WMC did not reach significance, *F* (1,110) = 2.59, MSE = 37985.04, *p* =.098, η_p^2 = .026. Given that the no cue, 8-location trials were not performed differently from cued trials, and therefore would not be suitable to use as a baseline measure, the remaining analyses will only include trials which cued 2 or 4 locations.

Figure 11A presents onset trial RTs by WMC, locations cued, and fixation duration. To investigate fixation duration effects on cued search a 2 (WMC: High vs. Low) x 2 (Locations cued: 2 vs 4) × 4 (Fixation duration: 500ms vs. 1,000ms vs. 1,500ms vs. 2,000ms) repeated measures ANOVA was performed on the onset RT data with WMC as a between subjects factor. RTs were longer at 4 than 2 location cued trials, *F* (1,110) = 508.19, MSE = 82142.48, *p* <.001, η_p^2 = .822, and there was a significant effect of duration, *F* (3,330) = 3.45, MSE = 13692.12, *p* =.017, η_p^2 = .030, but locations cued did not interact significantly with duration (*F* < 1). An inspection of the graph suggests this fixation duration effect is driven by slightly shorter RTs at the longer durations. High WMC subjects were faster than Low WMC subjects, *F* (1,110) = 7.56, MSE = 614737.65, *p* =.007, η_p^2 = .064, but WMC did not interact significantly with locations cued, *F* (1,110) = 2.53, MSE = 82142.48, *p* =.114, η_p^2 = .023, or fixation duration, *F* (3,330) = 2.30, MSE = 13692.11, *p* =.077, η_p^2 = .020. The three-way interaction of WMC with locations cued and duration was also not significant, *F*(3,330) = 2.34, MSE = 13432.94, *p* =.073, η_p^2 = .021.

Offset RTs are presented in Figure 11B by WMC group, locations cued, and fixation duration. Offset RT data were subject to a 2 (WMC: High vs. Low) x 2 (Locations cued: 2 vs 4) × 4 (Fixation duration: 500ms vs. 1,000ms vs. 1,500ms vs. 2000ms) repeated measures ANOVA with WMC as a between subjects factor. RTs were longer at 4 than 2 location cued trials, *F* (1,110) = 422.63, MSE = 74262.73, *p* <.001, η_p^2 = .793, and there was a significant effect of duration, *F* (3,330) = 11.17, MSE = 17915.37, *p* <.001, η_p^2 = .092, but the interaction between locations cued and fixation duration was not significant (*F* < 1).

RTs were shorter for High WMC than Low WMC subjects, *F* (1,110) = 18.00, MSE = 662850.23, *p* <.001, η_p^2 = .140 and unlike the findings with onset trials, for offset trials, WMC interacted significantly with both locations, *F* (1,110) = 5.33, MSE = 74262.73, *p* =.046, η_p^2 = .046, and fixation duration, *F* (3,330) = 7.77, MSE = 17915.37, *p* <.001, η_p^2 = .066, which were qualified by a three-way interaction, *F* (3,330) = 3.42, MSE = 18724.27, *p* =.018, η_p^2 = .030. High WMC subjects had shorter RTs than Low WMC subjects and this span difference appears to be greatest on trials that cue 4 locations. The WMC span difference is greatest for short fixation durations and smallest at largest durations.

RTs for cued trials presented as offsets were performed faster overall than onsets. High WMC subjects were faster on cued search trials overall, but only on offset trials did the advantage for high over low WMC subjects diminish with increasing fixation duration.

Error Rates. Table 3 presents mean proportion errors for cued search by WMC group, trial type, and locations cued. Error rate analyses demonstrated the 8-cue trials to have lower error rates than 2 or 4 cue trials for both onset and offset trials (remember that 8-cue trials presented no lures). Further, errors were greatest with trials cueing 4 locations and with shorter fixation durations.

The error rate data were analyzed with a 2 (WMC: High vs. Low) x 2 (Trial Type: Onset vs. Offset) x 3 (Locations cued: 2 vs. 4 vs. 8) mixed ANOVA with WMC as a between subjects factor. Errors were slightly higher for the offset compared to onset trials, though the difference was not significant, F (1,110) = 0.004, MSE = 0.004, p =.061, η_p^2 = .031. Errors appeared to be greatest on trials cueing 4 locations, F (2,220) = 93.21, MSE = 0.003, p <.001, η_p^2 = .459, but the interaction of trial type with locations cued was not significant ($F < 1$).

Error rates were higher for Low than High WMC subjects overall, F (1,110) = 20.46, MSE = 0.026, p <.001, η_p^2 = .157. WMC interacted with locations cued, F (2,220) = 9.02, MSE = 0.003, p <.001, η_p^2 = .075, driven by a greater difference between span groups on trials cueing 4 compared to 2 locations. None of the other interactions involving WMC approached significance (all *F*s < 1).

Table 4 presents mean proportion error data for onset trials by WMC, locations cued and fixation duration. Fixation duration effects were investigated for the onset error data with a 2 (WMC: High vs. Low) x 2 (Locations cued: 2 vs 4) × 4 (Fixation duration: 500ms vs. 1,000ms vs. 1,500ms vs. 2000ms) repeated measures ANOVA with WMC as a between subjects factor. There was a main effect of locations cued, F (1,110) = 39.53, MSE = 0.004, p <.001, η_p^2 = .264, with fewer errors for trials cueing 2 locations, as well as a significant effect of fixation duration, F (3,330) = 7.31, MSE = 0.003, p <.001, η_p^2 = .063, driven by lower error rates for 1,500ms and 2,000ms fixation duration trials, but their interaction did not approach significance (F <1).

High WMC subjects had lower error rates than did Low WMC subjects, F (1,110) = 19.28, MSE = 0.046, p <.001, η_p^2 = .149 and WMC interacted with locations cued, F (1,110) = 8.67, MSE = 0.004, p =.004, η_p^2 = .074, reflecting a greater WMC span difference on 4-location cued trials. WMC did not interact with fixation duration and the three-way interaction of WMC with locations cued and duration was also not significant (*F*s < 1).

Table 4 also presents error rates for offset trials by WMC group, locations cued and fixation duration. Offset error data were subjected to a 2 (WMC: High vs. Low) x 2 (Locations cued: 2 vs 4) × 4 (Fixation duration: 500ms vs. 1,000ms vs. 1,500ms vs. 2000ms) repeated measures ANOVA with WMC as a between subjects factor. Error rates were greater for 4-location cued trials, F (1,110) = 28.91, MSE = 0.004, p <.001, η_p^2 = .208, and also seemed to be greatest at the shortest fixation durations, F (3,330) = 3.00, MSE = 0.003, p =.031, η_p^2 = .026. The two-way interaction of locations cued and fixation duration was not significant, F (3,330) = 1.43, MSE = 0.003, p =.234, η_p^2 = .013.

Again, Low WMC subjects had greater errors than High WMC subjects, F (1,110) = 18.51, MSE = 0.061, p <.001, η_p^2 = .144. WMC only interacted with locations cued, F (1,110) = 5.31, MSE = 0.004, p =.023, η_p^2 = .047, driven by a greater WMC span effect at 4-location cued trials. All other interactions with WMC did not reach conventional significance ($F < 1$). Again, note that RTs were reliably measured; Cronbach's alpha calculated on subjects' mean RTs across the 3 locations cued (2, 4, and 8-baseline trials) were .89 for onset trials and .90 for offset trials.

Error analyses indicated fewer errors for trials cueing 8 as opposed to 2 or 4 locations. No WMC effects in the error analysis compromise interpretation of the WMC effects reported above in RTs.

Capture Search

Reaction Time. Figure 12A presents onset capture and baseline trial RTs by distractor set size and WMC group. Figure 12B presents color and baseline RTs by distractor set size and WMC group. The results indicated a surprising *reverse* capture effect, with shorter RTs to capture than baseline trials. WMC was generally unrelated to RTs in this task.

In order to determine whether onset and color capture search trials differed, a 2 (WMC: High vs. Low) × 3 (Trial Type: Onset vs. Color vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) repeated measures ANOVA was performed on the RT data with WMC as a between subjects factor. RTs did differ by trial type, F (1,88) = 105.19, MSE = 71160.89, p <.001, η_p^2 = .562, and distractor set size, F (2,164) = 653.53, MSE =108312.07, p <.001, η_p^2 = .889, and these were qualified by an interaction between trial type and distractor set size F (2,164) = 12.63, MSE = 41118.87, p <.001, η_p^2 = .133. An inspection of the data indicates that, whereas onset trials were faster than their baseline counterparts, they were also faster than the color capture trials. Further, RTs on color capture trials seemed to differ little from the baseline RTs except at distractor set size 32, where color capture RTs were shorter. The following analyses are performed separately for onset and color trials to further clarify these relationships.

High and Low WMC subjects had similar RTs overall, and WMC did not interact with the other variables of interest (all *F* s<1).

Onset trials were analyzed with a 2 (WMC: High vs. Low) × 2 (Trial Type: Onset vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) repeated measures ANOVA with WMC as a between subjects factor. Onset capture trials had shorter RTs than baseline trials, F (1,82) = 170.12, MSE = 73455.20, p <.001, η_p^2 = .675. RTs were longer at greater distractor set sizes, F (2,164) = 540.62, MSE =95766.80, p <.001, η_p^2 = .868, and these were qualified by an interaction between trial type and distractor set size, F (2,164) = 14.15, MSE = 50789.00, p <.001, η_p^2 = .147. The difference between onset and baseline trials appears to get larger with increasing distractor set size.

RTs did not differ based on WMC, nor did WMC interact significantly with any of the other variables of interest (all *F*s < 1).

Color trials were similarly investigated with a 2 (WMC: High vs. Low) × 2 (Trial type: Color vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) repeated measures ANOVA with WMC as a between subjects factor. The main effect of trial type did not reach significance, F (1,82) = 2.38, MSE = 68881.32, p =0.127, η_p^2 = .028, but RTs did increase with distractor set size, F (2,164) = 552.44, MSE = 90752.31, p <.001, η_p^2 = .871 and these were qualified by an interaction between trial type and distractor set size, F (2,164) = 15.53, MSE = 49429.06, p <.001, η_p^2 = .159. This appears to be driven by comparable RTs for the two trial types across all distractor set sizes except the largest, presenting 32 distractors. On trials presenting 32 distractors, color capture trials were performed approximately 190 ms *faster* than the baseline trials, keeping in line with prior findings of a reverse capture effect. A 2 (WMC: High vs. Low) × 2 (Trial type: Color vs. Baseline) repeated measures ANOVA with WMC as a between subjects factor on the 32 distractor set size trials confirmed this, *F* (1,82) = 11.56, MSE =134048.81, *p* =.001, η_p^2 = .124. RTs again did not differ based on WMC group (all *F* s<1).

Figure 13 presents RTs for the onset capture trials by distractor set size and onset duration. To investigate potential effects of duration manipulation on onset trials the onset trials were analyzed with a 2 (WMC: High vs. Low) x 3 (Distractor set size: 8 vs. 16 vs. 32) x 3 (Duration: 150ms vs 300ms vs 500ms) repeated measures ANOVA with WMC as a between subjects factor. RTs differed by Distractor set size, *F* (2,164) = 479.19, MSE = 136294.32, *p* <.001, η_p^2 = .854, and onset durations, *F* (2,164) = 239.96, MSE =46682.69, *p* <.001, η_p^2 = .745, but these effects were qualified by a significant distractor set size by duration interaction, *F* (4,328) = 31.16, MSE = 56791.43, *p* <.001, η_p^2 = .275. An inspection of the figure indicates a benefit for longer durations for trials presenting 8 or 16 distractors but a relative lack of a benefit at greater durations for trials with 32 distractors.

RTs again did not differ based on WMC group (all *F* s < 1).

The RT data indicated a surprising reverse capture effect such that the experimental trials were performed faster than the baseline trials. RTs for these trials were unrelated to WMC.

Error Rates. Table 5 presents mean error rates for onset, color, and baseline trials, combined for High and Low WMC subjects, and distractor set size. Errors appeared to be highest on color capture trials. Error rates were similar across onset and baseline trials. WMC was unrelated to error rates overall.

Error rate data were investigated with a 2 (WMC: High vs. Low) × 3 (Trial type: Onset vs. Color vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) mixed ANOVA with WMC as a between subjects factor. However, there were main effects of both trial type, *F* (1,88) = 69.89, MSE = 0.004, *p* <.001, η_p^2 = .460, and distractor set size, *F* (2,164) = 26.11, MSE = 0.003, *p* <.001, η_p^2 = .242, and these were qualified by an interaction of these two factors, *F* (2,164) = 35.78, MSE = 0.001, *p* <.001, η_p^2 = .304. Baseline trials had the highest error rates at trials presenting 32 distractors. Baseline error rates were similar overall to those for onset trials. Error rates for color trials were greatest at set size 16 and 32, and were greater than both the onset and baseline trials.

Similar to findings involving RTs, no main effect or interaction involving WMC was significant (all *F* s < 1).

Error rates for onset trials were analyzed with a 2 (WMC: High vs. Low) × 2 (Trial type: Onset vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) repeated measures ANOVA with WMC as a between subjects factor. And though the effect of trial type was not significant, (*F* < 1), there was a significant effect of distractor set size, *F* (2,164) = 13.80, MSE =0.003, *p* <.001, η_p^2 = .144, which was qualified by a two-way interaction, *F* (2,164) = 13.80, MSE = 0.001, *p* <.001, η_p^2 = .145. While errors appear to be greatest for baseline trials presenting 32 distractors, errors for onset trials were high and approximately equal for distractor set size 16 and 32.

Again, errors did not differ by WMC (all *F* s<1).

Error rates on color trials were also investigated using a 2 (WMC: High vs. Low) × 2 (Trial type: Color vs. Baseline) × 3 (Distractor set size: 8 vs. 16 vs. 32) mixed ANOVA with WMC as a between subjects factor. There was a main effect of trial type, *F* (1,82) = 113.29, MSE = 0.003, *p* =.0.127, η_p^2 = .580, as well as distractor set size, *F* (2,164) = 18.37, MSE = 0.003, *p* <.001, η_p^2 = .183. These main effects were qualified by a significant two-way interaction trial type and distractor set size *F* (2,164) = 63.64, MSE = 0.001, *p* <.001, η_p^2 = .438. An inspection of Table 5 suggests baseline trials have the greatest error rate for distractor set size 32 but color trials have the greatest errors at 16 distractor trials.

The main effect of WMC was not significant (*F*s < 1). WMC did not interact with either trial type, *F* (1,82) = 1.64, MSE = 0.003, *p* =.204, η_p^2 = .021, or distractor set size (*F* < 1).

Table 5 also presents error rates for onset trials by distractor set size and duration. Duration manipulation effects in error rates were investigated with a 2 (WMC: High vs. Low) x 3 (Distractor set size: 8 vs. 16 vs. 32) x 3 (Duration: 150ms vs 300ms vs 500ms) mixed ANOVA with WMC as a between subjects factor (note: color capture and baseline trials were static displays and are therefore not included in this analysis). Errors increased with distractor set size, *F* (2,164) = 20.71, MSE = 0.004, *p* <.001, η_p^2 = .202, and were greatest at the lowest onset duration, *F* (2,164) = 4.91, MSE =0.003, *p* =.008, η_p^2 = .057, but these were qualified by a significant distractor set size by duration interaction, F (4,328) = 29.93, MSE = 0.002, p <.001, η_p^2 = .267. This interaction may be driven by the highest error rates for trials presenting 16 distractors at the shortest duration, 150 ms.

The main effect of WMC did not approach significance (F < 1). WMC did not interact significantly with either distractor set size, F (2,164) = 2.18, MSE =0.004, p =.116, η_p^2 = .026, or duration (F < 1). Finally, RTs were reliably measured; Cronbach's alpha calculated on subjects' mean RTs across the 3 distractor set sizes (and so, 3 variables) was .91 for onset trials, .89 for color trials, and .82 for the baseline trials.

Analysis of errors indicated higher error rates for color than onset or baseline trials. WMC was unrelated to errors on any capture trials.

Discussion

In line with expectations, based on the executive attention view and findings relating WMC and constraining visual attention (Poole & Kane, 2009), individual differences in WMC was found to be related to preview search. This relationship was especially evident on offset compared to onset trials, based on the greater attentional demands required in order to use the less salient visual information available on offset trials (e.g., Braithwaite et al., 2006; Pratt, Theuwees & Donk, 2007). Further, baseline search performance was unrelated to WMC in agreement with previous research (Kane et al., 2006). Error rates did not vary with WMC.

In agreement with prior findings from Poole and Kane (2009), WMC was related to cued search RTs. This WMC effect was greater on offset compared to onset trials even though overall offset trials were performed faster than onset trials. The effect of WMC was important at all fixation durations tested though it was stronger at short compared to long durations. No error effects were related to WMC.

Performance on capture search trials was unexpectedly faster than on baseline trials. While an analysis of error rates revealed greater errors for color than onset or baseline trials, no other variables were related to WMC. Based on these findings capture search will not be used in the latent variable analyses below.

Structural Model Analyses

Models. In the figures presented here, observed variables are represented with rectangular boxes and the latent variables derived from the variance shared between or among those variables are represented by circles or ovals. Values on paths leading from latent variables to observed variables indicate the factor loadings for each task. Double headed arrow lines connecting latent variables indicate the correlation between those variables; single headed arrow lines between latent constructs (i.e., path coefficients) can be interpreted as semi-partial correlations–squaring them indicates the proportion of variance in the criterion variable accounted for by the predictor. The correlation matrix for all manifest variables which appear in the models is presented in Table 6.

WMC-WMK Analyses. Of particular interest in the literature is how WM should be conceptualized; some evidence supports viewing WM as having two separate and distinct components, based on its control and attentional-scope characteristics (e.g. Cowan et al., 2005). The two-factor view of WMC is depicted in Model 1a (see Figure 14). The latent WMC variable is derived from those observed variables designed to tap primarily the control aspect of WM, namely OSPAN, SSPAN, and RSPAN. Similarly, the latent WMK variable is derived from the variance shared by the attentional scope tasks-Visual Arrays (Vis. Arrays), Running Span (Run. Span), and Brief Report. The separate WM factors had respectable loadings from their observed variables with larger overall loadings onto the WMC than WMK factor from their respective tasks. Further, the correlation between the latent WMC and WMK factors is large, at 0.90, indicating a very strong relationship between the control and scope of attention aspects of WM. The fit indices for this model depicting a two-factor WM model indicated good fit: Chi-square (8, N = 131) = 5.17, p = 0.74; Chi-square/df = 0.56, RMSEA= 0.01, SRMR= 0.04, CFI= 1.0, NFI= 0.97.

Given the strong correlation between WMC and WMK factors, an alternative view, conceptualizing a unitary WM factor, is presented in Model 1b (Figure 15); here all the tasks load directly on a single WM factor. The factor loadings in Model 1B are similar to those obtained in Model 1A. Further, the fit statistics showed good fit, comparable to those in the two-factor model: Chi-square (9, N = 131) = 6.10, p = 0.73; Chi-square/df = 0.68, RMSEA = 0.01, SRMR= 0.03, CFI= 1.0, NFI= 0.97. A chi-square difference test did not indicate a significant difference between the two models, Chi-square (1, N = 131) = 1.09, p = 0.30, providing evidence in support of the one-factor conceptualization as more parsimonious than the two-factor conceptualization. Thus, a single WM factor is used in the remaining models, which test the relations between WM and control processes in visual search.

This following section will examine the relationship of a unitary WM construct to individual differences in preview and cued searches separately (capture search was excluded from these analyses due to the null WMC effects and reverse capture effects discussed above). After presenting those models the subsequent section will present a full visual search model testing the relationship between controlled and traditional search tasks and, finally, WM's relation to the full visual search model will be presented.

WMC and Controlled Search. The relationship between WM and the control processes involved in Preview search was tested in Model 2 (Figure 16; factor loadings for WM for all subsequent models appear in Table 7, factor loadings for the Base latent variable appear in Table 8); recall that one purpose of this study was to determine if the control processes tapped by Preview search overlap with those measured in WM tasks. Separate latent Preview factors were proposed based on whether the trials presented the search displays as onsets or offsets, due to their different attentional demands. Further, a path was proposed between the latent WM factor and the control search factors while a Baseline factor was proposed to be unrelated to the other latent factors (i.e. a null path between the Baseline factor and the other latent variables). This variable, labeled "Base" in the figures, reflects shared variance between the experimental and baseline tasks (the baseline observed variables used in all subsequent modeling here come from preview search visual search, each set reflecting the baseline block for its respective salience type). Separating the variance shared by all the baseline and controlled visual search tasks from that variance unique to the controlled tasks alone allows the separation of speed, response selection, or other processes related to visual search but not involving control, to be removed from modeling of the latent control factor. Again the model fit the data: Chi-square (127, N = 131) = 247.10, p <0.001, Chi-square/df = 1.95, RMSEA = 0.09, SRMR= 0.10, CFI= 0.92, NFI= 0.85. Also of interest is that the notion that that offset searches should be more attentionally demanding than onset searches; indeed the data showed a larger path loading for the latent offset variable on WM than the less attention demanding onset searches, at –0.55 and –0.21 respectively.

Cued searches were tested in a similar way and are represented in Model 3 (Figure 17). In agreement with the proposal that the attentional requirement in search should vary based on the salience manipulation, separate factors for onset and offset cue search were also proposed. Similar to the previous model, cued search factors were predicted by the WM variable while a separate, independent baseline factor, was not. The model fit the data: Chi-square (98, N = 131) = 205.24, $p < 0.0001$, Chi-square/df = 2.09, RMSEA = 0.10, SRMR= 0.10, CFI= 0.90, NFI= 0.88. Further, in line with predictions based on differences in attentional requirement based on the salience manipulation, factor loadings with WM were nominally higher for the Offset than Onset factors, at -0.41 and –0.32, respectively.

Structure of Visual Control. Another aim of the current study was to determine whether the same type of control processes were involved across different visual search tasks purported to involve control in the literature. Model 4 (Figure 18) proposed separate latent factors for Preview search and Cued search task variables separated by their salience manipulations. This model also included a second-order latent factor, labeled Control, reflecting the shared variance among the first order latent controlled search factors. A baseline latent variable, unrelated to Control was also included in this model. T The model provided marginally adequate fit to the data: Chi-square (89, N = 131) =

254.52, $p < 0.0001$[3], Chi-square/df = 2.86, RMSEA = 0.12, SRMR= 0.10, CFI= 0.91, NFI= 0.95[4]. The data support the model put forth here, with a latent Control factor derived from experimental trials independent of baseline searches processes which do not involve control related to WM.

Model 5a (Figure 19) investigates the relationship between WM and controlled search tasks. This model posits a path from WM to a second-order Control factor derived from the first order search factors separated by salience manipulation. Importantly, this model posits a null path from WM to the Base factor, which removes the non-control speed and search variance common to baseline and controlled searches. The model fit the data adequately: Chi-square (193, N = 131) = 388.60, $p < 0.001$, Chi-square/df = 2.01, RMSEA = 0.09, SRMR= 0.09, CFI= 0.90, NFI= 0.87. Important to the theoretical motives here, the factor loadings from the first order visual search factors on the higher order control factor are all significant (range from 0.21 to 0.75). Further, the factor loading from Control to WM is also significant, at -0.56.

Among alternative models tested, one which proposed a baseline search factor loading onto WM is presented in Model 5b (Figure 20). This path between WM and Base indicates a relationship between these two constructs analogous to that between controlled search and WM. This model resulted in fit statistics comparable to those for Model 5a: Chi-square (192, N = 131) = 387.90, $p < 0.0001$, Chi-square/df = 2.02,

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[3] For moderate to large sample sizes even small differences between the observed and expected covariance matrices result in significant Chi-square tests and therefore these should not be taken as evidence of model misfit by themselves (Raykov and Marcoulides, 2000).

[4] Note that a number of additional versions of the following models were tested which included correlated disturbances for a small number of observed variables. Adding correlated errors did lead to increases in fit but such gains were minor and in favor of model simplicity and importance of theoretical fit, the current models are presented as the best overall fit to the data.

RMSEA = 0.09, SRMR= 0.10, CFI= 0.90, NFI= 0.88. Importantly, however, the path loading between WM and the Base factors was very low, at –0.09, so even if one were to argue against parsimony and for this alternative model, the relationship between WM and baseline search processes is, at best, extremely weak.

Model 5c (Figure 21), unlike the previous models, does not specify a separate baseline search variable. So, in this model the variance shared between all of the controlled search tasks loads onto the Control factor. Importantly, this variance also included the variance involved in non-controlled visual search tasks such as speed or response selection. Fit statistics for this model approach the general guidelines used here: Chi-square (98, N = 131) = 239.07, $p < 0.0001$, Chi-square/df =2.43, RMSEA = 0.11, SRMR= 0.11, CFI= 0.90, NFI= 0.87. Including both control and baseline search variance results in a moderate path loading between WM and Control here, at -0.39. Unlike Model 5a, then, the path between WM and Control does include variability involved in baseline visual search tasks. This change from Model 5a to Model 5c results in a reduction in the WM-Control path coefficient from -0.56 to -0.39. Thus, *neglecting* to account for non-control related variance (e.g., speed, response selection, etc.) obscures the relationship between WM and controlled search performance.

Discussion

Structural models indicated the expected relationship between a unitary WM variable and latent preview search variables with path coefficients ranging from -0.21 to -0.55. This relationship held true even in alternative models which specified a path between WM and a latent baseline variable. This point is critical in that one might otherwise argue other, non-control factors, such as overall speed or response selection, were responsible for the relationship between WMC and preview search. Further, the path loadings from WM were higher for the offset preview variable compared to the onset variable, indicating a greater relationship with WM for the more attention demanding trials (e.g., Pratt et al., 2007). Finally, here is another instance, along with that demonstrated by Sobel et al. (2007) and Poole and Kane (2009), in which individual differences in WMC play a role in a visual search task.

Regarding cued search, structural models indicated relationships between cued search task performance and the latent WM variable with path coefficients ranging from -0.32 to -0.41. This relationship between WM and cued search was significant even in models where a latent baseline factor loaded on the WM variable, again indicating that it was the controlled aspects of the search task and not other aspects, common to traditional visual searches, driving this relationship. These findings replicate those from Poole and Kane (2009) demonstrating the involvement of WM in cued search performance.

Modeling involving control in visual search tasks showed that all the tasks purported to require control processing loaded on a single control factor (Figure 18). Such a finding of commonality between these tasks is not trivial. Consider the differences in surface characteristics, such that preview search requires attention to deprioritize varying numbers of stimuli in the preview display to speed search through the new display stimuli. Cued search, on the other hand, requires attention to be constrained to a small subset of closely arranged spatial locations. Further, when modeling WM's relationship to controlled visual search (Figures 19, 20, 21) the path loadings are nominally higher for those variables representing less salient and purportedly more attention demanding (Soto et al., 2006) variants of these control tasks. Finally, when aspects of visuals search common to baseline visual search tasks are not partialled out of the WM-Control relationship (Figure 21) their relationship is somewhat diminished in comparison to the models where the baseline variance is excluded (Figure 20).

CHAPTER IV

DISCUSSION

Overall the results relating measures of WM and controlled visual search tasks generally followed the predictions proposed in the introduction. WM measures were related to preview search and this relationship was stronger for offset than onset trials, which present a greater attentional demand in preview search (Braithwaite et al., 2006). Cued search was influenced by WM under conditions presenting the fixation displays as offsets as well as onsets like those from Poole and Kane (2009). However, in capture search both color and onset trial types were performed faster than baseline trials resulting in an unexpected capture effect. No aspect of capture search task performance was related to WMC.

Latent Variable Modeling and WM

The first two models presented here tested the structure of WM. Theorists have mainly focused on two aspects of WM —control and attentional scope. Measurement of the former has relied on complex WM span tasks like OSPAN (Turner & Engle, 1989; see also Conway et al., 2005, regarding complex WM span tasks) which require participants to memorize items interleaved with a processing component. Measurement of the latter aspect, attentional scope, has relied on tasks which present the subject with a large number of items very briefly and then tests how many items could be perceived in that limited time period, as in the visual array comparison task (Luck & Vogel, 1997). Such a disparity in task characteristics reflects the notion that complex span tasks tap primarily the central executive aspect of WM (Kane et al., 2004) while attentional scope tasks are meant to primarily reflect how much information can be held in active memory (Cowan, 2001). The current study tested whether these two aspects of WM should be conceptualized as separate entities or related parts of a single WM construct. Though Model 1a and 1b here had comparable fit statistics, the second model, presenting a unitary WM variable, was chosen in favor of parsimony such that there is no compelling statistical reason to choose the model positing two separate factors over the model with one factor. Model 1a had a correlation of .90 between the separate latent control and attentional scope factors indicating that, even if one were to argue in favor of this model as representing the valid underlying structure of WM, that the control and attention scope aspects are very closely related.

This finding agrees with proposals put forth in the introduction based on the work of Cowan, et al. (2005). Remember that their latent variable analysis indicated a strong relationship between control and scope constructs like those used here. Similar to the models here, they selected a model with a single WM factor over one positing separate control and attention scope factors. This interpretation agrees with that put forth by Cowan, et al. (2005). Remember that they tested WM control and scope tasks and their relationship to aptitude measures. While their model selection favored a unitary WM factor they also demonstrated that control and scope measures related to different specific variance in reasoning tasks beyond that which they shared in common. While the current modeling favors a unitary view of WM, their finding suggests caution regarding the use of WMC and WMK measures interchangeably at least at the manifest level.

In addition to the interest based on WM measurement and its relationship to other intellectual tasks, this investigation also contributes to our knowledge of the nature of WM. Specifically, in regards to the unitary nature of WM. Initially, WM was proposed as a non-unitary system by Baddeley and Hitch (1974). Their model was composed of 2 separate slave systems responsible for auditory and visual information, respectively, and a central executive which served as a coordinator (but additional components have also been proposed, e.g., Baddeley, 2000). Other views are unitary in nature, notably the executive attention view (Kane et al., 2007) which has been the impetus for the study presented here. Under this theoretical view, references to WMC, its measurement and variation between individuals, focuses on those characteristics of the central executive itself. The model selection indicating a single latent WM factor best characterizes both the control and attention scope aspects of WM supports a unitary view of WM.

Evidence for Control in Controlled Search Tasks

Remember from the introduction that previous research testing the boundary conditions of the attention control–WMC relationship found traditional visual search and WMC were unrelated (Kane et al., 2006). Visual search researchers have proposed a role for attention in visual search such that it serves to identify and locate targets after being deployed to a location in order to bind features together to form a coherent object (Wolfe, 1998) or by matching stimuli in the search display to an actively held target template (Duncan & Humphreys, 1989). Individual differences in WMC have been shown to be unrelated to several traditional visual search tasks in spite of long, difficult searches (Kane et al., 2006). This has led to the conclusion that while ample evidence supports WMC's relationship with attentional tasks when they require the restraint of habitual responses or constraint of attentional focus amidst distraction that WMC may not be related to all tasks which involve attention. One potential danger in testing the relationship between WMC and tasks thought to require attentional control involves a circularity of logic, namely calling the current visual search tasks *controlled* because they vary with individual differences in WMC and determining tasks are not controlled because they lack a relationship with WMC. In order to avoid such a criticism, the following subsections cite further evidence supporting the theoretical position that the visual search tasks used here rely on attentional control processes or mechanisms. Due to the unexpected finding of a reverse capture effect, the subsection about capture search will instead address potential explanations for this finding.

Preview Search. The benefit of presenting half of the search display as a preview before the remainder of the stimuli are also presented has been attributed to visual marking, an active, top-down controlled process (Olivers & Humphreys, 2002; Watson & Humphreys, 2000). Research supports the contention that such an effect is driven by top-down processing because a secondary task performed during the time when items are previewed extinguishes the preview benefit (Watson & Humphreys, 1997). Further, theorists have proposed that this effect is based on a central attentional mechanism. Humphreys, Watson, and Jolicoeur (2002) put subjects under dual task demands using either auditory or visual secondary tasks presented at the onset of the preview or soon after. Both modality types disrupted the preview effect but, if the secondary task was performed soon after the preview onset, only the visual task disrupted performance. They interpreted their findings as supportive of a view where controlled attention serves to initially encode the preview items then, in a secondary stage, attention must be maintained over the preview period and this is more susceptible to modality specific interference. Another attention-based view explains the preview effect via inhibition of a particular feature which distinguishes the preview items from the new items (Braithwaite & Humphreys, 2003; Braithwaite, Humphreys, Watson, & Hulleman, 2005). The current preview task did not present the two sets of distractors in different colors and therefore the possibility of using feature-based inhibition to aid in the deprioritization of previewed stimuli was likely very limited. Finally, recent work has demonstrated a role for individual differences in visual WM storage measures in inhibitory effects in preview search (Experiment 4 of Al-Aidross, Emrich, Ferber & Pratt, 2011). Importantly, the methodology of this work encouraged the involvement of visual WM by limiting the number of items presented in the preview and full display. The current study was not intended to encourage such behavior, and instead follows more typical methodology, presenting both a wide range and large number of previewed items and full displays. While the potential relationship of visual WM to inhibiting previewed locations is interesting, the methodology employed by Al-Aidross et al. (2011) makes a comparison with the current work speculative at best.

At this point it is appropriate to address some competing views of preview search which do not explain the preview benefit with controlled mechanisms or processes. One such view, put forth by Donk, Theeuwes, and colleagues (Donk & Theeuwes, 2001; Donk & Verburg, 2004), attributes the benefit to automatic processes such that newly presented items (i.e., after the preview) capture attention without the involvement of control. New items appear as onsets and the sudden change in luminance captures attention. Because the target is always a member of this new group searches are quickened as if they proceeded only through the newly appearing items. According to this view, the preview benefit is brought about by automatic capture of attention to the newly presented items which contain the target. Researchers have tested this view of the preview effect by controlling aspects of the new, target-containing stimuli after the preview, such that the presentation of new items occurs without a change in luminance. The preview benefit still occurs even without luminance changes which may serve to capture attention, though the specific time course required to set up the initial encoding of preview items may be longer without the aid of such luminance changes (Braithwaite et al., 2005; Braithwaite et al., 2006). Such a finding indicates that while automatic prioritization of newly presented items is not the sole cause of the preview effect, it may still contribute to it. The current work did not explicitly attempt to eliminate such influences, so some small portion of the overall advantage of using previews to speed search may be due to automatic factors. What should be noted, however is that there is no compelling reason to suspect the findings relating individual differences in WMC to preview search here as being based on automatic influences. In addition to the work showing individual differences in WMC to be unrelated to traditional visual search (Kane et al., 2006) WMC has also been shown to be unrelated to aspects of other tasks which rely primarily on automatic processes (e.g., Kane et al., 2001, Kane & Engle, 2003). Further, we found longer RTs for offset compared to onset trials and importantly, individual differences in WMC was related to preview search on offset trials corroborating the proposal that limiting bottom-up changed in luminance imposes greater attentional demands to use the previews to limit search. Such results suggests if automatic processing plays any meaningful role in preview search here, that it serves to limit the reliance on WM for task performance.

Another alternative view of the preview benefit has been put forth by Jiang, Chun and Marks (2002). They explain the effect as due to temporal segmentation of the old and new displays; since they are presented in two halves they are separated into groups automatically. Subjects then simply attend to the new group of items. According to this view new items are prioritized but not via active processing at old, previewed locations. Evidence against the temporal segmentation account has been presented by Olivers and Humphreys (2002) who had subjects perform a preview search task in the midst of a rapid serial visual presentation stream (e.g., Raymond, Shapiro & Arnell, 1992). They induced an attentional blink so they could vary the amount of attentional resources available during the preview period and intermittently probed identification at both previewed and new locations. When the preview stimuli were presented during the attentional blink they were included, with newly presented stimuli, in the set of items to be searched suggesting the typical preview effect depends on attentional processes or mechanisms unavailable during the attentional blink. Further, in general they found probe identification was worse at old than new locations, in line with an explanation that activation at preview locations was inhibited. When the preview items were presented during the attentional blink, however, probe identification was equivalent for previewed locations and new locations, indicating that they had been searched as if presented all at once. Because the previewed items were presented when attention was unavailable during the blink, those items were not de-prioritized when the second half of the display was presented.

Of particular interest for the current discussion is what processes or mechanisms involved in the preview effect depend on WMC? According to Humphreys, Watson, and Jolicoeur (2002), controlled attention serves to either set up the initial encoding of locations to be inhibited or in the maintenance of those locations or both. An inspection of the relevant data in Figure 9B regarding preview duration in offsets, where WMC played a significant role in performance offers evidence regarding which aspect of visual marking involves WMC. We see, generally, a lack of WMC span differences at the two fastest preview durations but robust span differences at preview durations of 600 ms or greater across all distractor set sizes. Further, the WMC span differences do not appear to systematically change across these long preview durations. If high spans were faster at greater durations or low spans were slower it might suggest a difference in maintaining the inhibition of distractor locations over time. So, while these findings are congruent with the involvement of WMC for the initial encoding or setting up of inhibitory influence during the time the preview items are presented, it does not rule out potential WMC differences in maintenance of visual marking. Further research including a wider variety of distractor set sizes as well as longer preview durations will be required to determine what specific role WMC play in the preview effect.

Cued Search. Endogenous spatial cueing effects like those shown here are often attributed to top-down attentional control limiting the effects of distractor interference (e.g., Awh et al., 2003; Shiu & Pashler, 1994). Such noise reduction is explained by direct suppression of interference at distractor locations or by blocking of inputs from those spatial locations (Awh et al., 2003). Support for the biased competition view (Desimone & Duncan, 1995) comes from a variety of studies from Awh and colleagues (e.g., Awh and Pashler, 2000; Awh et al., 2003; Awh, Sgarlata and Kliestek, 2005) which used endogenous cues and distractor-laden displays similar to those used here. For example, Awh and Pashler (2000) found benefits of cueing target locations on distractor laden trials but not on trials which presented no distractors. Further, cueing effects on the identical distractor-laden trials were larger when they were presented within a block containing many compared to a block presenting few distractor-laden trials (Awh et al., 2003). These findings indicate that the benefit of cueing results from avoiding the effects of distractor noise and that the cueing benefit relies on the searcher’s top-down knowledge of likelihood of distractor interference. These are also in agreement with the biased competition view such that it proposes top-down attentional control settings serve to limit distractor interference based on the searcher’s expectation of distractor noise.

The evidence cited above indicates that cueing leads to better performance due to attentional control settings which serve to limit interference from non-target locations. This interpretation agrees with the current findings of a relationship of individual differences in WMC being related to this effect as well as prior research showing individual differences in WMC to be related to performance on several other interference-rich tasks (e.g., Conway et al., 2001; Heitz & Engle, 2007; Kane et al., 2001). Some theorists propose a different relationship between spatial WM and spatial attention that would likewise predict a relationship between individual differences in WMC and cued search. The reason for WMC's involvement in tasks like those described above may be due instead to a close functional relationship between mechanisms of spatial WM and spatial attention. One part of this proposal is that spatial attention serves as a rehearsal mechanism by which spatial aspects of WM operate. In support of this notion Awh, Jonides and Reuter-Lorenz (1998; see also, Awh & Jonides, 2001) showed a decrement in spatial WM performance when subjects were prevented from attending to memorized locations during the delay part of a memory task (Experiment 3). Their findings suggest a functional relationship between WMC and cued search performance here such that spatial contents of WM are maintained or rehearsed by spatial attention. Recent work has offered evidence further supporting this relationship. Theeuwes, Kramer and Irwin (2011) briefly presented subjects with colored stimuli at 4 corner locations of an imaginary box and on each trial questioned if a particular color had been presented. They also intermittently probed one of the formerly occupied locations for a speeded response, reasoning that if retrieval of the colored item from memory coincided with shifts of attention toward the location of that item, that RTs to subsequent probes in the target's location would be faster. RTs were faster to the previously occupied locations, leading to the conclusion that spatial attention is how information is retrieved from visual working memory. Importantly, this spatial effect occurred even though, unlike Awh et al. (1998), their task had no requirement to memorize spatial information—subjects were only asked whether the item was presented and therefore subjects had no incentive to remember spatial information.

Certainly, these two views ─ that WM is related to the ability to limit spatial attention to target areas and that the maintenance or rehearsal mechanism of spatial WM is spatial attention itself, may not be an either-or proposition. Recent work has suggested a close relationship between visual storage capacity limits and the ability to limit distractor interference such that individuals with higher capacity are better able to avoid influence from distractors than are those with lower capacity (Vogel et al., 2005; see also Machizawa & Driver, 2010). Remember from the introduction that the ERP work of Vogel et al. (2005) found a relationship between visual storage capacity and the ability to deal with irrelevant visual information such that those with smaller capacity were less able to filter out irrelevant information. Not only were they able to store less than their high capacity counterparts but they also stored more irrelevant visual items than did the high capacity subjects. Evidence presented here and by Poole and Kane (2009) indicate the involvement of WMC in endogenously cued search when displays present a high amount of distractor interference. Whether WMC is related to such performance based on an ability to limit distractor interference or from a close relationship between visuo-spatial WM abilities and spatial attention is not clear. The available data does not offer an answer regarding which of these aspects of the task may rely on WMC and it is not clear if the intimate relationship of these two views precludes empirical testing to choose view one over the other. It is worthwhile to note, however, that the WM tasks used here included verbal tasks as well, suggesting that the visuo-spatial aspects of the WM tasks cannot be the sole reason why their performance is related to the ability to limit distractor interference.

Another point of interest regarding the cued search findings here relates to fixation timing effects found by Poole and Kane (2009). Experiment 3 from that article found WMC differences at long (1,550 ms) but not short (300 ms) fixation durations which they interpreted as supporting a view where WMC was related to proactively maintaining the constraint of visual attention over time. Results from the cued search task here reveal a different relationship. High WMC subjects were faster than Low WMC subjects overall but, interestingly, the trend was for WMC differences to be greatest at the shortest fixation durations tested and smallest at the longest durations (which ranged from 500 to 2,000 ms). Though the WMC by duration interaction did not reach our significance threshold (*p* =.077) for onset trials which are the most similar to those employed by Poole and Kane (2009), it did reach significance on offset trials. An inspection of Figure 11b suggests that High WMC subjects' performance is constant across increasing fixation durations while Low WMC subjects appear to be improving performance with longer time to limit attention to target locations. Such an interpretation agrees with the findings of Braithwaite et al. (2006) indicating attentional effects occur in situations of limited bottom-up information but take longer to execute. Taken together, it appears that at some very short fixation duration (on the order of 300 ms) limiting visual attention in endogenously cued search is unrelated to WMC. The current results show that High but not Low WMC subjects are able to use the cues to constrain attention with more time (500 ms or more). With increasing time available to constrain attention low spans are able to improve performance but never reach the level of High WMC subjects (at least over a time course of 2,000 ms) which stays relatively stable across fixation durations. It should be noted however that one important difference between the current work and that reported by Poole and Kane (2009) is that the prior work separated the fixation durations by block but here they were mixed within the same block. Though speculative, the apparent ability of Low WMC span subjects to improve performance with increasing fixation durations may be due to the uncertainty imposed by the mixed durations. This may have encouraged Low WMC span subjects to limit attention as quickly as possible and they found increasing benefits of this on trials where the fixations were presented for greater durations.

Capture Search. In addition to the established literature demonstrating the basic attention capture effect (e.g., Theeuwes, 1991; Yantis and Jonides, 1984), a recent experimental investigation has shown individual differences in WMC to be involved in capture. Specifically, Lavie and DeFockert (2005) manipulated memory load and found that capture effects increased with greater memory loads. While these findings agree with our expectations here based on the executive attention view of WMC, namely that low WMC subjects should show greater capture than high WMC span subjects based on their differences in the ability to control attention, results do not always a match between studies manipulating available WMC with a memory load and those using individual differences in WMC (see e.g., Kane et al., 2006, for more regarding this disconnect relevant to WM and visual search).

The reverse capture effect observed here may be due to several task characteristics. First is the blocked nature of the task—baseline searches were always performed in a separate block between performance of the onset and color capture blocks. Though not a documented manipulation to reduce capture effects in the visual search literature, having all the capture trials performed in the same block may serve to reinforce the goal to protect against capture (as in the pure incongruent Stroop block used by Kane & Engle, 2003). Further, the complexity of the stimuli used here may have also limited any effect of capture. Han and Kim (2009) showed that attention was not captured when an item held in visual WM was the same as a distractor when searches present large perceptual difficulty (Experiment 1); conversely, when searches were relatively easy, WM's contents did lead to capture (also see the section below regarding Lavie's load theory). They proposed that at a certain temporal threshold control is able to exert an effect during the trial. Before this time window (i.e., with fast searches) it plays little or no role in search performance; with more time control can aid in avoiding capture. Such proposals agree with other findings where irrelevant distractors exert little influence in cases of inefficient visual search and long RTs (Gibson & Peterson, 2001; Lamy & Tsal, 1999). Though not common, several investigations regarding capture and how the contents of WM affect capture have resulted in reverse capture effects like that observed here. In brief, these studies had subjects remember an item for a later memory test and during the delay the subjects performed a visual search task. The main manipulation of interest was whether the to-be-memorized item matched a distractor in the display. Three experiments reported by Woodman and Luck (2007) and one by Downing and Dodds (2004) showed faster searches when the memory item matched a distractor in the visual search task suggesting that the subjects were able to direct searches away from those distractor locations. Taken with the results of Han and Kim (2009) it appears that the contents of WM can direct attention away from known distractors and that this is more likely when searches are long, as is often the case when complex stimuli are used.

Other basic experimental investigations have demonstrated that capture effects do not occur in all circumstances. Some research have shown that when a target is not defined by its color, as in our capture task here, that color singletons fail to capture attention (e.g., Folk, Remington & Johnson, 1992). However, other research has shown that when subjects search for a specific shape among other shapes, RTs are slowed by the presence of an irrelevant color singleton (Theeuwes, 1992; but also see Bacon and Egeth, 1994, for contradictory findings). Such contradictory findings make unclear the necessary conditions under which capture is reliably produced. Future work determining how individual differences in WMC relate to the capture effect in visual search will be informative and the findings related to timing and other task specifics required to produce the effect will aid in illuminating the nature of attentional control generally and as it relates to WMC.

When is Control Involved in Visual Search?

In spite of the research cited above, predicting what visual search tasks will or will not involve control as measured in WMC is not a trivial task. Research indicates individual differences in WMC to be unrelated to traditional visual search with consistent target-distractor mapping, and a variety of distractor set sizes when the searches were based on feature absence, conjunctions of color and orientation, and spatial configuration, under situations of pop-out and inefficient visual search (Kane et al., 2006). Individual differences in WMC is also not involved in a version of command search (Wolfe et al., 2000) where, unlike traditional searches, attention must proceed through search displays in a predetermined pattern (Kane et al., 2006). Conversely, individual differences in WMC are important in visual search when subjects are forewarned of target and distractor locations on each trial and the displays present large amounts of distractor noise (Poole & Kane, 2009). Further, as shown here, WMC plays a role in visual search performance when the search display is presented in two halves such that the subject receives a preview of which locations will not contain the target stimuli (Watson & Humphreys, 1997). Finally, the SEM analyses reported here indicate a relationship between preview search and cued search task performance; additionally, a latent control factor based on these tasks has a strong relationship with WM. What characteristics are common to these controlled tasks, but not involved in traditional visual search, which makes them dependent on WMC? These tasks both forewarn subjects on each trial of the spatial location of the upcoming target. It may be more precise however, to say that subjects are informed of the distractor locations because the preview display in preview search informs the subject of the locations where the target will *not* appear while in cued search the target pre-cues also indicate distractor locations. In addition to this foreknowledge of spatial locations of target and distractors, characteristics of other search tasks shown by Sobel et al. (2007) to be related to WMC should also be considered. They found individual differences in WMC to be important when the search context predisposed subjects to search through a more salient dimension (color) even though task characteristics would result in faster searches through a less salient dimension (similar orientations). What appears to be common among these three WMC-related tasks is that subjects are able to constrain focus to some aspect of the display (based on either spatial or feature qualities) in order to quicken search. Constraining visual search to a limited subset of the display is one of the ways in which control can be involved in visual search.

A useful framework to determine when individual differences in WMC will be related to visual search performance is the load theory put forth by Lavie and colleagues (e.g., Lavie, 1995, 2010; Lavie, Hirst, DeFockert & Viding, 2004). This theory deals with selective attention and cognitive control in interference rich situations and proposes that the amount of interference experienced is determined by whether a load is perceptual or cognitive in nature. Perceptual load is increased either by presenting more items in a display or by increasing their complexity; cognitive load is determined by the amount of information held in WM (Lavie, 2005). In situations of low perceptual load processing of the target occurs and, if there are resources left over, processing proceeds automatically to other items (including distractors) resulting in performance decrements. In cases of high perceptual load, attentional resources are consumed in processing the target such that little or no processing is left to spill over to distractors resulting in no interference. Cognitive loads have an opposite effect such that increasing loads result in increased interference. Here, the resources or mechanisms of control which typically serve to limit interference are occupied and unable to limit the interference. Such a distinction suggests a framework to determine what visual search tasks will and will not involve control as measured in WMC. This framework is concordant with the areas in which we see WMC important in controlled visual search here such that the advantage for presenting the display in two halves in preview search is eliminated by putting subjects under a demanding memory load (Watson & Humphreys, 1997). Also, the differences in the distribution if visual attention which varies with individual differences in WMC (Bleckley et al., 2003) can be extinguished with the addition of a memory load such that high WMC spans perform like low spans, demonstrating a more diffuse focus of attention (Bleckley, 2001). The involvement of cognitive load in performance of these tasks may be related to setting up or maintaining the encoding of the locations for deprioritization in preview search (Braithwaite et al., 2005; Braithwaite et al., 2006) or in constraining visual attention in cued search (Bleckley, 2001; Poole & Kane, 2009). Further, as detailed in the paragraph below, this framework explains why WMC effects do not appear in traditional visual search (Kane et al., 2006), in spite of sharing some characteristics with controlled search tasks.

Remember how traditional visual searches occur according to guided search theory (e.g. Wolfe, 1998). Simple features are analyzed automatically in parallel and then summed to a master map consisting of varying levels of activation based on those local, feature-based differences. Knowledge of target characteristics serves to augment activation and attention moves from location to location in order of decreasing activation. Remember from above that according to load theory increasing the number of stimuli in the display increases perceptual load (Lavie, 2005). Manipulating search stimuli based on feature complexity or by increasing the number of distractors presented in the displays are two common ways search difficulty has been manipulated in traditional visual search experiments (Wolfe, 1998). Accordingly, while these manipulations often lead to longer search RTs, they do not, however, recruit control processes according to load theory (Lavie, 2005); in line with this proposal are findings from multiple experiments reported by Kane et al. (2006). Again, this work presented a variety of visual search tasks where the search criteria was based on feature absence, color and orientation conjunction, and spatial configuration, and they also manipulated the number of distractors presented in the search displays. Across these experiments there was no relationship between individual differences in WMC and visual search, in spite of long search times that increased with greater distractor set sizes (Kane et al., 2006). Considering these findings under the framework of load theory, such manipulations only affected perceptual and not cognitive load and agrees with the findings that control processes or WMC were not related to search performance in that study.

Other views of traditional visual search explicitly posit a role for WM such that it stores target templates which are matched to items in the search display (Bundesen, 1990; Duncan & Humphreys, 1989). According to load theory, increasing loads on WM decreases the ability to deal with interference. Though some research suggests that subjects can maintain a load of at least up to four simple visual items without disrupting search processes (Woodman, Vogel & Luck, 2001), increasing cognitive demand with a complex spatial load disrupts search with fewer items (Oh & Kim, 2004; Woodman & Luck, 2004). Recently, Woodman, Luck and Schall (2007) had subjects perform a change discrimination task along with visual search under articulatory suppression. Search was unaffected except when the target changed across trials; additional cognitive demands from this requirement to update the target template lead to performance decrements. Other support for this view comes from Han and Kim (2009). As mentioned above in this section, they found attention capture effects in situations of low but not high perceptual load. As discussed in the previous paragraph, a cognitive load leads to decreased control and increased capture effects, in agreement with load theory (Lavie & De Fockert, 2005). With these findings in mind, it appears that the manipulations employed by Kane et al. (2006) affected perceptual load while leaving cognitive load constant across their experiments. All experiments reported by Kane et al. (2006) had subjects respond to targets which were relatively simple shapes or shape-color combinations and likely imposed minimal demand on WM storage. Further, subjects made either a target present/target absent response or indicated which of two possible targets was present on the trial and the targets remained the same within experiments. These tasks likely presented minimal cognitive load to the participants.

Recently visual search researchers have begun explicitly including load level manipulations in experimental investigations. This work is described briefly below as additional evidence of load theory's (Lavie, 2010) value as a framework for understanding when control is involved in visual search. For example, He and McCarley (2010) manipulated both WM load and the visual quality of search items (varying cognitive and perceptual loads, respectively) in a visual search task. Both the demanding counting task and degraded discriminability of items interfered with search. Importantly, these effects were additive, suggesting independent influences from the cognitive load and perceptual quality manipulation, in support of load theory's (Lavie, 2010) claim that cognitive and perceptual loads effect performance separately. Caparos and Linnell (2010) had subjects perform a flanker-like visual task (Eriksen & Eriksen, 1974) in which they varied the distance between the target location and an incongruent distractor in order to measure the distribution and quantity of visual attention. Across studies they manipulated perceptual and memory loads which, according to load theory (Lavie, 1995), would affect performance independently. As expected, they found that the "Mexican hat" shape of visual attention (i.e., short RTs at the center of fixation and an outer ring area with longer RTs in the area in between) was compressed towards the center by a perceptual load (Caparos & Linnell, 2009; Caparos & Linnell, 2010, Experiment 3). Additionally, the amount of interference experienced was related to individual differences in WMC with low spans more impaired than high spans. Also, in Experiment 3 a greater amount of interference was observed with a demanding cognitive load (a difficult calculation). The authors interpreted these findings as in agreement with load theory (Lavie, 1995) such that a perceptual load influenced the perceptual level, tightly focusing the shape of visual attention; the cognitive load acted on post-perceptual processes limiting the ability to combat interference, as evidenced by longer RTs irrespective of spatial location. Note, however, that the clear demarcation of load effects between cognitive and perceptual domains proposed by load theory (Lavie, 2010) was not universally supported such that Caparos and Linell (2010) reported some instances where WM loads resulted in changes to the shape of visual attention (Experiments 4 and 5). Remember from the discussion above that the work of Bleckley (2001) showed changes in the shape of visual attention due to a WM load; the precise nature of these effects may be more complex than proposed by this view. While the value of load theory to predict when control is involved in visual search tasks is promising, further work is needed to test the framework and clarify whether different load types have independent effects on interference.

Control in Traditional Visual Search?

What then can be said regarding the role of control in traditional visual search? Though top-down influences on search behavior are important in visual search theories, for example in the role of augmenting activation based on knowledge of task demands (e.g., Wolfe, 1998), little reference to cognitive control is made by theories of traditional visual search. For example, consider a traditional search task where the target is a blue circle among blue squares and red circles. Increasing the number of stimuli in conjunction search tasks like these results in longer RTs. While this non-zero search slope may be taken as evidence that such searches do not occur in parallel, unlike pop-out searches (e.g., blue circle among red circles) that have RTs independent of distractor set size, such increases in RT do not necessarily indicate the involvement of control. Again, according to Lavie’s (2010) load theory, this increase in RT is due to perceptual changes and not recruitment of control processes. Such an interpretation agrees with other research indicating a limited role for top-down strategy in the most common conjunction searches in which an equal distribution of distractor types does not offer an opportunity for performance improvements from top-down factors (Bacon & Egeth, 1997; Sobel & Cave, 2002). Similarly, increasing the number of distractors presented while keeping their relative distribution equal leads to longer RTs but likewise, this increase in RT is not due to involvement of control. Again, in agreement with load theory, such manipulations do not involve control or involve more control; increased RTs in visual search cannot be interpreted as unambiguous evidence of control.

Current evidence has demonstrated two ways in which control processes can be involved in visual search. The first, taken from views like that put forth by Duncan & Humphreys (1989), is to frequently change the target across trials during the task. The evidence cited above indicates that such a requirement involves active updating of the target template in WM and the controlled nature of this is supported by findings that performance is disrupted by a simple WM load when the target in visual search changes across trials (Woodman, Luck & Schall, 2007). The second way to involve control in visual search is to constrain search to a subset of the display. Although the majority of the empirical evidence to date has the constraint of search to a particular spatial location or locations (as in preview search here and cued search, also in Poole & Kane, 2009), control seems to be involved with constraining searches more generally. Sobel et al. (2007) reported WMC related to search with a difficult to distinguish subset of stimuli when a habit to search through a more salient but less advantageous subset was induced. In this study the typical, equal distribution of bottom-up salience signals was changed in order to offer an opportunity for top-down influences to affect search. Due to the novelty of using load theory as a framework for determining whether control will be involved in visual search performance and the notion that increases in RTs do not necessarily indicate the involvement of control processes, at this time determining control's involvement in search should be based on multiple types of evidence.

Incongruent Findings

Recent research challenges the relationship between WMC and traditional visual search task performance that has been espoused here and elsewhere (Kane et al, 2006; Poole & Kane, 2009) such that individual differences in WMC play little or no role in traditional visual search performance. Research calling this view into question shows visual search performance determined in part by individual differences in visual WM storage measures. Luria and Vogel (2011) varied search difficulty and found both individual differences in WMK, as well as a physiological measure indicative of online storage of items in visual WM, contributed independently to search performance. Pertinent to the current discussion, individual differences in visual WM were related to visual search at all difficulty levels including easy, single feature-based search, considered by some theorists as performed virtually automatically (e.g., Wolfe, 1994). Luria and Vogel (2011) attributed the absence of a WMC-search relationship in the Kane et al. (2006) study as due to the use of verbal WM measures; specifically that the verbal measures used lacked the specificity and sensitivity of their visual WM storage measures.

Though these findings seem problematic for the relationship between WMC and visual search espoused here (and by Kane et al., 2006; Poole & Kane, 2009), several deviations from the methodology typically employed in traditional visual search are likely responsible for their contradictory findings. Luria and Vogel's (2011) search display contained two circular groups of letters with one on each side of a central fixation point. These letter sets were presented in two different colors for the left and right hemifields, which varied randomly on each trial; subjects searched through one of two possible colors for the entire task. Further, potential target locations were surrounded by neutral distractors and a flanker distractor. Therefore, subjects had to selectively attend to one side of the display and ignore the other side on each trial, based on a color which randomly changed on each trial. This additional requirement to constrain search to a particular spatial location makes their "traditional" visual search task similar to the preview and cued search tasks used here and elsewhere which are related to individual differences in WMC (Poole & Kane, 2009).

As a final note in support of this notion is recent work demonstrating the importance of constraining attention to spatial locations in order to involve control. Bengson and Mangun (2011) manipulated expectancy in a variant of Posner's (1980) cueing task and found that WM was related to search when the target and distractors differed by a simple feature, on trials which validly cued the target location. However, when spatial locations were not cued, search was unrelated to WM in agreement with other research (Kane et al., 2006). In what would otherwise be a simple, quick visual search task unrelated to control processes, requiring constraint to a spatial location recruited WMC involvement. WM's ubiquitous involvement in search at all difficulty levels reported by Luria and Vogel (2011) may be due to their requirement to limit search spatially to one half of the display. Even if this is not the case, due to these task characteristics, it still stands that the involvement of WMC in traditional visual search task performance is yet to be demonstrated.

General WM Theory

Executive Attention. Remember from the introduction that a main objective of this study was to investigate the interrelations of control as they operate in different types of visual search tasks and to determine how that control relates to WM. The driving force behind this was the executive attention theory of WMC and previous research demonstrating no relationship between individual differences in WMC and performance on a variety of traditional visual search tasks (Kane et al., 2006) as well as other work showing a large role for individual differences in WMC in other visual search tasks (Poole & Kane, 2009). According to the executive attention view, complex span measures of WMC tap some domain general attentional control ability which is important in situations that require the activation and/or maintenance of goals in the face of distraction or interference and it is also important for the resolution of conflict between competing action plans (e.g., Poole & Kane, 2009). Further, the predictive relationship of these complex span measures with higher order intelligence exists because such measures index some aspect of executive attention abilities and these abilities play an important role in a variety of intellectual tasks (Engle & Kane, 2004). A number of studies have offered compelling evidence supporting the executive attention view by demonstrating a relationship between WMC and performance of attention demanding tasks which also put a premium on goal maintenance such as antisaccade (Kane et al., 2001), dichotic listening

(Conway, Cowan & Bunting, 2001), and Stroop (Kane & Engle, 2003). The discussion above indicates that control and WMC, because of their close relationship, are not involved in all tasks which are demanding or difficult (e.g., Kane et al., 2006). There is a strong reliance on WMC when tasks require the restraint of habit, as is common to tasks like antisaccade and Stroop. Further, WMC is also important in tasks which require attention to be constrained as is the case in the dichotic listening task (Conway et al., 2001; see also, Colflesh & Conway, 2007). The controlled visual search tasks shown here to rely on WMC, namely cued search and preview search, also appear to share in common this requirement to constrain attention amidst distraction. Remember from the earlier discussion about involving control in visual search tasks that one way to do so is to frequently change the target within the same task (e.g., Woodman et al., 2007). While the importance of individual differences in WMC has not yet been demonstrated in a search task like this, the executive attention view predicts a strong reliance on WMC for efficient performance. In particular, this aspect of having the targets items often change within the visual search task would place demands on the WM system in order to resolve conflict between goals or action plans (i.e., search for the current target and not for the target of a previous trial). Future research should investigate whether individual differences in WMC relate to visual search in this context and how that relates to other constraint-type search like cued search and preview search used here.

Dual Component. Unsworth and colleagues (Unsworth & Engle, 2007; Unsworth & Spillers, 2010) proposed a theory of WM, of which one component encapsulates the executive attention view described above but in addition proposes that controlled retrieval from secondary memory is an important additional aspect of WM. In short, while this view agrees that attentional control is an important aspect of WMC, cue-based retrieval from long term memory is also considered critical as well and adds explanatory value to WMC's relationship with higher order cognition. Evidence supporting the value of this second component comes from work investigating measures of WMC, recall from secondary memory, and attention control tasks and how they relate to intelligence measures (Unsworth & Engle, 2007; Unsworth & Spillers, 2010). Briefly, Unsworth and Spillers (2010) reported a study investigating the relationships among latent variables reflecting fluid intelligence, WMC, measures of retrieval from secondary memory, and attentional control tasks like antisaccade and stroop. In agreement with the executive attention view, they found a large amount of variance in fluid intelligence was accounted for by a WMC factor derived from several complex span measures. Critically, and in support of their second component, they also reported separate and unique variance in fluid intelligence was accounted for by measures of recall from secondary memory above and beyond that accounted for by the latent WMC variable. The value of this dual component view is also apparent in that it predicts WMC to be important in tasks tapping primarily long term memory, like cued recall (Unsworth, 2009) and free recall (Unsworth, 2007), which are not readily predicted from some other views of WMC. In regards to accounting for the current findings of interest, namely the relationship between individual differences in WM and controlled visual search tasks demonstrated here, the dual component view, because it encapsulates the executive attention view of Kane, Engle and colleagues (e.g., Engle & Kane, 2010; Kane et al.,

2006) naturally makes the same predictions and explanations in regards to WMC's relationship with controlled visual search tasks. Unfortunately, the results reported here neither support nor refute the additional component of the dual component model relating WM to retrieval from secondary memory.

Inhibitory. The view of WM put forth by Hasher and colleagues (Hasher, Zacks & May, 1999; Hasher & Zacks, 1988) proposes that WM measures are important because they indicate the quality of an individual's inhibitory abilities. Such inhibitory processes serve to streamline what is represented in consciousness to goal-relevant items by way of preventing irrelevant content from entering it and deleting or removing information which is no longer relevant. Finally, these inhibitory processes also serve to restrain habitual responses when novel ones are more closely aligned with goal-relevant behavior. The inhibitory view is admittedly (Hasher, Lustig & Zacks, 2007) a close relative to the executive attention theory described first in this section. The executive attention view proposes the broader umbrella of attentional control processes that are important to WM while the view of Hasher and colleagues focuses solely on inhibitory processes. Though prevalent explanations for some of the findings here are inhibitory in nature regarding both cued search (Awh et al., 2003; Desimone & Duncan, 1995) as well as preview search (Watson & Humprehys, 1997) they support these closely related views equivalently. However, findings implicating attentional abilities in the creation and maintenance of visual marking in preview search across time (Humphreys, Watson, and Jolicoeur, 2002) seems to favor the executive attention view over a solely inhibition based view.

Embedded Processes. Cowan's (2001) theory views WM as an information processing system consisting of three processes, with each one as a smaller portion embedded within the other. Conceptually this view consists of the overall long term memory system; within this system is a smaller portion of LTM which is at a heightened state of activation. Finally, the third embedded process is an even smaller area consisting of an item or items currently active in the focus of attention. Development of this view of WM has concentrated on the capacity aspect of the focus of attention, emphasizing how much can be kept active in the focus of attention rather than control of the focus. The focus of attention is seen as flexible such that it can be expanded in order to encompass more than one item (as in the visual array comparison task used here and by Cowan et al., 2005) or, conversely, to zoom in tightly to focus on a single idea or goal (e.g., "look away from the flash of light" during the antisaccade task). Rather than being limited to these two options, the focus can be set at an intermediary level such that it is wide enough to encompass more than a single item but is also set to counteract the effects of interference, as is the case when performing the Stroop task (Cowan et al., 2006). Due to the flexible nature of the focus of attention, the embedded process view is similar to some models of selective visual attention (e.g., Eriksen & St. James, 1986), and therefore naturally accounts for findings relating individual differences in WM to visual search performance when the task requires the constraint of visual attention amidst distraction. Further, considering the other aspect of the focus of attention described above, such that the focus of attention can zoom in to focus on a single goal, this view seems to make parallel predictions to the executive attention theory regarding what other kinds of visual search tasks should involve WMC, namely tasks similar to that used by Woodman et al. (2007) in which the valid target changes across trials.

Binding. Not all theories attribute the value of WM measures to an attentional control construct. The view put forth by Oberauer and colleagues (Oberauer, 2005; Oberauer, Sub, Wilhelm & Sander, 2007) proposes that WM's value is that it indexes an ability to create flexible temporary bindings between chunks of information. According to this view, an individual's WM is limited by this ability to create relationships between or among cognitive representations and it is this limited ability that is responsible for the predictive relationship between WM measures and higher order cognition (Oberauer, 2009). Further, in the same way that memoranda can be bound in temporal order for subsequent recall (e.g., words presented aurally for ordered recall in a running span task), likewise visual objects are also bound to locations in space in some under this view items can be temporarily bound to space in a coordinate system (akin to a representation of pieces on a chess board). This view of items bound to physical locations offers a different explanation for WM's involvement in cued and preview search than that offered by the executive attention and embedded processes views described above. The relationship between individual differences in WM we report in cued search can be attributed to differences in efficiency of building and breaking down these temporary relationships between spatial locations and abstract grouping because the searcher knows what locations will contain targets and which will contain distractors. Explaining the benefit of preview search is less straightforward under the binding view because, unlike cued search, the searcher only knows the locations of distractors before the full displays are presented. Further, while one might argue that searchers could bind attention to only the unpopulated locations which will contain the target and new distractors after the preview, such an interpretation would be in conflict with the leading explanation of the preview effect which focuses on inhibition of distractor locations (Olivers & Humphreys, 2002).

Conclusion

Prior research has demonstrated the involvement of control processes in some (Poole & Kane, 2009) but not all (Kane et al., 2009) visual search tasks. The current study extends this work showing that, in addition to cued search, preview search also depends on controlled processing and, as such, relates to individual differences in complex span measures of WM. Further, the common involvement of control to these visual search tasks was supported by latent variable modeling showing they loaded onto the same latent factor after partialling out variance common to traditional visual search tasks, which has been shown not to rely on control processes (Kane et al., 2009). Additional modeling indicated a unitary WM factor to be related to this latent control factor and that this WM-control relationship was greater when processes common to traditional search were partialled out of the relationship with WM. Lastly, the ways in which these findings fit in with leading theories of WM are discussed.

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APPENDIX A

TABLES

Table 1
Counterbalancing order for visual search tasks

Task order	1	2	3
A	Cued Onset-Offset	Preview Onset-Offset	Capture Onset-Color
B	Preview Onset-Offset	Cued Onset-Offset	Capture Onset-Color
C	Preview Onset-Offset	Capture Onset-Color	Cued Onset-Color
D	Cued Onset-Offset	Capture Onset-Color	Preview Onset-Offset
E	Capture Onset-Offset	Cued Onset-Offset	Preview Onset-Color
F	Capture Onset-Offset	Preview Onset-Offset	Cued Onset-Color
G	Cued Offset-Onset	Preview Offset-Onset	Capture Color-Onset
H	Preview Offset-Onset	Cued Offset-Onset	Capture Color-Onset
I	Preview Offset-Onset	Capture Color-Onset	Cued Color-Onset
J	Cued Offset-Onset	Capture Color-Onset	Preview Offset-Onset
K	Capture Offset-Onset	Cued Offset-Onset	Preview Color-Onset
L	Capture offset-onset	Preview Offset-Onset	Cued Color-Onset

Note. Baseline Blocks for Preview and Cued Search Were Always Performed in Between the Experimental Blocks

Table 2

Means and standard deviations of error rate for preview search by trial type and distractor set size

Trial Type/ WMC Span	Distractor size 8	 16	 32
	Onset trials		
Hi	0.044 (0.044)	0.027 (0.051)	0.041 (0.077)
Lo	0.050 (0.053)	0.041 (0.062)	0.066 (0.101)
	Offset trials		
Hi	0.046 (0.037)	0.034 (0.049)	0.053 (0.065)
Lo	0.040 (0.043)	0.037 (0.056)	0.063 (0.091)
	Baseline trials		
Hi	0.034 (0.043)	0.027 (0.037)	0.057 (0.080)
Lo	0.027 (0.044)	0.037 (0.064)	0.070 (0.099)

Note. Standard Deviations are Reported in Parentheses

Table 3

Means and standard deviations of error rates for cued search by WMC, trial type and locations cued

	Locations Cued		
Trial Type	2	4	8
Onset Hi	0.060 (0.049)	0.074 (0.057)	0.029 (0.034)
Onset Lo	0.110 (0.087)	0.149 (0.107)	0.066 (0.078)
Offset Hi	0.067 (0.051	0.080 (0.060)	0.032 (0.031)
Offset Lo	0.128 (0.106)	0.160 (0.122)	0.069 (0.078)

Note. Standard Deviations are Reported in Parentheses

Table 4

Means and standard deviations of error rates for cued search by WMC, trial type, locations cued and fixation duration

	Fixation Duration			
Trial Type/ Locations Cued/ WMC	500	1,000	1,500	2,000
Onset 2 Hi	0.074 (0.074)	0.057 (0.056)	0.063 (0.061)	0.045 (0.050)
Onset 2 Lo	0.121 (0.112)	0.115 (0.100)	0.108 (0.089)	0.097 (0.089)
Onset 4 Hi	0.077 (0.065)	0.070 (0.066)	0.078 (0.067)	0.071 (0.077)
Onset 4 Lo	0.163 (0.133)	0.150 (0.116)	0.151 (0.117)	0.133 (0.100)
Offset 2 Hi	0.083 (0.075)	0.068 (0.051)	0.057 (0.067)	0.059 (0.059)
Offset 2 Lo	0.123 (0.114)	0.133 (0.121)	0.131 (0.101)	0.124 (0.123)
Offset 4 Hi	0.081 (0.077)	0.080 (0.073)	0.084 (0.075)	0.074 (0.061)
Offset 4 Lo	0.175 (0.131)	0.149 (0.124)	0.170 (0.141)	0.148 (0.135)

Note. Standard Deviations are Reported in Parentheses

Table 5

Means and standard deviations of error rates for capture search by WMC, trial type, duration and distractor set size

	Distractor size		
Trial Type/ Duration	8	16	32
	Onset trials		
Onset (Overall) Hi	0.031 (0.031)	0.054 (0.042)	0.053 (0.069)
Onset (Overall) Lo	0.086 (0.150)	0.125 (0.145)	0.132 (0.163)
Onset 150ms Hi	0.029 (0.050)	0.097 (0.065)	0.043 (0.067)
Onset 150ms Lo	0.080 (0.176)	0.161 (0.144)	0.131 (0.175)
Onset 300ms Hi	0.037 (0.043)	0.029 (0.041)	0.050 (0.073)
Onset 300ms Lo	0.104 (0.163)	0.097 (0.148)	0.133 (0.171)
Onset 500ms Hi	0.029 (0.039)	0.036 (0.054)	0.067 (0.096)
Onset 500ms Lo	0.073 (0.127)	0.117 (0.169)	0.131 (0.165)
	Color trials		
Color Hi	0.064 (0.036)	0.133 (0.058)	0.082 (0.073)
Color Lo	0.135 (0.155)	0.211 (0.147)	0.175 (0.166)

	Baseline trials		
Baseline Hi	0.031 (0.052)	0.027 (0.044)	0.057 (0.096)
Baseline Lo	0.096 (0.140)	0.110 (0.194)	0.131 (0.168)

Note. Standard Deviations are Reported in Parentheses

Table 6

Correlation matrix of WM and visual search variables

	OSPAN	RSPAN	SSPAN	VisArray	RunSpan	BriefR	PreOn8	PreOn16
OSPAN	1							
RSPAN	0.732	1						
SSPAN	0.644	0.594	1					
VisArray	0.208	0.190	0.270	1				
Runspan	0.433	0.463	0.310	0.065	1			
BriefR	0.397	0.488	0.328	0.146	0.277	1		
PreOn8	-0.127	0.008	-0.217	-0.136	-0.091	-0.166	1	
PreOn16	-0.144	-0.053	-0.297	-0.077	-0.136	-0.145	0.846	1
PreOn32	-0.002	0.021	-0.156	0.038	-0.101	-0.141	0.657	0.748
PreOff8	-0.307	-0.208	-0.353	-0.046	-0.269	-0.291	0.651	0.658

	OSPAN	RSPAN	SSPAN	VisArray	RunSpan	BriefR	PreOn8	PreOn16
PreOff16	-0.313	-0.195	-0.325	-0.014	-0.269	-0.295	0.497	0.565
PreOff32	-0.275	-0.172	-0.267	0.021	-0.300	-0.265	0.462	0.538
CueOn2	-0.255	-0.081	-0.246	-0.173	-0.128	-0.077	0.452	0.351
CueOn4	-0.209	-0.113	-0.208	-0.113	-0.172	-0.097	0.336	0.250
CueOff2	-0.328	-0.187	-0.318	-0.074	-0.147	-0.038	0.229	0.187
CueOff4	-0.218	-0.167	-0.232	-0.087	-0.185	-0.026	0.120	0.102
Base8	-0.064	-0.008	-0.193	-0.098	-0.055	-0.124	0.701	0.631
Base16	-0.137	-0.010	-0.155	-0.088	0.025	-0.092	0.481	0.431
Base32	0.026	0.013	-0.073	0.032	-0.066	-0.244	0.447	0.465
Base8	-0.190	-0.009	-0.188	0.047	-0.027	-0.135	0.649	0.573
Base16	0.017	0.101	-0.137	-0.036	-0.076	-0.117	0.531	0.509
Base32	0.137	0.152	-0.060	0.054	0.089	-0.015	0.381	0.469

	PreOn32	PreOff8	PreOff16	PreOff32	CueOn2	CueOn4	CueOff2	CueOff4
PreOn32	1							
PreOff8	0.533	1						
PreOff16	0.546	0.755	1					
PreOff32	0.555	0.727	0.766	1				
CueOn2	0.251	0.342	0.289	0.202	1			
CueOn4	0.174	0.273	0.248	0.159	0.894	1		
CueOff2	0.113	0.333	0.273	0.223	0.566	0.448	1	
CueOff4	0.044	0.297	0.313	0.239	0.429	0.455	0.830	1
Base8	0.530	0.531	0.518	0.438	0.349	0.244	0.284	0.214
Base16	0.395	0.384	0.448	0.367	0.307	0.246	0.285	0.238
Base32	0.514	0.384	0.501	0.457	0.125	0.096	0.037	0.040
Base8	0.558	0.577	0.549	0.429	0.322	0.215	0.268	0.128
Base16	0.636	0.427	0.447	0.440	0.302	0.207	0.189	0.120

	PreOn32	PreOff8	PreOff16	PreOff32	CueOn2	CueOn4	CueOff2	CueOff4
Base32	0.538	0.313	0.425	0.487	0.109	0.080	0.086	0.104

Table 6, continued

	Base8	Base16	Base32	Base8	Base16	Base32
Base8	1					
Base16	0.688	1				
Base32	0.567	0.564	1			
Base8	0.607	0.521	0.427	1		
Base16	0.576	0.511	0.483	0.592	1	
Base32	0.466	0.484	0.548	0.442	0.528	1

Table 7

Factor loadings for WM tasks by model

	Model 2	Model 3	Model 5a	Model 5b	Model 5c
OSPAN	0.78	0.77	0.79	0.78	0.78
SSPAN	0.80	0.81	0.79	0.81	0.81
RSPAN	0.72	0.74	0.72	0.74	0.74
VisArray	0.50	0.47	0.51	0.48	0.48
RunSpan	0.55	0.54	0.55	0.54	0.54
BriefR	0.30	0.31	0.31	0.31	0.31

Table 8

Factor loadings for baseline latent variable by model

	Model 2	Model 3	Model 4	Model 5b	Model 5c
PreOn8	0.69	-	0.71	0.69	0.68
PreOn16	0.73	-	0.74	0.73	0.72
PreOn32	0.73	-	0.74	0.73	0.72
PreOff8	0.66	-	0.70	0.66	0.62
PreOff16	0.73	-	0.73	0.72	0.68
PreOff32	0.73	-	0.73	0.72	0.69
CueOn2	-	0.32	0.32	0.29	0.18
CueOn4	-	0.19	0.18	0.16	0.10
CueOff2	-	0.32	0.32	0.26	0.22
CueOff4	-	0.22	0.19	0.17	0.10
Base8	0.82	0.84	0.81	0.83	0.83
Base16	0.76	0.81	0.76	0.77	0.77
Base32	0.76	0.73	0.74	0.76	0.76
Base8	0.76	0.76	0.77	0.76	0.76
Base16	0.78	0.78	0.79	0.78	0.78
Base32	0.71	0.67	0.67	0.70	0.70

APPENDIX B

FIGURES

Figure 1a

Sample display for first half of distractors presented in a preview search trial

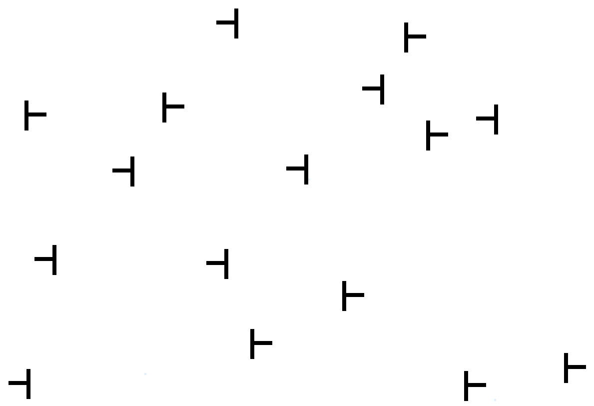

Figure 1b

<u>Sample display for a full trial of preview search</u>

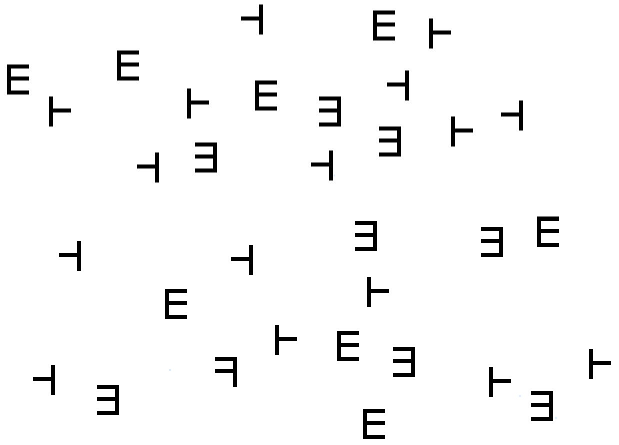

Figure 2a

<u>Sample display of offset preview search trial with locations populated with figure 8 shapes</u>

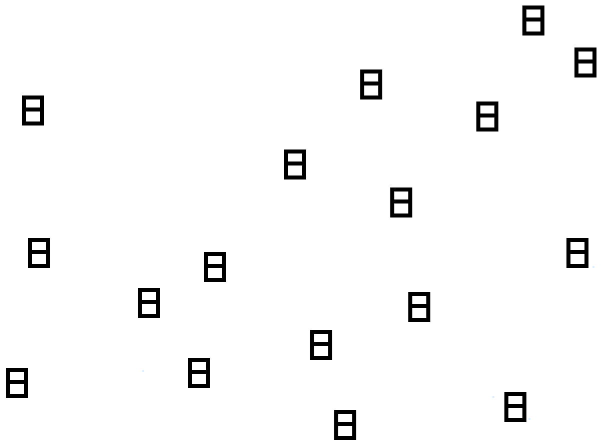

Figure 2b

Sample preview display with first half of distractors revealed from figure 8 shapes

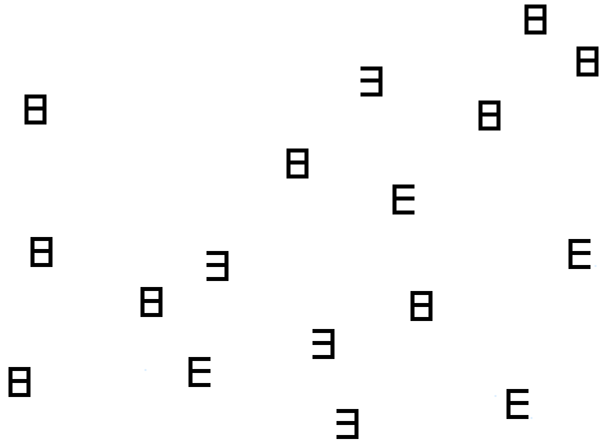

Figure 2c

Sample full preview display with all stimuli revealed from figure 8 shapes

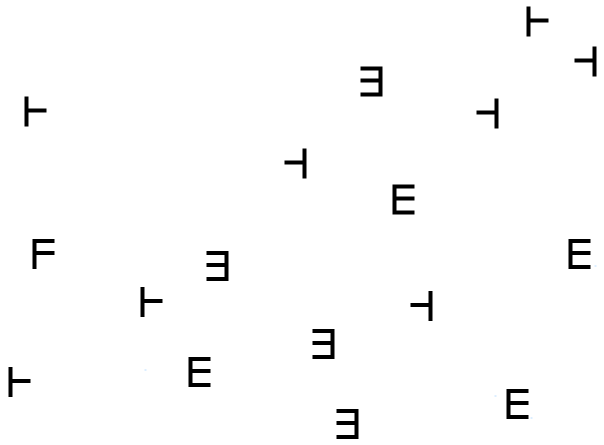

Figure 3

Cues indicating target locations in cued search

Figure 4

Sample of a cued search display

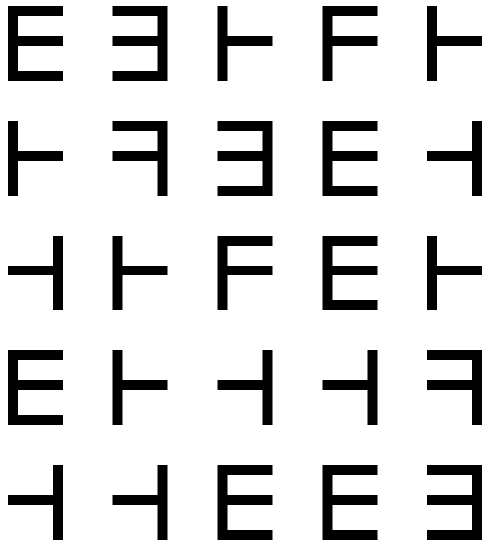

Figure 5

Sample of an offset cued search fixation display

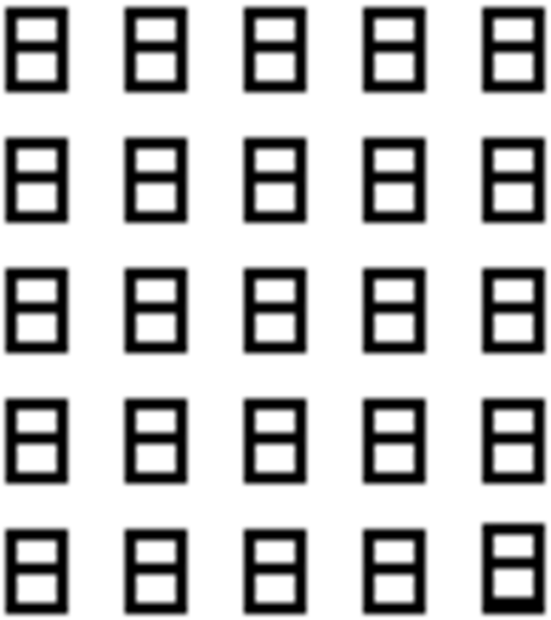

Figure 6

Sample of a color capture trial

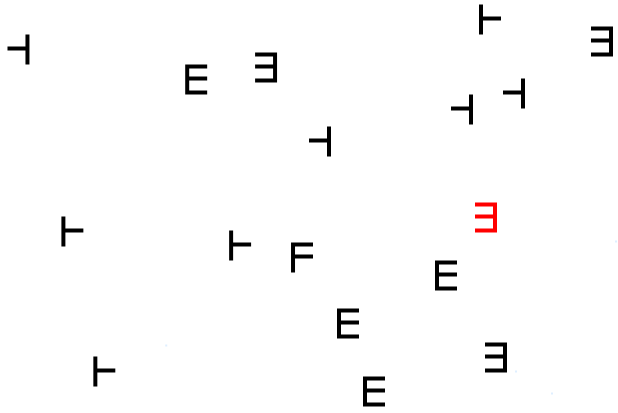

Figure 7a

<u>Sample of an onset capture trial before presentation of the singleton</u>

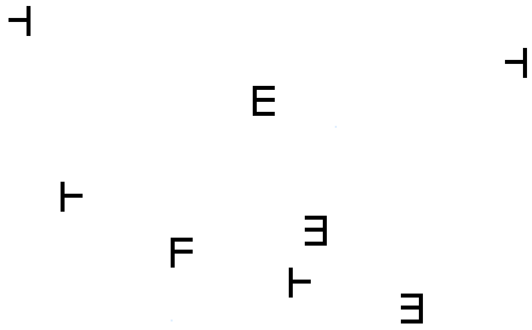

Figure 7b

Sample of an onset trial with singleton present (E in the bottom left of the display)

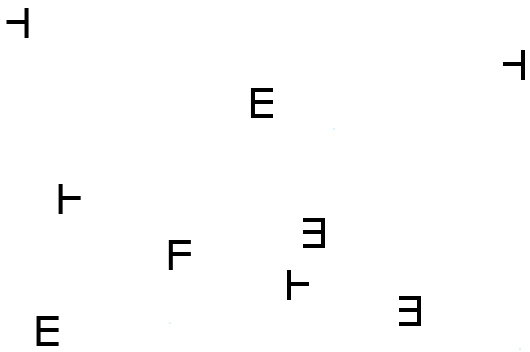

Figure 8a

RTs for preview search for onset and baseline trials by distractor set size for High and Low WMC groups

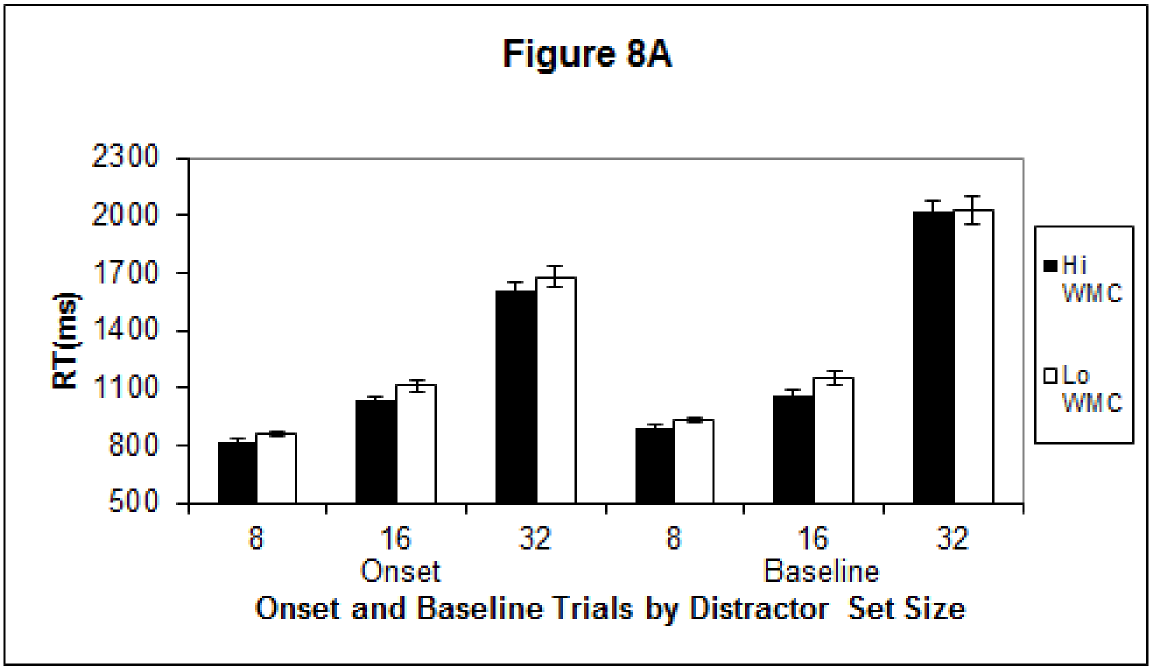

Figure 8b

<u>RTs for preview search for offset and baseline trials by distractor set size for High and Low WMC Groups</u>

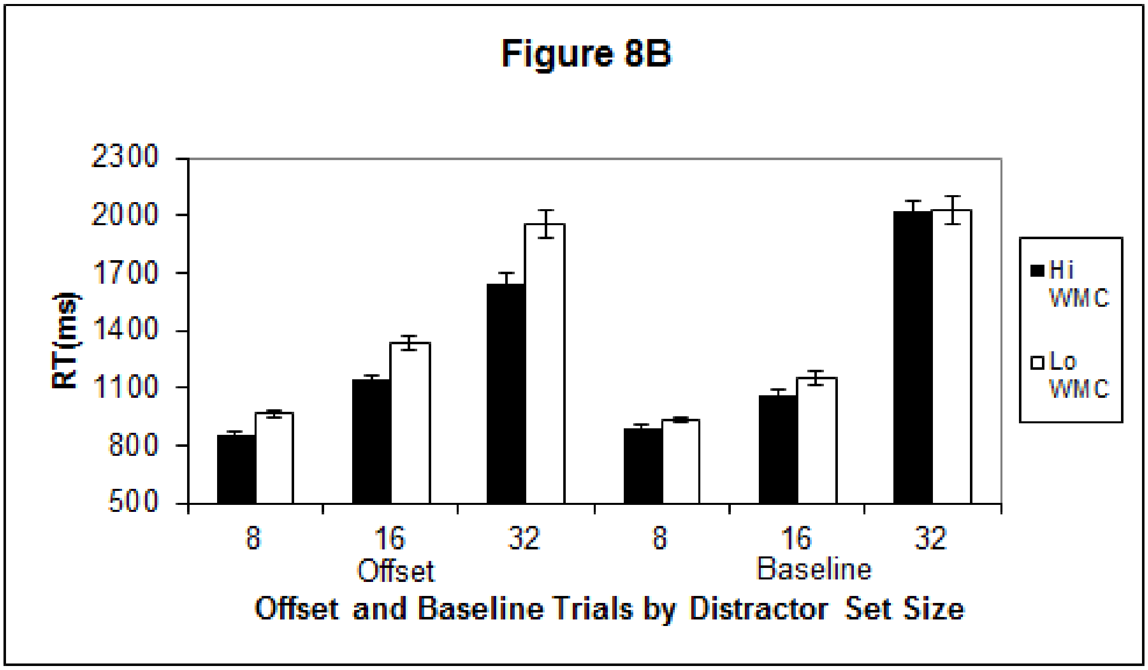

Figure 9a

RTs for preview search for onset trials by duration and distractor set size for High and Low WMC groups

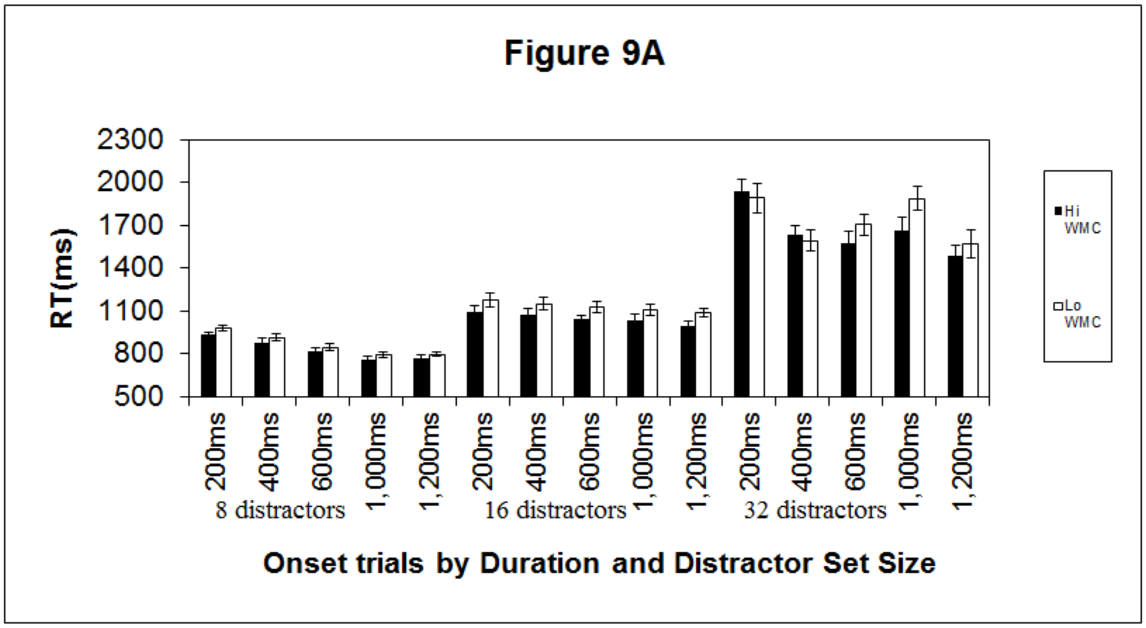

Figure 9b

RTs for preview search for offset trials by duration and distractor set size for High and Low WMC groups

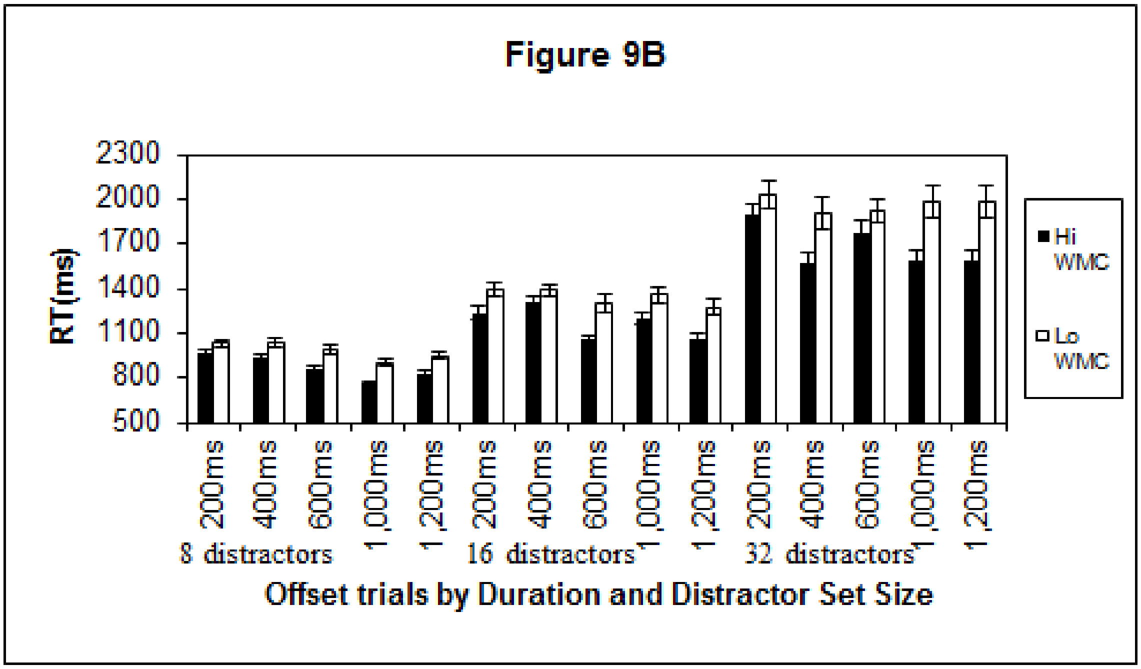

Figure 10

<u>RTs for cued search for onset and offset trials by locations cued for High and Low WMC groups</u>

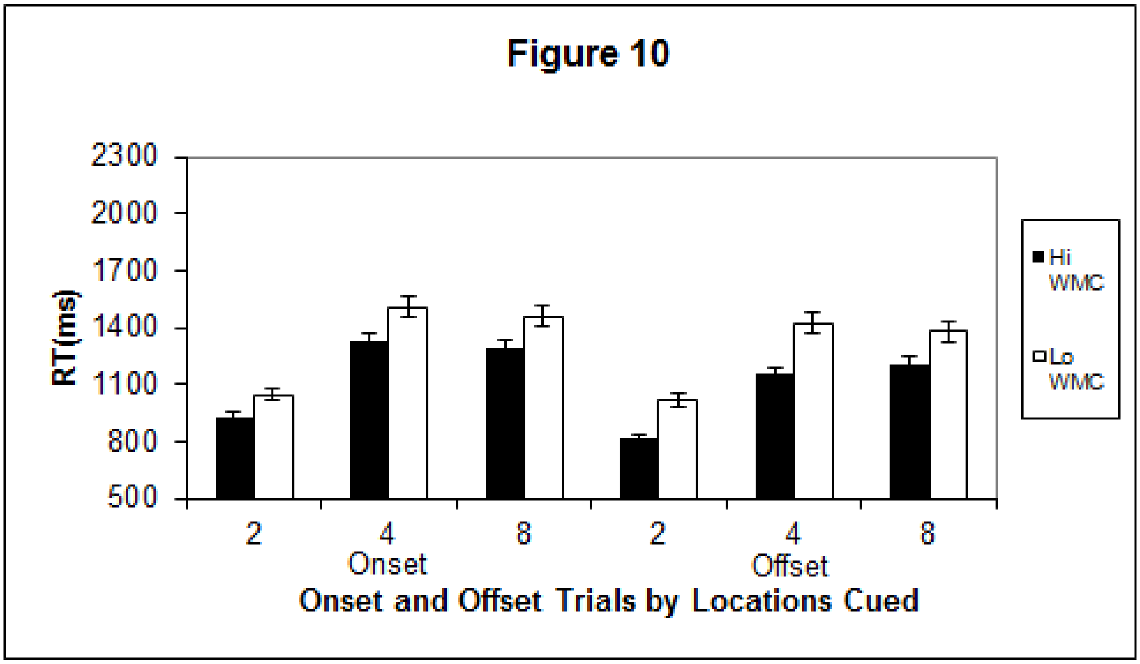

Figure 11a

RTs for cued search for onset trials by duration and locations cued for High and Low WMC groups

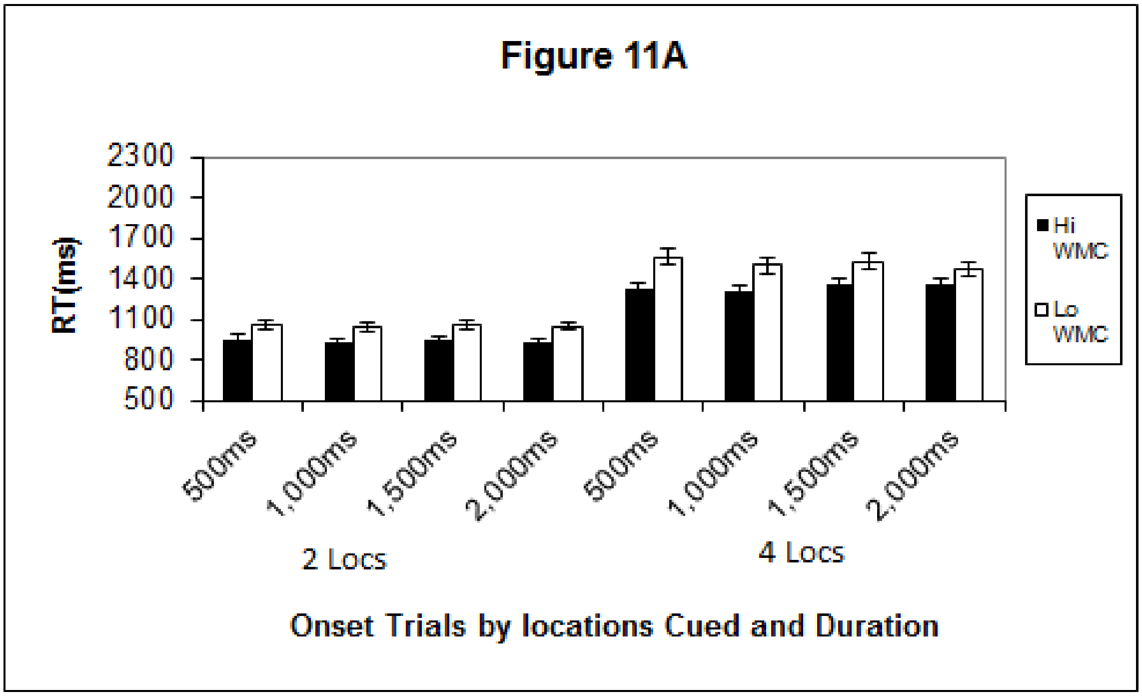

Figure 11b

<u>RTs for cued search for offset trials by duration and locations cued for High and Low WMC groups</u>

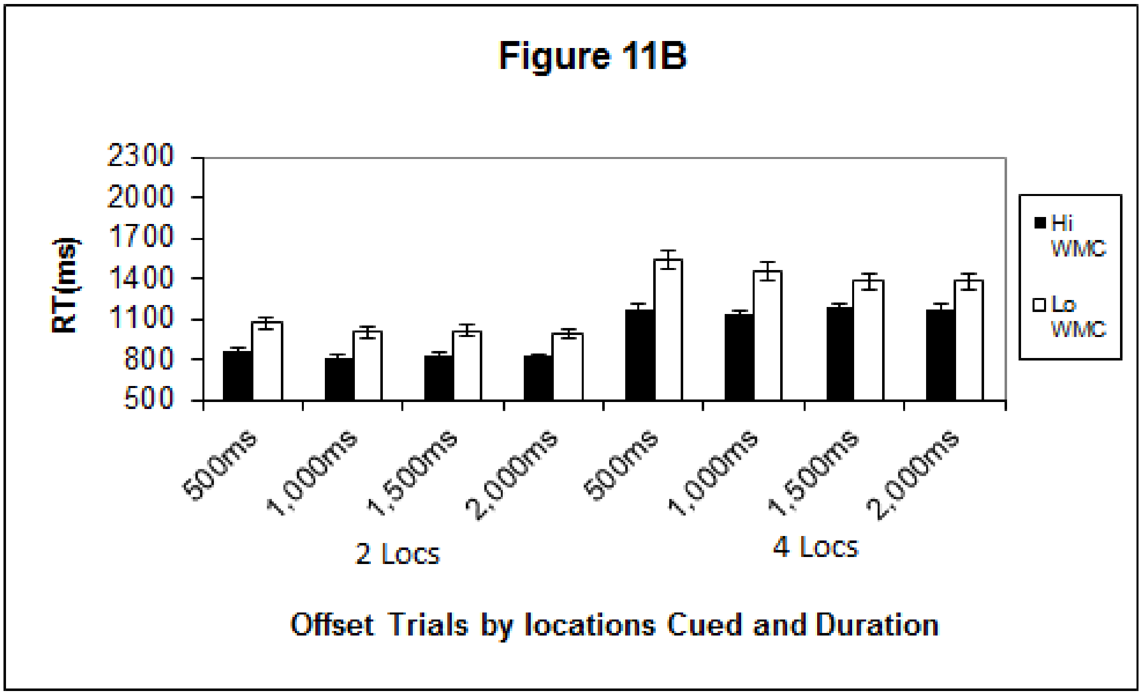

Figure 12a

RTs for capture search for onset and baseline trials by distractor set size for High and Low WMC groups

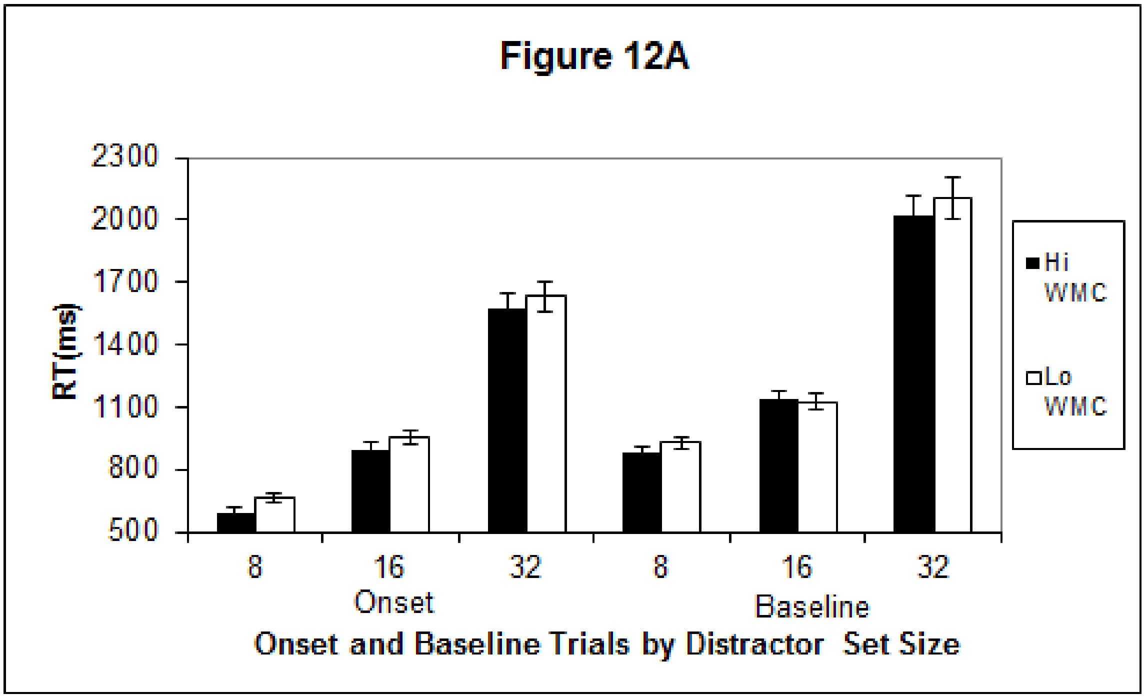

Figure 12b

RTs for capture search for color and baseline trials by distractor set size for High and Low WMC groups

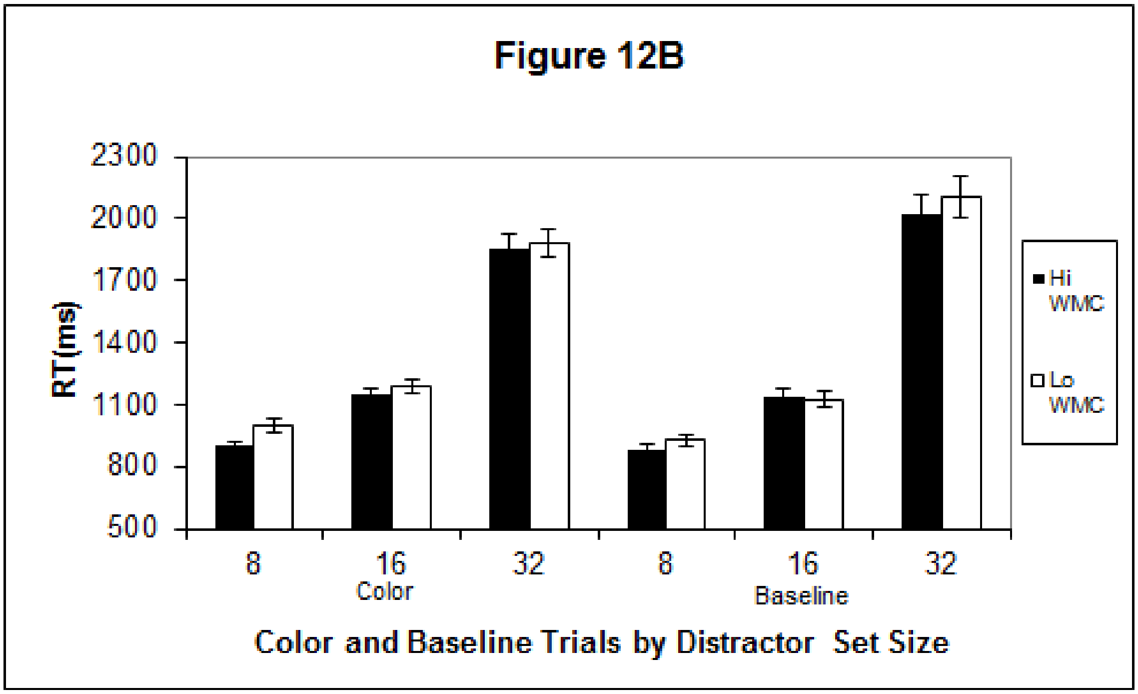

Figure 13

<u>RTs for capture search for onset trials by onset duration and distractor set size for High and Low WMC groups</u>

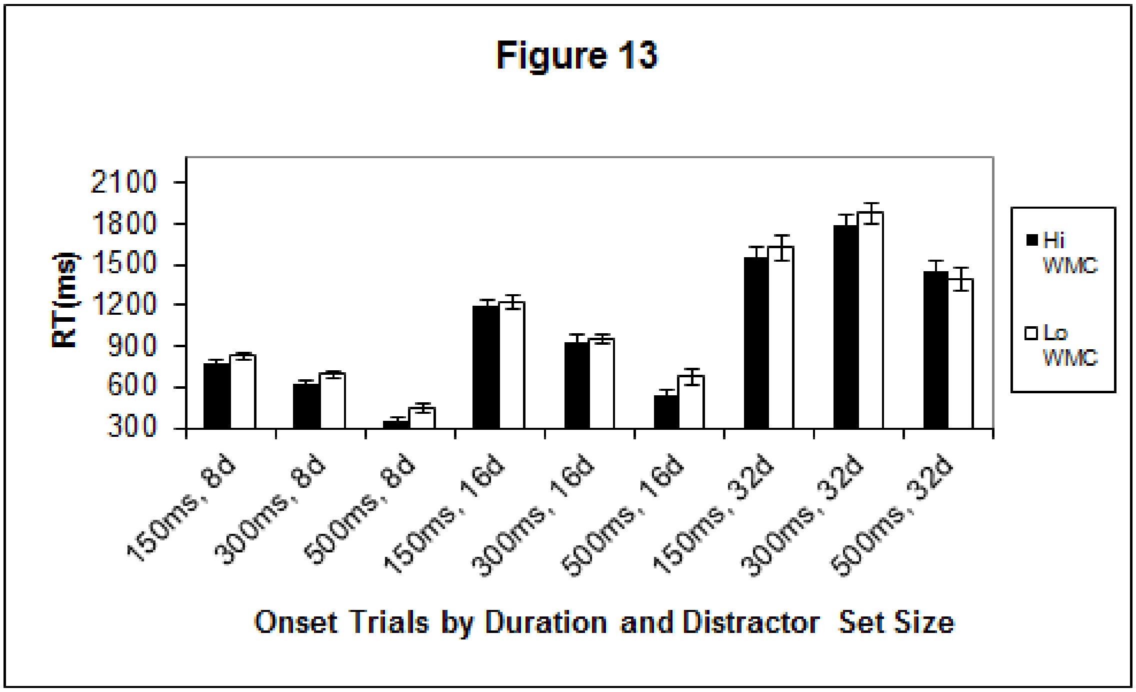

Figure 14

Path diagram for Model 1a depicting a two-factor view of WM

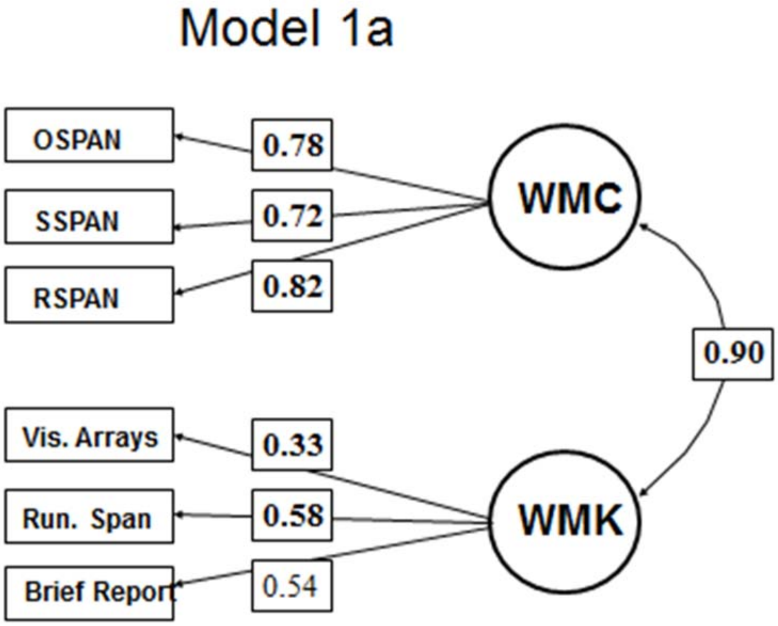

Figure 15

Path diagram for Model 1b depicting a unitary WM

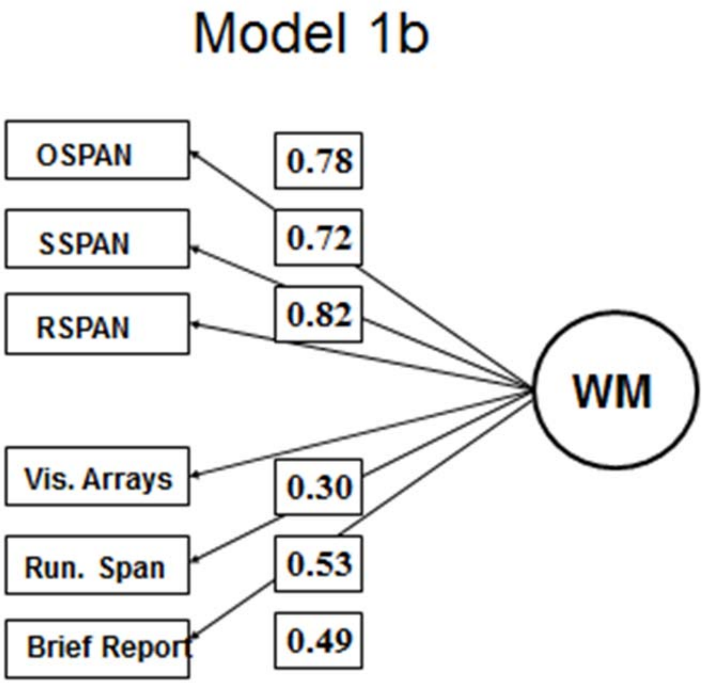

Figure 16

Path diagram for Model 2 investigating the relationship between WM and preview search

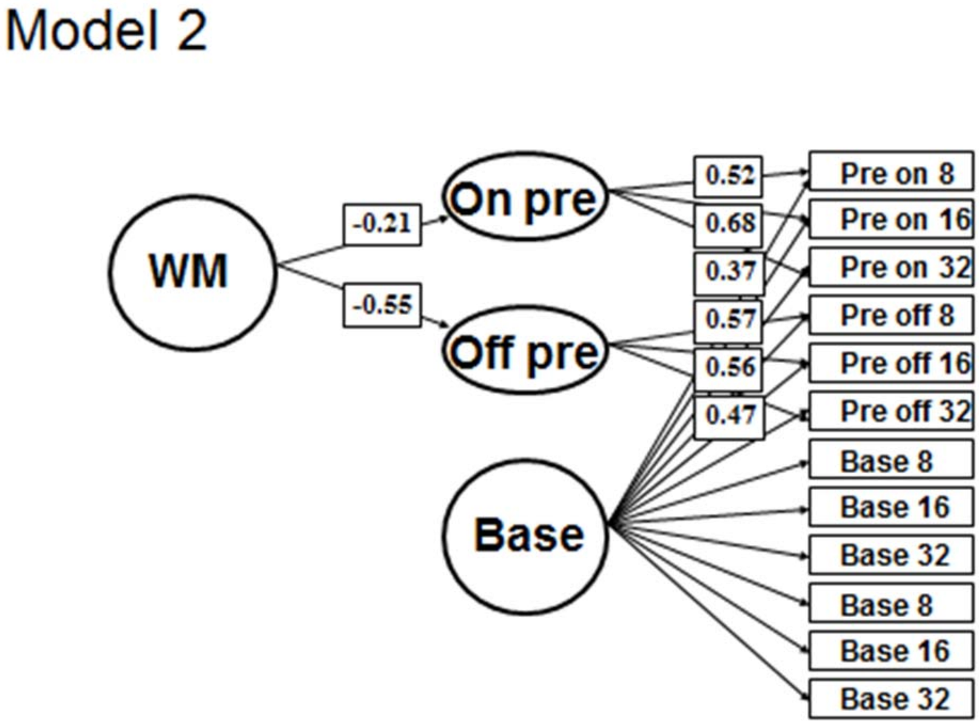

Figure 17

Path diagram for Model 3 investigating the relationship between WM and cued search

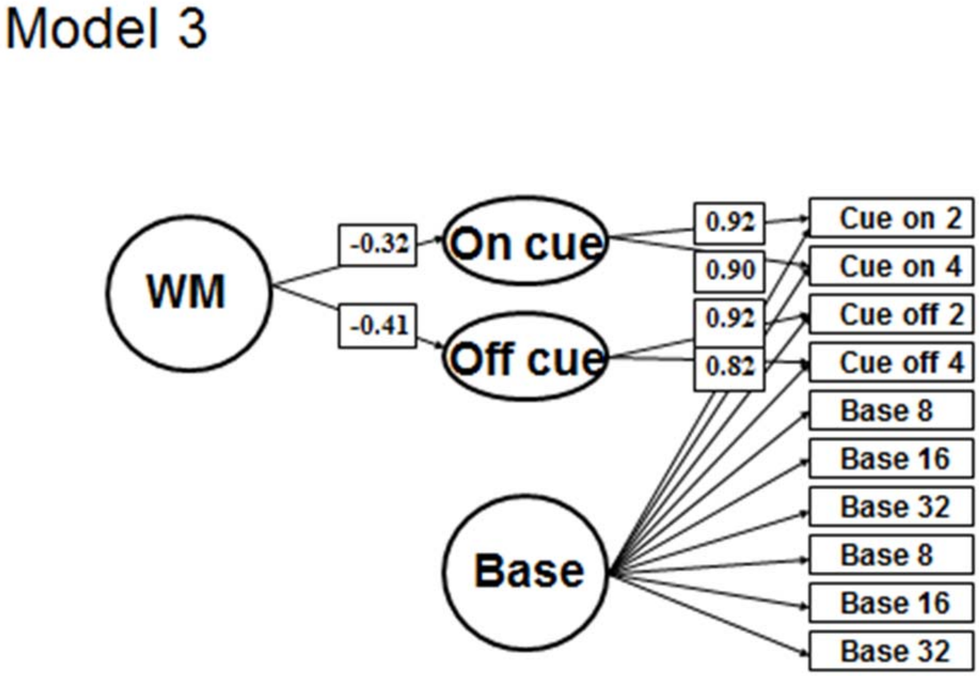

Figure 18

Path diagram for Model 4 investigating the relationship among controlled search tasks

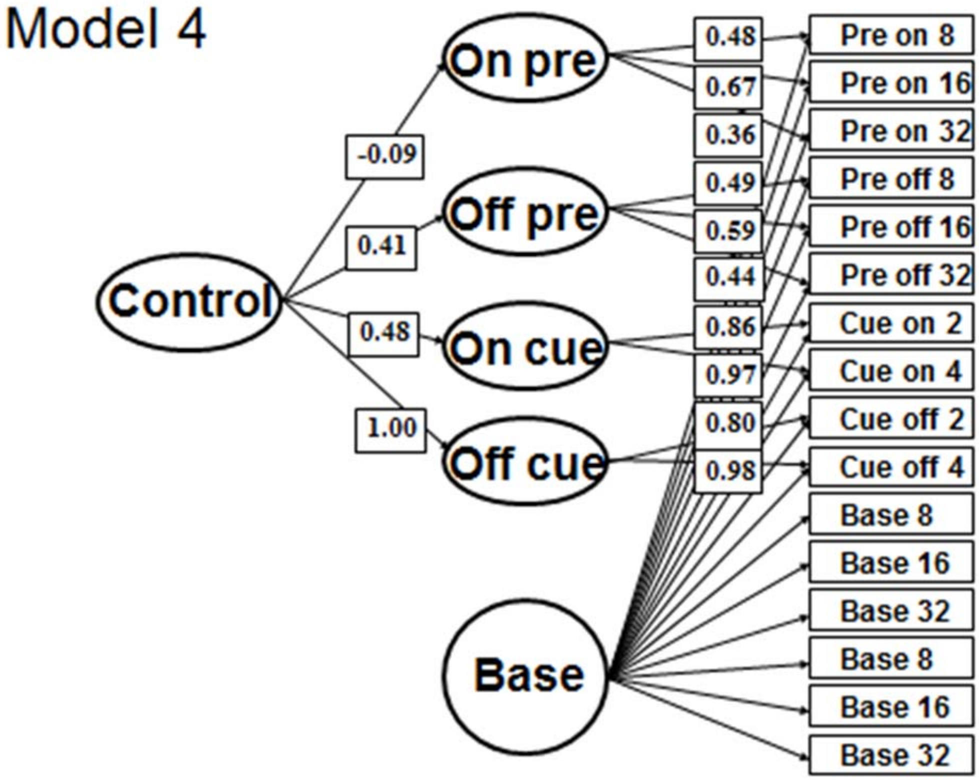

Figure 19

Path diagram for Model 5a investigating the relationship between WM and Control

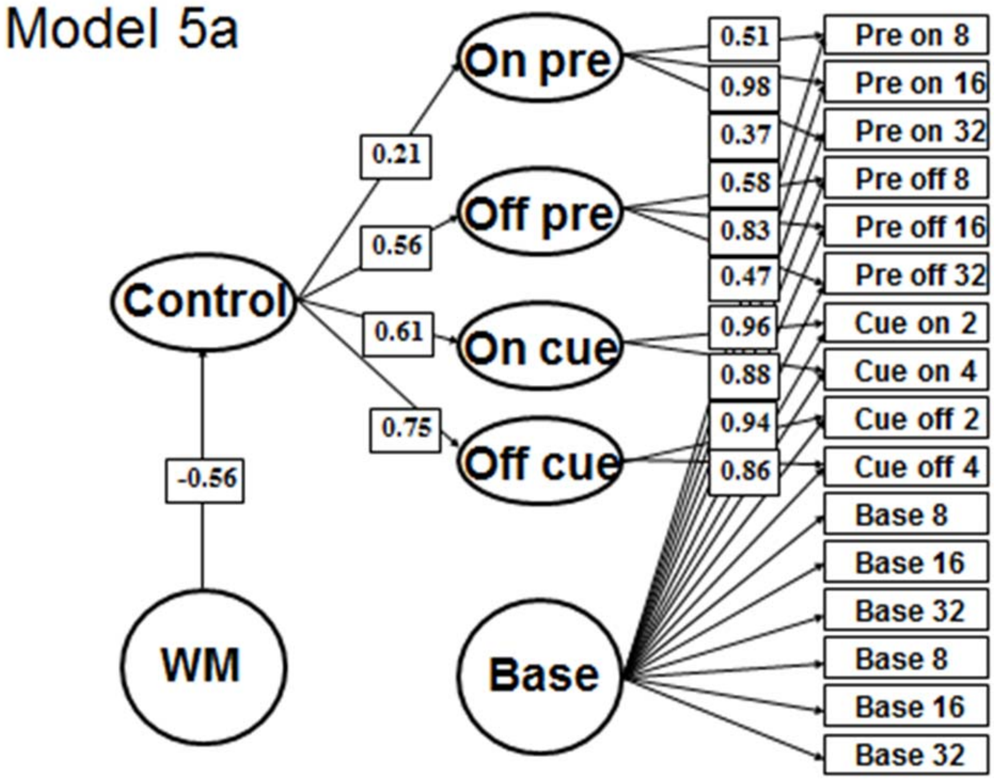

Figure 20

Path diagram for Model 5b investigating the relationship between WM and Control with Base loading onto WM

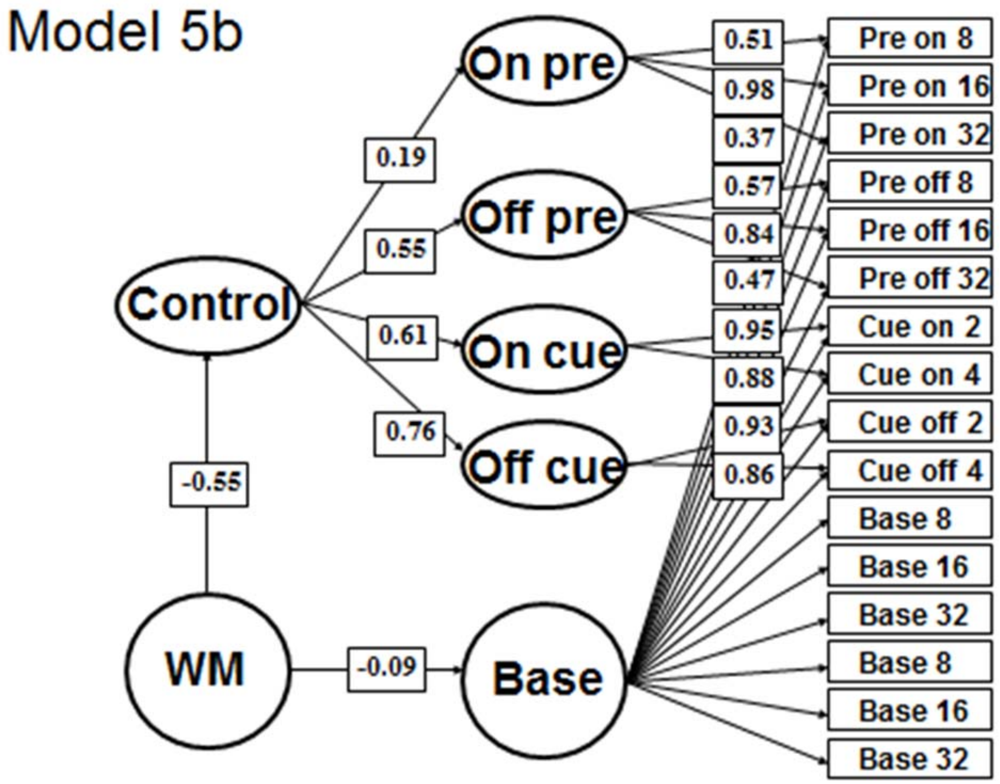

Figure 21

<u>Path diagram for Model 5c investigating the relationship between WM and Control without baseline search trials</u>