

Ocular and Attentional Pursuit Tracking in Visuo-Spatial Working Memory

by

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Abstract

Research shows that spatial memory span is selectively impaired by concurrent tasks that require spatially directed attention such as pursuit eye movements (Baddeley, 1986; Lawrence et al, 2001; Pearson & Sahraie, 2003; Postle et al., 2006). Despite this clear interference between *spatial* working memory and ocular control, an equivalent interference to *visual* working memory has never been carefully examined. In Experiment 1 (n=18), participants made either pursuit eye movements or equivalent shifts of attention during the retention of visual information. Visual working memory was disrupted by both conditions but eye movements produced a larger impairment. In Experiment 2 (n=12), a novel paradigm for investigating the effects of eye movements and shifts of attention on visuo-spatial encoding processes was used. Discrimination performance was better when visuo-spatial representations were encoded using attentional tracking than when encoded using eye movements. The results suggest that visual *and* spatial working memory encoding and maintenance processes are impaired by concurrent tasks that require spatial attention and ocular motor processing.

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1. Overview

Many researchers have hypothesized that a relationship exists between the ocular system and the processing of visual and spatial information in working memory (e.g., Baddeley, Grant, Wight, & Thomson, 1975; Baddeley & Lieberman, 1980; Logie & Pearson, 1997; Postle, Idzikowski, Sala, Logie, & Baddeley, 2006). Specifically, it has been suggested that the ocular system plays a role in establishing a spatial frame of reference used to support the processing of visual and spatial information in working memory. Given that spatial attention often coincides with visual fixations, the studies that have investigated the role of eye movements in visuo-spatial processing are often faced with the challenge of separating the effects of attention from the effects of the ocular system. Because attention can be dissociated from visual fixations, it is possible that both ocular movements and shifts in attention may be involved in processing and maintaining visuo-spatial information in working memory.

The objective of the present research was to investigate how the encoding and maintenance of visuo-spatial information in working memory is influenced by ocular movements and shifts in spatial attention. This document is organized as follows. First, a brief summary of the Baddeley (1986) multicomponent model of working memory is discussed. Second, research that has investigated the role of eye movements and shifts of attention on visuo-spatial information processing is reviewed and critiqued. Finally, two experiments are presented that investigated the role of eye movements and shifts of attention on visuo-spatial maintenance (Experiment 1) and encoding (Experiment 2).

2. Introduction

Working memory is a highly flexible cognitive system that is responsible for short-term manipulation and maintenance of information. The working memory system is assumed to involve at least two basic stages of processing. First, information is acquired by the system from either the environment, or retrieved from long term memory and *encoded* into a mental representation within the working memory system. Second, once the representation is in working memory, it is temporarily *maintained* to prevent decay of the memory trace (Baddeley, 1986; Logie, 1995). Based on these processing stages, Logie suggests that there are two basic requirements for a working memory system (Logie & Pearson, 1997; Logie, 1995): (a) a rehearsal-like mechanism that can refresh a mental representation when the source of the representation is no longer available in the environment, and (b) a storage mechanism to keep the representation in memory for a brief period of time in the absence of rehearsal. Although many alternative models of working memory exist (for a review of earlier models see Richardson, Engle, Hasher, & Logie, 1996), working memory is commonly conceptualized by Baddeley's (1986) multicomponent model which consists of three main components: the central executive, which acts as an executive control to two domain specific "slave" systems, the phonological loop and the visuo-spatial sketchpad. A brief summary of key characteristics of the phonological and visuo-spatial sketchpad are discussed in the following section. Given that the central executive mediates and coordinates attentional control to these two sub-systems, its role is discussed last.

2.1. The Phonological loop

The phonological loop is a memory system that specializes in the storage and temporary maintenance of phonological (auditory and vocal) information. The phonological loop is composed of two sub systems, the articulatory loop which is an active rehearsal mechanism, and the phonological store which is viewed as a temporary passive store. Both of these processes (i.e., rehearsal and storage) are forms of memory and are sometimes referred to as active storage and passive storage (Barrouillet & Camos, 2011; Lawrence, Myerson, & Abrams, 2004; Lawrence, Meyerson, Oonk & Abrams., 2001). Unfortunately, the distinction between active and passive storage is not maintained consistently in the literature. For example, other researchers (e.g., Pearson & Sahraie, 2003) describe active processes as requiring mental manipulation or transformation of information while reserving the term passive storage for rote rehearsal-based processes. In the context of this thesis, both information manipulation and rehearsal processes are considered active processes as it is generally accepted that both processes are performed intentionally by the individual and therefore require directed attention. Using this approach, a critical difference is made between working memory and short-term memory where working memory involves processes that “work” on information in the form of information manipulation or extended maintenance supported by rehearsal. Together, the articulatory loop and phonological store sub-systems are used to receive input from the environment or from long-term memory, encode the input into a phonological representation and maintain the representation for later use. Active maintenance in the articulatory loop is believed to be performed by a process akin to mentally repeating the

information, a process called sub-vocal rehearsal. Early evidence from Baddeley, Thomson and Buchanan (1975) showed that the serial memory span for a list of words is sensitive to word length such that the memory span is equivalent to the number of items than can be mentally articulated in approximately 2 seconds. This finding suggests that phonemically-based information is actively rehearsed in the phonological loop by mentally articulating its phonological structure and that the passive store has a retention limit of approximately 2 seconds before information is forgotten.

2.2. The Visuo-Spatial Sketchpad

The visuo-spatial sketchpad is a memory system that specializes in the temporary storage of visual and spatial information. Relative to the phonological loop, there has been very little research on the visuo-spatial sketchpad. One reason for this is because the visuo-spatial sketchpad research is complicated by the fact that it (purportedly) processes information from two different domains: visual and spatial. By comparison, research in phonological memory is easier because it only handles information from the phonological domain (Logie, 1995).

Unlike the phonological loop, which, from an early date, was subdivided into active (articulatory loop) and passive (phonological store) memory subsystem, the subsystems of Baddeley's (1986) visuo-spatial sketchpad were not described in detail until nearly 20 years later (Logie, 1995). Drawing an analogy to the phonological loop, Logie (1995) proposed that the sketchpad must also consist of an active and passive memory system, the inner scribe and visual cache, respectively. In Logie's (1995) model of visuo-spatial

working memory, spatial information is maintained actively in the inner scribe while visual information is stored passively in the cache. Logie and Pearson (1997) elaborated on the differentiation between spatial and visual information domains by arguing that the inner scribe is primarily responsible for the active maintenance and manipulation of location and movement sequence information (i.e., spatial information) while the visual cache is responsible for passively maintaining form and colour information (i.e., visual information). Logie and Pearson (1997) also hypothesized that spatial information is refreshed by rehearsal processes supported by eye movements. Indeed, many other researchers have considered the possibility that eye movements play an active role in establishing and maintaining a spatial frame of reference to which visuo-spatial representations are processed (Baddeley, Grant, Wight, & Thomson, 1975; Baddeley & Lieberman, 1980; Logie & Pearson, 1997; Postle, Idzikowski, Della Sala, Logie, Baddeley, 2006). In turn, the role of the inner scribe has, in some instances, been described as an “inner eye” that mentally retraces the spatial representation (e.g., Logie & Pearson, 1997).

A standard task used in visuo-spatial working memory research is pursuit tracking because it is assumed to demand processing resources. Tracking tasks are therefore often used in dual-task paradigms as a secondary task to interfere with a concurrent primary task. Tracking involves attending to a dynamic target and is assumed to require constant on-line updating of target information. That is, tracking is typically considered a *processing* task as it does not make explicit demands on memory. Pursuit tracking tasks

are operationalized in the visual domain by displaying a moving target on a computer screen and asking participants to follow the target.

One limitation of Logie's (1995) conceptualization of the inner scribe and the visual cache is that it does not adequately address the requirement that visual representations need to be actively maintained. Because the visual cache is characterized as a passive store, by definition it lacks the ability to actively rehearse information. By extension, visual information, which is purportedly only processed by the cache, would only be active for a short duration (seconds) before decaying. Contrary to this characterization, visual memories can be maintained for longer periods (upwards of 12 seconds) and are sensitive to concurrent tasks such as word reading (Postle, Desposito, & Corkin, 2005; Postle et al., 2006). Given that visual information can be maintained in working memory for longer than a few seconds and is subject to interference by concurrent tasks, it appears that visual information is actively maintained and that the system responsible for its maintenance shares processing capacity with other cognitive faculties in working memory.

To address the seemingly obvious requirement for active maintenance of visual information in the visuo-spatial sketchpad, Rudkin, Logie and Pearson (2007) proposed a more general role for the inner scribe that includes actively maintaining information from the spatial domain in addition to refreshing visual information in the cache. Although this revised model of visuo-spatial working memory allows for active rehearsal of spatial and visual information, it is inconsistent with findings that show that the maintenance of

visual memories are not disrupted by tasks that have been shown to interfere with the inner scribe, such as limb movement (Lawrence et al., 2001), eye movement (Postle et al., 2006) or shifts in attention (Pearson & Sahraie, 2003). If visual and spatial information are maintained by the same system (i.e., the inner scribe), then the maintenance of spatial and visual information should be equally disrupted by interference tasks affecting the inner scribe. These conflicting interpretations point to the possibility that visual information is actively maintained by something other than the inner scribe. Alternatively, the active processing and storage of visual information may be performed within the cache itself.

2.3. The Central Executive

The central executive has three primary functions: it manipulates and integrates information that is maintained by the phonological loop and the visuo-spatial sketchpad (i.e., manages dual task performance), selectively attends to certain information while ignoring other information (inhibition), and retrieves long term memories into the working memory system (Baddeley, 1996). Although this conceptualization of the central executive risks comparison to a homunculus – a criticism that Baddeley (1996) acknowledges – evidence from neuropsychology has shown that central executive processing, such as random generation, is temporally organized in the frontal cortex (Jahanshahi, Profice, Brown, Ridding, Dirnberger, Rothwell., 1998; Joppich, Däuper, Dengler, Johannes, Rodriguez-Fomells, Münte., 2004). Jahanshihi et al. (1998) reported that random number generation was impaired when the dorsolateral prefrontal cortex was

suppressed by transcranial stimulation. Similarly, Joppich et al. (2004) observed elevated temporal brain activity during random number generation compared to ordered number generation. Together, these findings support the existence of the executive by demonstrating a correlation between executive functioning and anatomical regions in the brain.

One of the roles of the central executive that is relevant to this thesis is inhibition. In the context of working memory research, inhibition processes are sometimes induced by forcing participants to generate random output. Given that true randomness lacks pattern or trend, one could imagine that the production of random behaviour requires very little effort or attention on behalf of the individual. Despite this logical assumption, random generation is difficult and is generally assumed to involve inhibitory processes that actively suppresses immediate repetition and stereotyped responses. For example, random generation has repeatedly been shown to impair executive processes such as dual-task performance and reasoning (Ang & Lee, 2010; Baddeley, Emslie, Kolodny, & Duncan, 1998; Rudkin et al., 2007). Baddeley et al. (1998) observed an increase in repeated verbal output and stereotyped verbal responses (e.g., the letter series A-B-C-D) when participants were asked to generate random verbal output at a fast pace compared to when the pace was reduced or self-moderated. This finding suggests that random generation involves an initial processing stage that generates output candidates based on recency and familiarity. Because participants were able to create more randomness when the pace of output generation was reduced or self-moderated, random generation is

believed to involve a secondary stage of processing which involves inhibition that actively suppresses immediate repetition and stereotyped responses.

2.4. Ocular movements and Visuo-Spatial Working Memory

It has been hypothesized that visuo-spatial working memory may share capacity with the ocular motor system as a means to maintain information. During the 1970's and 1980's, Idzikowski and colleagues investigated this relationship through a number of experiments (reported in Baddeley, 1986; see also Postle et al., 2006). Unfortunately, the majority of these experiments were never published and therefore the details of the studies were limited to their brief description in secondary sources. Recently however, three of Idzikowski and colleagues' key experiments were published in their original detail by Postle et al. (2006).

In the first experiment, participants were asked to perform a spatial matrix task while making involuntary eye movements. Involuntary eye movements were induced by spinning the participants in a rotating chair for a short duration which produced nystagmus (i.e., quick involuntary left- right eye movements). The spatial matrix task (Brooks, 1968) consisted of imagining a 4×4 grid and placing numbers (1 through 8) in the grid according a set of auditory instructions. The participants always started with a "1" in the same location and subsequent numbers were placed adjacent to the previous number such that the numbers and their locations could be remembered as a spatial path

through the grid. Participants were scored on their ability to recall the matrix. The results showed that involuntary eye movements did not interfere with the matrix task.

In the second experiment, participants performed the same spatial matrix task but also tracked a moving target on a computer screen using voluntary eye movements. That is, participants fixated on a moving target while performing the matrix task. Unlike *involuntary* eye movements, *voluntary* eye movements interfered with the matrix task.

Based on this finding, Postle et al. (2006) argued that spatial maintenance processes share capacity with ocular control systems. That is, the interference was not attributed to eye movements per se, but rather to the cognitive control processes used to generate them.

The third experiment was identical to the second except that participants performed the pursuit tracking task either during the presentation of the spatial instructions, or during recall, or during both presentation and recall. The results showed that spatial working memory was equally impaired in all conditions. The authors argued that if spatial acquisition and retrieval processes were affected separately by eye movements then the interference would be additive. Because impairments were not additive the authors concluded that eye movements were interfering with spatial maintenance processes alone and not with encoding or retrieval processes. The authors based this claim on the assumption that the acquisition and retrieval stages in their experimental task inevitably required maintenance-related processing because the spatial information was encoded sequentially (i.e., over a period of 9 seconds) and retrieved sequentially during the recall phase. In summary, these three studies show that the cognitive control processes that

generate pursuit eye movements share capacity with the spatial maintenance systems whereas involuntary ocular motor behaviour does not. In the original – albeit brief – discussion of these three experiments, Baddeley (1986) concluded that the results were consistent with the view that spatial working memory depends on an eye-movement based rehearsal mechanism to maintain spatial information.

Lawrence, Myerson, Ook and Abrams (2001) challenged the claim that the cognitive processes that control eye movements uniquely disrupt visuo-spatial working memory rather than the working memory system as a whole. Specifically, they argued that Idzikowski et al.'s findings (reported in Baddeley, 1986) did not address the possibility that eye movements disrupted working memory in general by interfering directly with central executive processing. If ocular control could be shown to interfere with both visuo-spatial and phonological working memory systems, then it could be argued that eye movements interfere at the level of the central executive, which, in turn, disrupts the both subsystems. In Lawrence et al. (2001), participants performed a spatial memory task and a phonological memory task coupled with an interference task involving ocular control. The spatial task was presented visually. Participants were required to remember the position of a series of X's presented sequentially in random locations within a 4×4 matrix. In the phonological task, they were required to remember a sequence of letters that were presented sequentially on a computer screen. Participants were tested on the recall of the non-word letter sequence. Immediately following the presentation of each individual item within the sequence (i.e., an "X" in the spatial task or a "letter" in the

phonological task), participants performed either a pro-saccade or anti-saccade to a peripheral cue. On pro-saccadic trials, participants made an immediate eye movement toward a visual cue that was flashed in their periphery. In anti-saccadic trials, participants would inhibit the saccade toward the visual cue and move their gaze in the opposite direction. Lawrence et al. (2001) argued that anti-saccades likely involved more executive functioning than pro-saccades since anti-saccades required additional processing to inhibit the reflexive saccade toward the peripheral cue. The results showed that visuo-spatial memory was disrupted by saccadic eye movements but not by anti-saccades whereas phonological memory was unaffected by either type of eye movement. Using a similar paradigm in a second experiment, Lawrence et al. (2001) reported that limb movements produced equivalent disruptions to spatial memory as the pro-saccades. Based on these findings, the authors concluded that eye and limb movements interfered with spatial maintenance by consuming spatially directed attentional resources. By extension, Lawrence et al. (2001) proposed that spatial maintenance processes require the allocation of spatial attention.

In a series of experiments, Pearson and Sahraie (2003) further examined Lawrence et al.'s (2001) conclusion that all spatially directed attention produces equivalent interference in spatial working memory. Participants performed a modified Corsi task (De Renzi & Nichelli, 1975) where a set of unfilled shapes were sequentially filled-in on the screen. Participant's memory of the spatial sequence was tested after a retention phase in which they performed a visual pursuit tracking task. One difference between Pearson

and Sahraie's (2003) and Lawrence et al.'s (2001) methodologies is that Pearson and Sahraie's intervening task was performed after the entire spatial sequence was presented. This paradigm enabled the authors to attribute all intervening task effects to the maintenance of visuo-spatial information. By comparison, the intervening task in Lawrence et al. (2001) was performed following the presentation of each individual component of the spatial sequence. Thus, the interference effects could not be solely attributed to maintenance processes as they could have also affected the encoding phase proceeding stimuli. A second key difference between Pearson and Sahraie (2003) and Lawrence et al. (2001) was that Pearson and Sahraie asked participants to track the target using two different strategies; eye-based tracking and attentional-based tracking.

Attentional tracking is the ability to dissociate attentional fixation from visual fixation. In fact, it has been shown that multiple targets can be tracked simultaneously (e.g., Anderson, Ester, Serences, & Awh, 2013; Franconeri, Jonathan, & Scimeca, 2010; Pylyshyn & Storm, 1988) and is generally assumed to either involve switching attentional focus from one target to another or averaging attentional fixation between the targets. The ability to independently shift attention away from eye movements has been described using a spotlight metaphor of attention where processing is facilitated for up to four items that fall within the focal range of the spotlight (e.g., Jonides & Irwin, 1981; Jonides, 1980; Posner, 1980; Pylyshyn & Storm, 1988).

In one condition, Pearson and Sahraie (2003) asked participants to track a moving target with visual fixations (i.e., eye-based tracking). In another condition, participants tracked

the same target while keeping their eyes and head still (i.e., attentional-based tracking). That is, participants diverted their attention away from their visual fixation to track the target. Although the results showed that eye movements and attentional shifts disrupted the maintenance of spatial memory, the results were inconsistent with Lawrence et al.'s (2001) hypothesis that all spatially directed attention disrupts spatial working memory. In Pearson and Sahraie (2003), eye movements produced a significantly *larger* effect on spatial maintenance than were produced by equivalent shifts in attention. A follow-up experiment tested the possibility that the additional impairments to spatial working memory observed in the eye movement condition could be attributed to changes in retinal image caused by eye movements by repeating the experiment but having participants make eye movements either with their eyes open or shut. The results showed that working memory was equally impaired in the eyes open and eyes shut condition which ruled out the possibility that the effects observed in the first experiment were due to any masking-related effect caused by the changes in the retinal image during eye movements .

Pearson and Sahraie (2003) concluded that visual tracking interferes with spatial working memory in two phases. First, eye-based and attentional-based tracking both require a component of spatial attention, which taxes the working memory system. Subsequently, the interference caused by the attentional component of tracking disrupts the maintenance of spatial information. Second, an additional processing demand is imposed on the spatial working memory system by intentional ocular behaviour. Moreover, this additional impact of ocular behaviour appears to be unrelated to any effect attributed to the change

in retinal image during eye movements. That is, the cognitive processing cost related to generating pursuit ocular movements adds an additional processing load to the processing cost related to maintaining attentional fixation. In summary, the authors claimed that Lawrence et al.'s (2001) conclusion – that all spatially directed attention produces equal interference in working memory – was incomplete as it did not account for the differential effects of pursuit eye movements and shifts of attention on the maintenance of spatial information. Taken together, Lawrence et al.'s and Pearson and Sahraie's findings show that the maintenance of *spatial* information requires processing by systems that share capacity with systems responsible for the *control* of pursuit ocular behaviour. What is less clear is whether or not similar impairments caused by ocular motor activity exist for *visual* information processing.

Recall, in their first three experiments, Postle et al. (2006) showed that the control for ocular movements interfered with the maintenance of spatial information. In their fourth experiment, Postle et al. addressed the possibility that the interference caused by eye movements in their first three experiments would extend to visual working memory. The experiment used a delayed recognition task where a target shape was briefly displayed and then removed for a 12-second maintenance interval, after which a test shape was shown. Participants remembered either the visual characteristics (visual memory) or spatial location (spatial memory) of the target shape. During the test phase, participants indicated whether the tests shape contained a visual or spatial change by indicating *same* or *different*. On visual memory trials that contained a change, the foil shape was based on

its associated target but contained a modification of one of its salient features by adjusting several of its vertices. On spatial trials that contained a change, the test shape was identical to the target but changed location. Both conditions were equated for difficulty. During the 12-second maintenance interval, participants performed an interference task. In one condition, participants were instructed to make random eye movements while in another condition, participants silently read a series of words presented on the screen. Memory for object location was disrupted by eye movements, but not by word reading. Conversely, memory for object shape was disrupted by word reading but not by eye movements. Postle et al. concluded that this double dissociation shows that the control of eye movements selectively interferes with the maintenance of spatial information but not visual information.

In summary, it is fairly clear that the maintenance of *spatial* information is disrupted by concurrent tasks that require spatial attention and ocular control. What is less clear is whether or not the maintenance of *visual* information is also vulnerable to the same interference. Even though Postle et al. (2006) reported a null effect of eye movements on visual maintenance processes, it is important to note that this finding was observed in an experiment that used randomly generated eye movements. Therefore, the effects of eye movements using a *pursuit* (i.e., non-random) tracking task on visual working memory capacity has not been systematically investigated.

3. Present Research

The objective of the present research is to investigate to what extent spatially directed attention and ocular movement affect the visuo-spatial (i.e., visual *and* spatial) working memory system. Previous research has shown that pursuit eye movement control disrupts spatial maintenance processes (Lawrence et al., 2004; Postle et al., 2006) however only one study (Postle et al., 2006) has examined whether similar effects are observed with the maintenance of visual information. Critically, no research has investigated the role of pursuit eye movements on visual maintenance processes. The present thesis therefore investigates the possibility that pursuit eye movements may share processing capacity with the subsystems responsible for the maintenance of visual information within the visuo-spatial sketchpad.

4. Experiment 1

4.1. Participants

Nineteen Carleton University undergraduate/graduate students participated. Fifteen participants were recruited using Carleton University's online experiment sign-up system and received 1% course credit for their participation. The remaining participants were colleagues of the experimenter and participated on a voluntary basis. All participants were assumed to have normal or corrected-to-normal visual acuity.

4.2. Design

A 3 (Tracking Condition: No Tracking vs. Eye Tracking vs. Attentional Tracking) \times 2 (Discriminability: Easy vs. Hard) repeated measures design was used. Tracking Condition was a blocked factor whereas shape Discriminability was mixed. All factors were completely crossed with each level within each factor being sampled an equal number of times. Tracking Condition was counterbalanced across participants using a Latin-Square design such that the three conditions occurred in each position an equal number of times.

4.3. Apparatus

Visual information was displayed on a 24 inch (1920 \times 1200) LCD colour monitor slaved to a PC - computer (2.67 GHz processor, ATI Radeon HD 4800 Series Graphics, 6.0 G memory). Responses were made on a wired Xbox 360 gamepad controller by pressing the left bumper for *Same* responses and the right bumper for *Different* responses. The

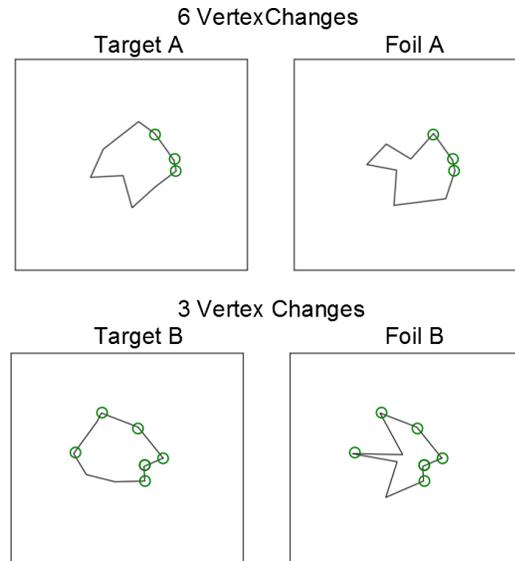
experiment was coded in Psychopy (Pierce, 2007), which is an open-source software application written in python programming language and is specifically designed for psychological experiments with critical timing.

4.4. Stimuli

All visual stimuli were white on a black background. A fixation cross appeared in the center for the display and subtended a visual angle of 0.76° vertically and horizontally. The Eye Tacking and Attentional Tracking conditions consisted of a pursuit tracking task in which participants tracked a small circle as it moved on the screen. The movement of the circle appeared to be random but was determined by the product of two cosine waves and moved at an average velocity of $2.2^\circ/\text{s}$. The movement of the circle was limited to 10° of visual angle both horizontally and vertically which approximated the dimension of the visual shapes.

The target and foil shapes were 120 unique 9-sided polygons that subtended an average visual angle of approximately 10° horizontally and vertically. The shapes were automatically generated by a computer program that divided the area of a circle (through the origin) into 9 equal “slices” and assigned a random coordinate within that slice to a vertex of the polygon. Each target shape had an associated foil shape that differed by randomly changing the location of vertices. Half of the target foil pairs differed by 3 vertices (i.e., 6 vertices remained the same) while the other half of the target/foil pairs differed by 6 vertices (i.e., 3 vertices remained the same) (Figure 1).

Figure 1. Examples of the target/foil shapes. Shapes could differ by either 6 or 3 vertices. Circles indicate common vertices between stimuli pairs.



Due to the automaticity of the target/foil shape generation program, some target/foil pairs were inevitably and obviously more discriminable than others. The level of discriminability of the target/foil pairs was subjectively evaluated a priori by the experimenter and binned into either Easy or Hard discriminability groups of 60 target-foil pairs each. The categorization of stimuli was determined by the qualitative similarity between the target and foil shapes. Target and foils that contained large (obvious) visual differences were categorized as Easy whereas stimuli pairs that differed by small (subtle) visual differences were categorized as Hard. The categorization of Easy and Hard created two groups of equal number Easy and Hard stimuli. Examples of easy and hard target/foil pairs are shown in Appendix A.

Critically, shape *discriminability* should not be confused with shape *complexity* since all shapes were assumed to be equally complex since they all contained 9 vertices and were generated by the same algorithm. Rather, shape discriminability refers to the degree of similarity between the target and associated foil shape.

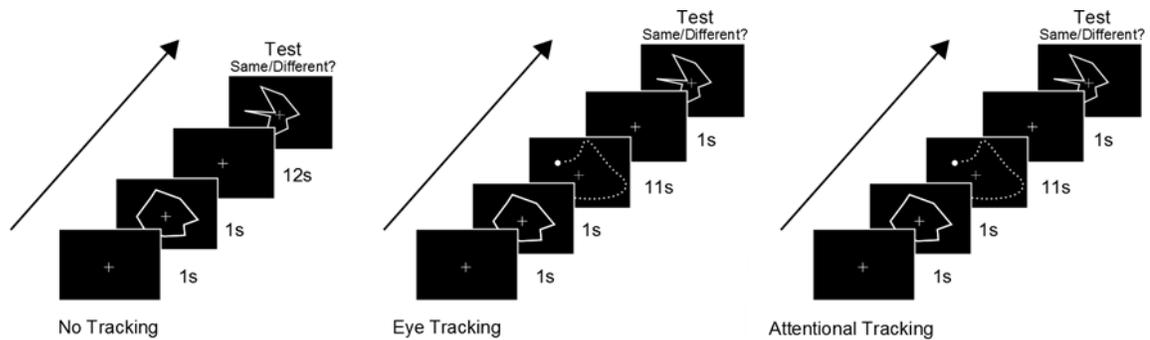
4.5. Procedure

In all three Tracking Conditions, participants were required to perform a delayed recognition task in which a test shape was either the same as or different from the target shape. Each Tracking Condition consisted of 40 trials with an equal number of No Change/Change trials using equal number of Easy/Hard stimuli. Participants were instructed to respond as quickly and as accurately as possible. Prior to the experimental trials, participants completed 4 practice trials from each tracking condition. None of the stimuli used in the practice trials were repeated in the experimental trials.

A fixation cross appeared at the beginning of each trial for 1 s. The fixation cross was replaced by a target shape, which was shown for 1 s followed by a 12-second retention interval. In the No Tracking condition, participants fixated on a stationary cross that was centered on the screen during the retention interval. In the Eye Tracking and Attentional Tracking conditions, participants performed an 11-second pursuit tracking task and then fixated on a stationary cross for 1 s during the retention interval. The test shape was displayed immediately after the retention interval and remained on the screen until participants made a same/different response. Trial sequences for each Tracking Condition are shown in Figure 2.

In the Eye Tracking condition, participants were instructed to track the circle by following it using eye movements while keeping their head still. In the Attentional Tracking condition, participants were instructed to fixate on a stationary cross in the center of the display while keeping their head still but to attend to the moving circle by shifting their attention away from visual fixation. Tracking instructions were displayed at the beginning of each Tracking Condition block to remind participants of their retention interval task.

Figure 2. Experiment 1 Trial Sequences



4.6. Results

The data from one participant were removed because they did not understand the task instructions and made improper responses throughout the experiment. RT outliers were identified using an outlier labelling technique described by Tukey and colleagues (Hoaglin, Iglewicz, & Tukey, 1986; Tukey, 1977) where trials with RTs that exceeded the 75th percentile plus 2.2 times the interquartile range of each tracking condition were

removed. Additionally, responses that were less than 250 ms were omitted as “fast guesses.” This resulted in a combined elimination of 4.7% of the data.

The remaining data were analyzed based on whether the test shape was the same or different from the target (Change vs. No Change). Data from Change trials were submitted to a 3 (Tracking Condition: No Tracking vs. Eye Tracking vs. Attentional Tracking) \times 2 (Discriminability: Easy vs. Hard) Analysis of Variance (ANOVA). Given that Discriminability was not manipulated on the No Change trials (the target and test shapes were identical), these data were submitted to a one-way ANOVA with three levels (Tracking Condition: No Change vs. Eye Tracking vs. Attentional Tracking). In all cases, Mauchly’s test indicated that the assumption of sphericity was met, thus the degrees of freedom were not adjusted. Post-hoc analyses were conducted using Jarmasz and Hollands’ (2009) 95% confidence intervals (CI), which were computed using MorePower6.0 (Campbell & Thompson, 2012). Means that differ by more than one half of the CI multiplied by $\sqrt{2}$ are significant and can be compared visually using the rule of thumb that if CIs overlap by less than one quarter of the entire interval, then the difference is significant.

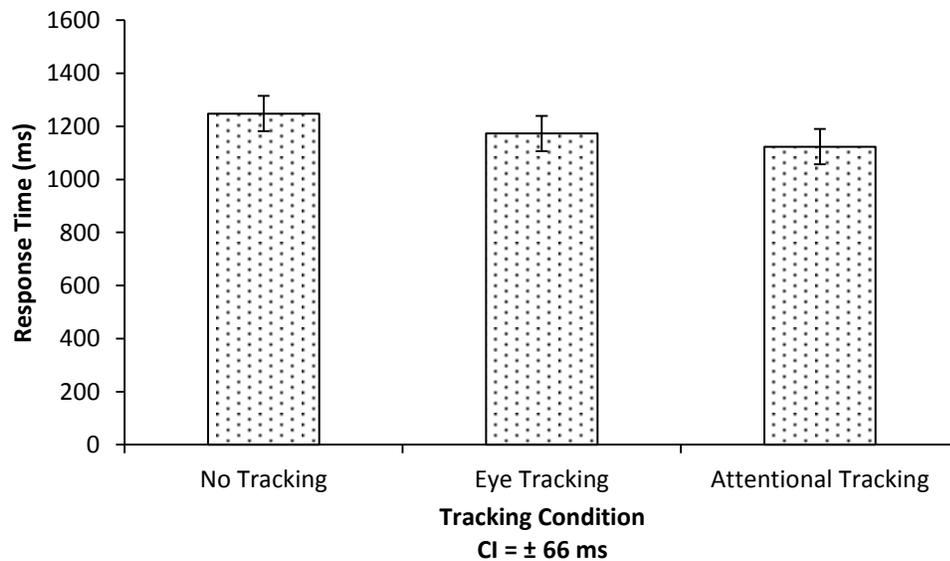
4.6.1. Change Trials

4.6.1.1. Response Time Analysis

Only RTs for correct responses were analyzed. Mean RTs for each tracking condition were aggregated by participant and submitted to the ANOVA for Change trials. There

was a significant main effect of Tracking Condition, $F(2, 34) = 3.692, p < .035$, $\eta_p^2 = .178$, $MSE = 38679.88$. RT means that differed by more than 93 ms ($66 \text{ ms} \times \sqrt{2}$) were statistically significant. As shown in Figure 3, RTs in the Attentional Tracking condition (1123 ms) were faster than in the No Tracking conditions (1248 ms). RTs in the Eye Tracking condition (1173 ms) were statistically equivalent to the other conditions. There was a main effect of Discriminability, $F(1,17) = 10.805, p < .004, \eta_p^2 = .389$, $MSE = 54764.28$ where RTs for Hard discriminations (1255 ms) were longer than for Easy discriminations (1107 ms) . The Tracking Condition x Discriminability interaction was not significant, $F < 1$.

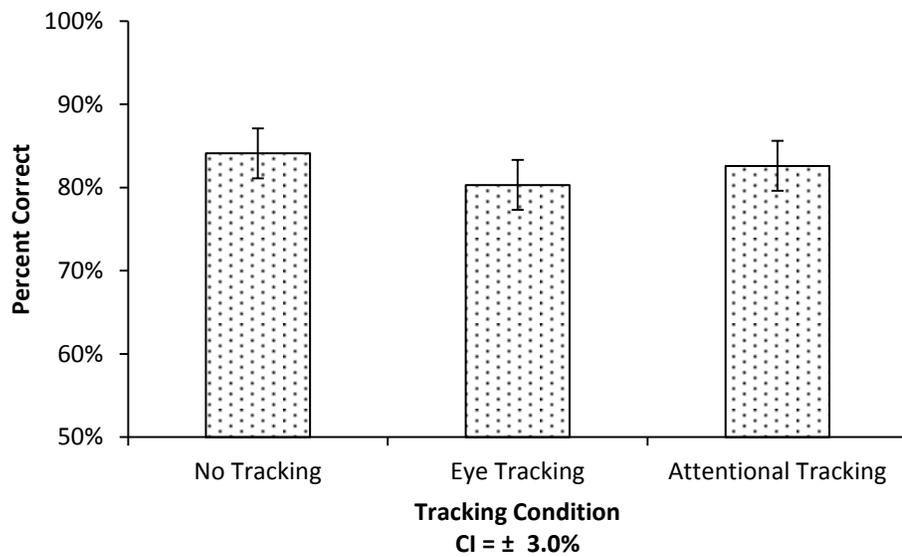
Figure 3. E1 Mean Response Times (ms) and 95% CIs for Change Trials as a Function of Tracking Condition.



4.6.1.2. Accuracy Analysis

There was no main effect of Tracking Condition, $F(2, 34) = 1.647$, $p < .208$, $\eta_p^2 = .008$, $MSE = .008$. Figure 4 shows that mean accuracy scores (~82%) were approximately equal across all conditions.

Figure 4 E1 Mean Accuracy (% Correct) and 95% CIs in Change Trials as a Function of Tracking Condition.



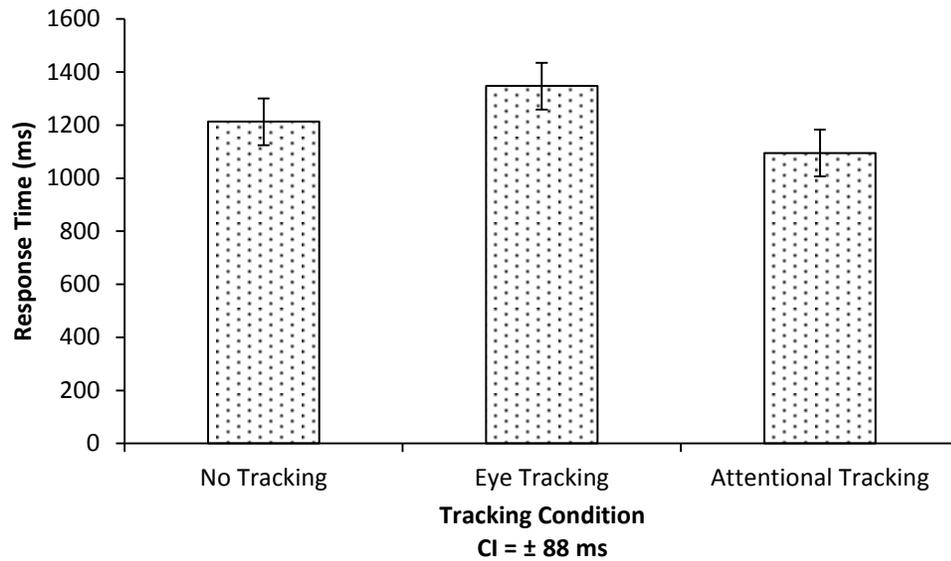
There was a significant main effect of Discriminability, $F(1, 17) = 81.406$, $p < .001$, $\eta_p^2 = .827$, $MSE = 0.018$. Responses were more accurate for Easy discriminations (93.9%) than for Hard discriminations (70.7%). There was no significant Tracking Condition \times Discriminability interaction, $F < 1$.

4.6.2. No Change Trials

4.6.2.1. Response Time Analysis

Only RTs for correct responses were analyzed. Mean RTs for each tracking condition were aggregated by participant and submitted to the ANOVA for No Change trials. There was a main effect of Tracking Condition, $F(2, 34) = 8.45, p < .001, \eta_p^2 = .332$, $MSE = 33958.39$. As shown in Figure 5, responses in the Attentional Tracking condition (1094 ms) were faster than responses in the Eye Tracking (1347 ms) condition. The difference between the Attentional Tracking condition and No Tracking condition (1213 ms) was not significant.

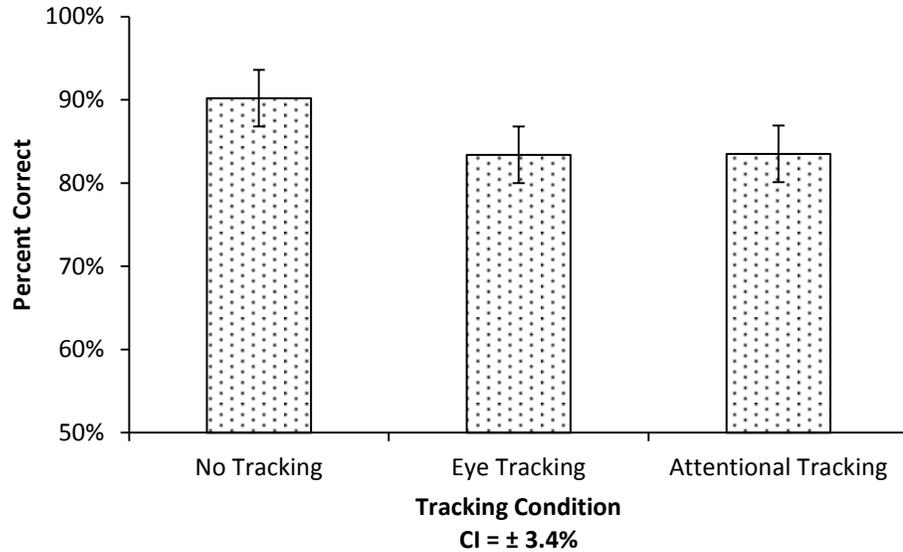
Figure 5. E1 Mean RT (ms) and 95% CIs on No Change Trials as a Function of Tracking Condition



4.6.2.2. Accuracy Analysis

There was a significant main effect of Tracking, $F(2, 34) = 5.685, p < .007, \eta_p^2 = .251$, $MSE = .005$. As is shown in Figure 7, responses were more accurate in the No Tracking condition (90.2%) than in the Eye Tracking (83.4%) and Attentional Tracking (83.5%) conditions. The difference between the Attentional Tracking condition and Eye Tracking condition was not significant.

Figure 6. E1 Mean Accuracy (% Correct) and 95% CIs on No Change Trials as a Function of Tracking Condition



4.7. Discussion

The two main findings from Experiment 1 were that (1) relative to no tracking, eye-based and attentional-based pursuit tracking disrupted visual maintenance and (2) eye-based tracking produced larger impairments than attention-based tracking. Under the assumption that the visual maintenance task in Experiment 1 required the activation of visuo-spatial working memory, the finding that pursuit tracking interfered with the maintenance of visual information is consistent with the claim that visual pursuit tracking is a function of visuo-spatial working memory. By extension, the on-line processes required for pursuit tracking must therefore compete for the same resources as the processes used to maintain visual information. In the context of domain-specific models

of working memory (e.g., Baddeley's (1986) multicomponent model of working memory), the current findings show that visual pursuit tracking involves the visuo-spatial sketchpad.

The finding that visual pursuit tracking disrupted the maintenance of visual information stands in contrast to Postle et al. (2006), who, using a nearly identical experimental design, showed that random eye movements did *not* disrupt visual maintenance. In particular, the effect of pursuit tracking on visual maintenance processes highlights that there is a difference between the systems responsible for pursuit tracking (present experiment) and those used for the random generation of eye movements (Postle et al., 2006). Specifically, the systems responsible for pursuit tracking appear to interfere with visuo-spatial working memory whereas the systems responsible for generating random eye movements do not. Given that the present experiment showed that visual maintenance is disrupted by eye-based tracking and, to a lesser degree, by attention-based tracking, it follows that Postle et al.'s null effect of ocular motor activity on visual maintenance processing may be limited to random eye movements. It is proposed here that Postle et al. may not have observed any effect of eye movements on the maintenance of visual information because their random eye movement task selectively taxed the central executive, which is responsible for generating random outputs (e.g., Baddeley, Emslie, Kolodny & Duncan, 1998; Towse, 1998). In contrast, the pursuit tracking task used here is more likely to be performed in the same visuo-spatial subsystems used to maintain visual information, and therefore produced an interference effect.

Experiment 1 also showed that eye tracking impaired the maintenance of visual information more than attentional tracking. Although the accuracy scores for these two conditions were similar on No Change trials, RTs in the Eye Tracking condition were 170 ms longer than in the Attentional Tracking condition. This finding is consistent with Pearson and Sahraie (2003), who reported a similar impairment for *spatial* information. Specifically, these authors reported that spatial memory span was disrupted by eye-based and attention-based pursuit tracking but that eye-based tracking produced larger impairments. Pearson and Sahraie argued that this difference was due to the interference produced by the ocular motor systems associated with eye-based pursuit tracking. The results of the present experiment extend Pearson and Sahraie's findings to the *visual* domain.

Since the No Tracking condition did not include an intervening tracking task, it was expected that this single-task condition would yield better performance than the (dual-task) eye-tracking and attentional-tracking conditions. The finding that (on Change trials) RTs in the No Tracking condition were significantly (125 ms) *longer* than in the Attentional Tracking condition and statistically equal to the RTs in the Eye Tracking condition do not support this seemingly obvious prediction. This effect was also observed on the No Change trials to a lesser (non-significant) extent. Upon reviewing the experimental method, it was realized that the inflated RT's in the No Tracking condition may have been caused by participants not being able to anticipate the onset of the test display. That is, the test display in the No Tracking condition appeared following a 12 s

retention interval during which participants fixated on a stationary point. Critically, there was no indication to cue the participants to the upcoming presentation of the test display. By comparison, the 12 s retention interval in the Eye Tracking and Attentional Tracking conditions consisted of an 11 s tracking task followed by a 1 s interval between the end of the tracking task and the presentation of the test display. This 1 s interval was included to allow participants to return their gaze to the center of the screen but may also have unintentionally provided a temporal cue for the upcoming test display. For this reason, the RTs in the No Tracking condition should be interpreted with caution, especially when comparing this condition with the two tracking conditions. Fortunately, this potential issue does not compromise the comparisons that can be made between the Eye Tracking and Attentional Tracking conditions.

The results of this experiment have several additional implications. First, this experiment extends previous work on the effects of eye-based pursuit tracking on the maintenance of spatial information (e.g., Pearson & Sahraie, 2003; Postle et al., 2006) by showing that the maintenance of *visual* information is also disrupted by processes associated with pursuit ocular motor components. Second, the differences between the current findings and those reported by Postle et al. (2006) highlight an important distinction between the working memory subsystems that support pursuit eye tracking (visuo-spatial working memory) and those that support random eye movements (the central executive). By extension, the combined results of the present experiment and those reported by Pearson and Sahraie (2003) and Postle et al. (2006) show that the memory subsystems that are

responsible for the active maintenance of visual and/or spatial information in working memory share capacity with those used for pursuit tracking and that the generation of ocular motor commands adds an additional cognitive cost to this process.

The purpose of Experiment 1 was to determine whether or not eye and/or attentional tracking interfered with the *maintenance* of visuo-spatial information in working memory. The purpose of Experiment 2 is to extend these findings by examining the effects of eye and attentional tracking on the *encoding* of visuo-spatial information. The relationship between pursuit eye movements and spatial encoding was investigated by Postle et al. (2006) who showed that pursuit tracking interfered with spatial memory span. For this purposes of this thesis, it is important to note that Postle et al.'s experiment required participants to generate a spatial representation of information that was presented acoustically. Postle et al.'s task was therefore not purely visuo-spatial in that it likely shared some of the encoding processing demands with the phonological loop. Experiment 2 addressed this issue by using a novel visuo-spatial task that ensured that the entire memory task (i.e., encoding and maintenance) did not involve the phonological loop. That is, Experiment 2 used a memory task that required the concurrent encoding and storage of purely visuo-spatial information.

5. Experiment 2

The unique challenge faced in Experiment 2 was designing a visuo-spatial memory task that could support eye movements during the encoding of spatial information. If spatial stimuli were to be presented visually, then participants would need to encode the stimuli while making eye movements. In order to satisfy this requirement, a novel visuo-spatial memory task was developed that required participants to track a moving visual target on the screen and remember the shape of the “drawn” path. Experiment 2 is similar to an experiment reported by Postle et al. (2006) with the exception that the present working memory task is purely visual. In Postle et al.’s experiment, participants formed a visuo-spatial representation of a Brooks matrix by processing acoustically presented stimuli. Here, participants built a visual representation of an object by tracking a visual stimulus (cursor), either by moving their eyes or by shifting their attention.

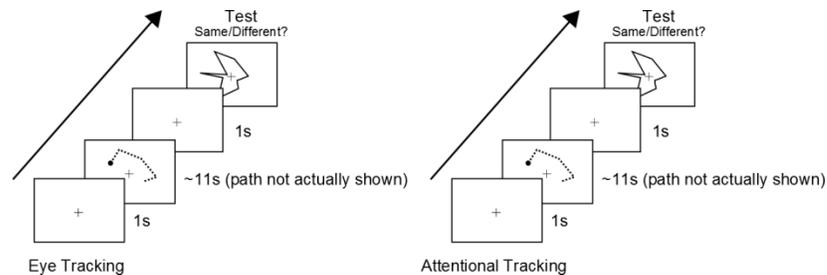
5.1. Participants

Twelve Carleton University undergraduate/graduate students participated. One participant was recruited using Carleton University’s online experiment sign-up system and received 1% course credit for their participation. The remaining participants were colleagues of the experimenter and participated on a voluntary basis. All participants were assumed to have normal or corrected-to-normal visual acuity.

5.2. Procedure

The procedure was identical to Experiment 1, except for the following: Instead of the target shape being displayed as a whole, the perimeter of the shape was traced by having a cursor follow its (invisible) outline at a constant speed of approximately $2.2^\circ/\text{s}$. The time required to outline the target shape averaged 11 s but varied slightly between shapes due to differences in shape perimeter length. In the Eye Tracking condition, participants tracked the moving cursor using eye movements. In the Attentional Tracking condition, participants fixated on a stationary cross in the center of the display and tracked the cursor by shifting attention away from their gaze. In both conditions participants were asked to remember the outline of the shape being traced and to decide whether the test shape was the same or different from the outlined (target) shape. The trial sequence is shown in Figure 7.

Figure 7. Experiment 2 Trial Sequences



5.3. Stimuli

The stimuli in Experiment 2 were identical to those in Experiment 1 with the exception that the (invisible) outline of the target shapes were traced in Experiment 2 rather than

being displayed as a whole as they were in Experiment 1. A common strategy reported by participants during the pilot phase of this experiment was to only remember the first and last segments of the shape (and ignore the middle segments) under the assumption that one of those two segments would be different in the (foil) test shape. To discourage this strategy, the first and last segments of all target shapes were always identical to those segments in their corresponding target shape. In other words, the difference between a target shape and its associated (foil) test shape *always* occurred in the middle segments. Participants were not informed of this constraint.

5.4. Results

Outliers were identified using the same techniques as Experiment 1, which resulted in an elimination of 3.8% of the data. The remaining data were analyzed using the same ANOVA design as Experiment 1, except that Tracking Condition was reduced to two levels (the No Tracking condition was removed). Change trials were submitted to a 2 (Tracking Condition: Eye Tracking vs. Attentional Tracking) \times 2 (Discriminability: Easy vs. Hard) ANOVA whereas No Change trials were analyzed using a paired samples t-test (Tracking Condition: Eye Tracking vs. Attentional Tracking).

5.4.1. Change Trials

5.4.1.1. Response Time Analysis

Only RTs for correct responses were analyzed. Mean RTs for each tracking condition were aggregated by participant and submitted to the aforementioned ANOVA. There was

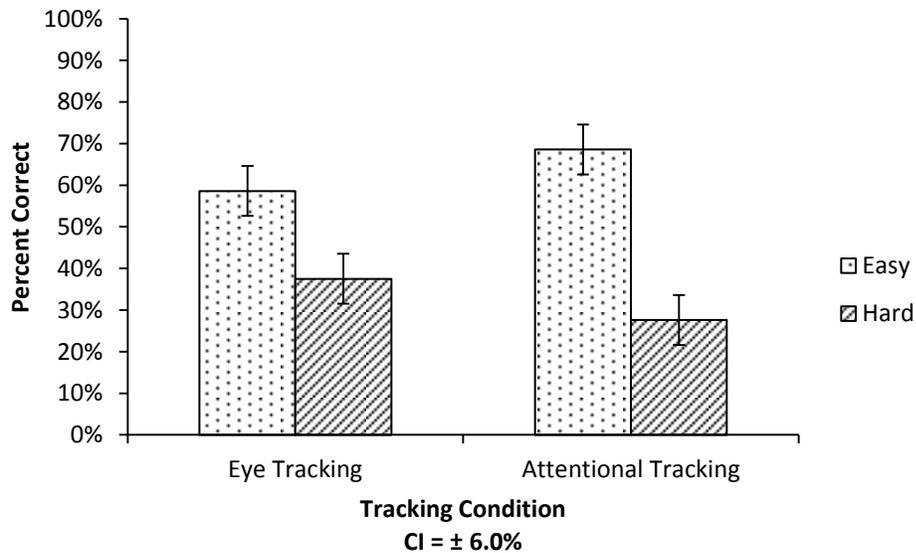
no main effect of Tracking Condition ($F < 1$). RTs were statistically equivalent between the Eye Tracking (1851 ms) and Attentional Tracking (1916 ms) conditions. Although RTs were longer for Hard discriminations (2055 ms) than for Easy discriminations (1711 ms), this difference failed to reach significance $F(1, 11) = 3.046, p < .109, \eta_p^2 = .217, \text{MSE} = .466204$. There was no Tracking Condition \times Discriminability interaction ($F < 1$).

5.4.1.2. Accuracy Analysis

There was no main effect of Tracking Condition ($F < 1$) with overall accuracy (collapsed across Discriminability) in both the Eye Tracking and Attentional Tracking conditions at 48%. The main effect of Discriminability was significant, $F(1, 11) = 33.033, p < .001, \eta_p^2 = .750, \text{MSE} = .035$, with higher accuracy for Easy discriminations (63.6%) than for Hard discriminations (32.6%). In fact, the results indicated that participants were consistently judging Hard foils as “*Same*” since performance for hard trials was below 50%. This finding shows that the visuo-spatial representations lacked the level of detail required to make detailed discriminations between similar shapes. The Tracking Condition \times Discriminability interaction was significant, $F(1, 11) = 12.795, p < .004, \eta_p^2 = .538, \text{MSE} = .009$. As shown in Figure 8, this interaction is driven by the relatively large difference between Easy and Hard trials in the Attentional Tracking condition (41%) compared to the difference between Easy and Hard trials in the Eye Tracking condition (21%). In fact, large differences (Easy condition) were easier to detect in the Attentional Tracking condition than in the Eye Tracking condition whereas small

differences (Hard condition) were easier to detect in the Eye Tracking condition than in the Attentional tracking condition.

Figure 8. E2 Mean Accuracy (%) and 95% CIs on Change Trials by Tracking Condition and Discriminability



5.4.2. No Change Trials

5.4.2.1. Response Time Analysis

Only RTs for correct responses were analyzed. Mean RTs for each tracking condition were aggregated by participant and submitted to a paired samples t-test. There was no difference between the Eye Tracking and Attentional Tracking conditions ($t < 1$). Mean RTs in both conditions were identical (1570 ms).

5.4.2.2. Accuracy Analysis

Mean accuracy scores for each tracking condition were aggregated by participant and submitted to a paired samples t-test. There was no difference between response accuracy in the Eye Tracking (84.6%) and Attentional Tracking (85.1%) conditions ($t < 1$).

5.5. Discussion

Experiment 2 shows that ocular behaviour affects visuo-spatial encoding processes. The interaction between discriminability and tracking condition showed that visuo-spatial representations were better suited for discrimination between large differences when they were encoded while eye movements were inhibited but were lacked the detail necessary to discriminate between small differences when eye movements were produced. Indeed, 68% of large changes (i.e., Easy condition) were detected in the Attentional Tracking condition compared to 58% in the Eye Tracking condition. At face value, this finding is inconsistent with the view that maintaining visual fixation on an object will always produce a superior representation in visuo-spatial working memory. The results from the present experiment are more consistent with the view that there is a trade-off between the ability to detect large and small changes and that this ability depends on what type of tracking strategy (eye-based vs. attention-based) is used.

The opposite also appears to be true for small changes. Small changes (i.e., Hard condition) were detected 38% of the time in the Eye Tracking condition compared to 27% of the time in the Attentional Tracking condition. The interpretation of the Hard

shape data, however, should be considered carefully since performance was below 50% which showed a strong bias for “same” responses.

One of the goals of the present research was to develop a new paradigm for investigating visuo-spatial working memory. The low performance on the Hard trials indicates that the present paradigm for investigating pursuit eye movements with visuo-spatial encoding processes is very difficult. Considering that the same stimuli were used in both experiments, it was surprising to observe such large decreases in performance. As is expected with novel paradigms there were some “lessons learned” that should be carefully considered if the task is to be replicated in future research. First, the discriminability of between the Hard shapes was too difficult. In fact, given that the performance for the Easy shapes in Experiment 2 were between 60-70% it is clear that the task could be successfully completed provided it is made easier. There are several ways that may result in an easier discrimination task such as: (1) reduce the complexity (i.e., number of sides) of the shapes, (2) adjust the tracing speed of the shape, or (3) introduce a new visual component to the task, such as a “tail” to the trace so that a portion of the target shape would be visible during the tracing phase.

Another suggestion for future research would be to subjectively assess the discriminability of the target/foil shapes using quantitative data. The present studies used novel shapes which were generated pseudo-randomly. One of the reasons for generating stimuli in this way was that the number of vertices changed between the target and foil

shapes could be controlled and that neither shape would resemble familiar forms that may have been able to be encoded phonologically.

Given that eye/attentional tracking interfered with the encoding of visuo-spatial information, the ocular motor system and visuo-spatial encoding processes must be related. In the context of domain specific models of working memory, the current results are consistent with the view that visuo-spatial encoding systems share capacity with systems responsible for pursuit tracking. Although other researchers (e.g., Postle et al., 2006; Baddeley & Lieberman, 1980) reached similar conclusions regarding the relationship between visuo-spatial encoding processes and pursuit tracking, their experimental paradigm did not use encoding tasks that selectively taxed visuo-spatial working memory. The present experiment addressed this issue by using a novel task that required participants to only encode visuo-spatial information using pursuit tracking.

6. Conclusion

Experiment 1 investigated whether pursuit tracking interfered with the maintenance of visual information in working memory. Data from the accuracy analysis showed that pursuit tracking interfered with the maintenance of visual information and that data from the RT analysis showed that eye-based pursuit tracking produced larger disruptions than attention-based tracking. Experiment 2 extended the findings of Experiment 1 by investigating whether eye-based tracking processes also disrupted visuo-spatial encoding processes. The additional purpose of Experiment 2 was to validate a new approach to investigating the role of eye movements on visuo-spatial encoding processes. The results of Experiment 2 showed that visuo-spatial representations that were formed by encoding sequential information contained only characteristics necessary to discriminate between large visual differences (i.e., easy shapes). This finding contrasts the performance for hard shapes which was below 50% which likely indicates that the task was too difficult. Nevertheless, the comparison of accuracy performance of only the easy trails shows that performance was lower in the Eye Tracking condition than the Attentional Tracking condition which may suggest that visuo-spatial encoding processes are disrupted more by eye movements than by attention shifts.

Given that pursuit tracking interfered with the maintenance (Experiment 1) and encoding (Experiment 2) of visuo-spatial information, it follows that the systems responsible for pursuit tracking share capacity with the entire visuo-spatial sketch pad. Under the assumption that pursuit tracking is a function of the spatially oriented inner scribe, the

results reported in this thesis are consistent with the more recent description of the inner scribe as being a system that actively maintains spatial and visual information (Rudkin et al., 2007). This new conceptualization suggests a compromise, or hybrid, between domain-specific (i.e., visual vs. spatial processing systems) and domain-general models (i.e., processing vs. storage systems) of visuo-spatial working memory where the inner scribe is responsible for active rehearsal of visual and spatial information and the visual cache is responsible for the passive storage of visual information. Framed in this context, pursuit tracking processes are likely performed by the inner scribe since tracking was shown to interfere with the maintenance of visual information (Experiment 1) and with the encoding of spatial information (Experiment 2).

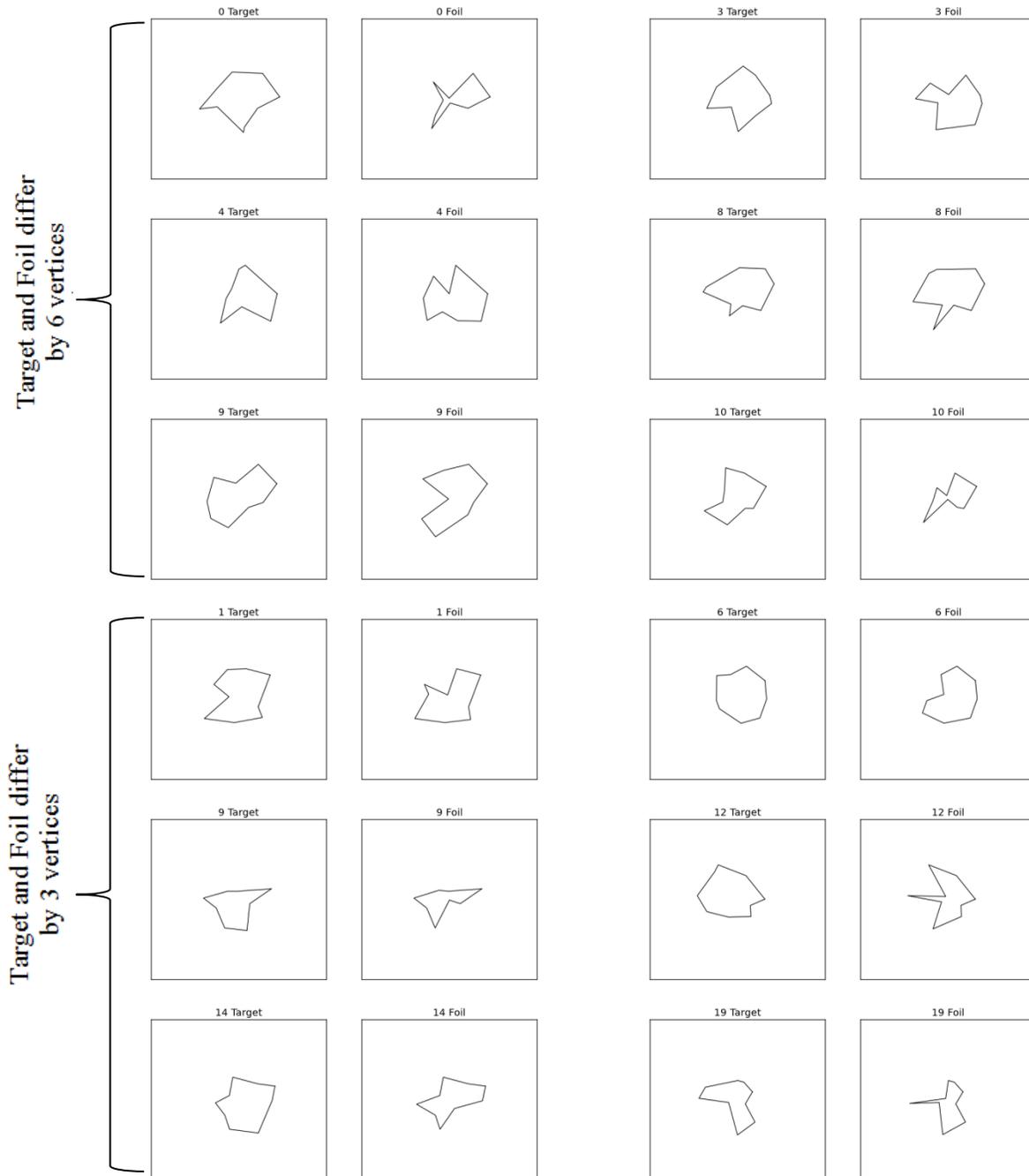
The results of Experiment 1 also showed that eye-based and attention-based pursuit tracking disrupted visual maintenance processes, which is consistent with the claim that visuo-spatial maintenance activities require directed attention (Lawrence et al., 2001; Pearson & Sahraie, 2003). However, given that eye-based pursuit tracking produced additional impairments to visuo-spatial maintenance over attention-based tracking, the ocular motor system may produce additional processing demands in the sketchpad. The results of the present experiments show that the system responsible for maintaining visual information is vulnerable to the same interference caused by the attentional demands associated with visual tracking and to the additional interference caused by ocular behaviour that have been reported to affect spatial working memory.

The second important finding reported here is that the method used to encode dynamic visual information (i.e., eye-based vs. attention-based tracking) influences the characteristics of the visuo-spatial information represented in working memory. That is, it appears that visuo-spatial details are lost or are unavailable to the working memory system when visuo-spatial representations are acquired sequentially. Moreover, visuo-spatial representations may contain even less detail as a result of interference caused by encoding using pursuit eye movements compared to pursuit attention (i.e., without eye movements).

The purpose of this thesis was to investigate the relationship between pursuit tracking and visuo-spatial working memory. The present findings contribute to the multicomponent model of visuo-spatial working by showing that the inner scribe is likely the system responsible for the maintenance of spatial *and* visual information (Logie & Pearson, 1997) as both types of information were disrupted by the on-line processing demands associated with pursuit tracking. The findings are also consistent with other researchers (e.g., Pearson & Sahraie, 2003), who claim that the system responsible for generating eye movement behaviour produces an additional impairment to visuo-spatial working memory. Additionally, the method used to encode dynamic visuo-spatial information influences the characteristic of the representation that is held in working memory.

Appendix A

A.1 Examples of Easy Stimuli



A.2 Examples of Hard Stimuli



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