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Strategic control of visual working memory during scene viewing

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University of Iowa


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STRATEGIC CONTROL OF VISUAL WORKING MEMORY
DURING SCENE VIEWING

by
Ashleigh Monette Richard

An Abstract

Of a thesis submitted in partial fulfillment of the
requirements for the Doctor of Philosophy degree
in Psychology in
the Graduate College of
The University of Iowa

May 2009

Thesis Supervisor: Associate Professor Andrew Hollingworth

ABSTRACT

During scene viewing, visual working memory (VWM) is used to retain information from recently attended and fixated objects. In the present study, I examined whether and how people can strategically control the content of VWM during scene viewing, prioritizing task-relevant objects for retention even as the eyes are directed to subsequent objects. Participants viewed a set of real-world objects presented serially within a 3-D rendered scene. One object in the sequence was cued by a tone as to-be-remembered. At the end of the sequence, memory for the visual form of one object was tested. Participants exhibited tight control over the content of VWM, implementing prioritization after the encoding of an object into VWM, protecting that item from subsequent interference. Participants also successfully reallocated protection to subsequent objects, regardless of the duration of prioritization of the original item. Such strategic maintenance of objects in VWM is likely to play an important role in real-world visual behavior, especially when object information must be maintained across shifts of attention and the eyes to other objects (such as when comparing two spatially separated objects).

Abstract Approved: _____

Thesis Supervisor

Title and Department

Date

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The University of Iowa

May 2009

Thesis Supervisor: Associate Professor Andrew Hollingworth

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CERTIFICATE OF APPROVAL

PH.D. THESIS

This is to certify that the Ph. D. thesis of

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ABSTRACT

During scene viewing, visual working memory (VWM) is used to retain information from recently attended and fixated objects. In the present study, I examined whether and how people can strategically control the content of VWM during scene viewing, prioritizing task-relevant objects for retention even as the eyes are directed to subsequent objects. Participants viewed a set of real-world objects presented serially within a 3-D rendered scene. One object in the sequence was cued by a tone as to-be-remembered. At the end of the sequence, memory for the visual form of one object was tested. Participants exhibited tight control over the content of VWM, implementing prioritization after the encoding of an object into VWM, protecting that item from subsequent interference. Participants also successfully reallocated protection to subsequent objects, regardless of the duration of prioritization of the original item. Such strategic maintenance of objects in VWM is likely to play an important role in real-world visual behavior, especially when object information must be maintained across shifts of attention and the eyes to other objects (such as when comparing two spatially separated objects).

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INTRODUCTION

Consider the task of scanning your garden for flowers to pick for a dinner party bouquet. You fixate one flower to determine its color, size, shape, texture and so on. Then you scan the garden looking for other similarly appealing candidates for the bouquet. After fixating several other flowers, you find one that you want to compare to the first flower. In order to make this comparison, one must be able to retain information about the original flower across disruptions to visual input created by saccades, blinks and intervening flowers and continue to maintain this information during the comparison and decision making process of determining which flowers are best suited for the bouquet. Have you been able to prioritize a representation of the first flower in visual working memory (VWM) to compare with the second, despite the interference created by fixating several flowers in between, or did the process of executing saccades and shifting attention to multiple intervening flowers displace much of the original representation? In general, are people able to exert strategic prioritization of task-relevant objects in VWM? If so, what are the effects of this prioritization, and how is it implemented?

In a highly influential model of working memory, Baddeley and colleagues segregated working memory systems by modality and proposed a network of storage systems with connections to perceptual, motor and long-term memory systems via a central executive at its core (Baddeley, 1976, 1986; Baddeley & Hitch, 1974; Baddeley & Logie, 1999; Baddeley & Warrington, 1970). One of these modality-specific working memory components is devoted to the visual system and hence the common term: visual working memory. The majority of research on this storage system has focused on characterizing core properties of VWM, such as its capacity and representational format. Relatively little research has addressed actual cognitive functioning, or “work”, in VWM, and relatively little is known about the properties of VWM that support intelligent behavior.

In this dissertation, I seek to understand strategic control over of the content of VWM, focusing on how items enter, are maintained within and exit VWM. Because the successful performance of real-world tasks requires managing the content of VWM, understanding strategic control in VWM is central to understanding how VWM serves real-world cognition. At a general level, I examine whether, and how, people can strategically control the content of VWM during scene viewing, retaining task-relevant objects in VWM even as attention and the eyes are directed to subsequent objects. I address five specific questions: A.) Can task-relevant object information be prioritized for retention in VWM? B.) To what extent are task-relevant objects protected from interference generated by subsequent perceptual processing? C.) What is the mechanism supporting that prioritization? D.) Can prioritization be strategically reallocated such that other task-relevant objects can be prioritized? E.) What is the fate of de-prioritized objects?

CHAPTER I

THE ROLE OF VWM IN REAL-WORLD COGNITION

Seminal work on visual memory distinguished between two systems involved in the brief retention of visual information: Visual working memory (VWM)¹ and iconic memory (Phillips, 1974). Phillips distinguished visual working memory from iconic memory based on several key differences. Items held in iconic memory enjoy a high-capacity sensory storage in a retinotopic format, are maskable, and decay rapidly (Averbach & Coriell, 1961; Sperling, 1960). In contrast, items in VWM are subject to a highly limited capacity (Irwin, 1992; Luck & Vogel, 1997), are not coded in precise retinal coordinates (Irwin, 1991; Phillips, 1974), are generally resistant to masking (Pashler, 1988; Phillips, 1974), survive perceptual disruptions such as saccades (Irwin, 1992), and can be maintained over intervals of multiple seconds (Luck, 2008; Vogel, Woodman, & Luck, 2001).

The majority of existing research on VWM has focused on four main issues: (1) the dissociation between VWM and other working memory systems, (2) the classification of subsystems within VWM, (3) the capacity of VWM and (4) the nature of its representational format. VWM has been clearly separated from verbal working memory (De Renzi & Nichelli, 1975; Scarborough, 1972; Vogel et al., 2001), as remembering verbal information concurrently with a visual working memory task does not create interference with either task. Evidence also suggests that VWM may consist of separate systems for “spatial/action” or “where/how” information and identity or “what” information, supported both by perceptual studies in which certain tasks interfere with one subsystem (e.g., spatial/action or identity) and not the other (Hyun & Luck, 2007;

¹ The term “visual short-term memory” is often used interchangeably with “visual working memory”, as both terms refer to the same system. However, “visual working memory” is the preferred term because the evidence from this study shows that VWM can be actively managed in the service of an ongoing task.

Logie & Marchetti, 1991; Tresch, Sinnamon, & Seamon, 1993; Woodman & Luck, 2004; Woodman, Vogel, & Luck, 2001) and neurophysiological evidence showing activation in posterior parietal cortex associated with spatial tasks and the inferotemporal cortex during identity tasks (Courtney, Ungerleider, Keil, & Haxby, 1997; Fuster & Jervey, 1981; Miller, Li, & Desimone, 1993; Smith & Jonides, 1997). Research assessing the limited storage capacity of VWM has found that it can retain approximately 3-4 objects (Luck & Vogel, 1997; Vogel et al., 2001). Current research determining the manner in which information is represented in VWM includes two proposed representational formats: one in which VWM consists of a limited number of fixed-resolution “slots” (Luck & Vogel, 1997; Zhang & Luck, 2008), under which a discrete number of items can be stored, and another suggests a variable-resolution system, within which stored information flexibly occupies a limited pool of cognitive resources (Alvarez & Cavanagh, 2004; Frick, 1988; Wilken & Ma, 2004). Heretofore, research on VWM focused on delineating these basic attributes. However, now that the core representational properties of VWM are relatively well understood, research has turned to the *function* of VWM. How does VWM support the performance of real-world tasks in the service of visually guided behavior?

Preliminary evidence has indicated the involvement of VWM in a variety of tasks that are involved in active vision. One manner in which VWM supports real-world visual behavior is establishing correspondence between objects across disruptions to visual input, such as shifts of attention, saccades, blinks, and occlusion (Currie, McConkie, Carlson-Radvansky, & Irwin, 2000; Hollingworth, 2008; Hollingworth & Henderson, 2002, 2003; Hollingworth, Richard, & Luck, 2008; Richard, Luck, & Hollingworth, 2008). A second function of VWM is to provide top-down guidance of attention, biasing attention and the eyes toward objects that match the current content of VWM (Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Hollingworth & Luck, in press;

Hollingworth et al., 2008; Olivers, Meijer, & Theeuwes, 2006; Richard et al., 2008; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006; Woodman, Luck, & Schall, 2007). A third is to serve as a holding area for object representations during visual manipulation. For example, Hyun and Luck (2007) found that mental rotation tasks interfered with a color change detection task, each of which is presumed to involve VWM as temporary storage system. A fourth function of VWM is maintaining spatial locations that have been examined in visual search tasks. Inhibition of return experiments have found that attention is slow to return to previously attended locations during visual search (Dodd, Van der Stigchel, & Hollingworth, 2009; Klein, 1988, 2000; Posner & Cohen, 1984). This inhibition is impaired when VWM is engaged in an alternate task (Castel, Pratt, & Craik, 2003; Woodman & Luck, 2004).

It is clear that VWM is important for real-world tasks, such as those described above. In order to support such tasks, there must be some degree of strategic control over the content of VWM. The whole concept of a “working” memory is that it is strategically managed in service of a task. But there has been little research devoted to this aspect of VWM: how information retained in VWM is managed. In the next section, I will review work addressing the management of VWM content in service of real-world behavior. First, I will review the *passive maintenance* view of VWM, according to which attention is needed to maintain items in VWM. Then I will discuss recent evidence of robust representations in VWM in the absence of attention. This work indicates that VWM is subject to strategic control, in order to manage the content of VWM while attention is directed to additional objects.

The role of attention in maintaining VWM representations

VWM often has been thought of as a passive system in which items that are no longer receiving focal attention are replaced automatically by newly attended items (Becker & Pashler, 2002; Horowitz & Wolfe, 1998; Kahneman, Treisman, & Gibbs, 1992; O’Regan, 1992; O’Regan & Nöe, 2001; Rensink, 2000a, 2000b, 2002; Rensink,

O'Regan, & Clark, 1997; Treisman, 1993; Treisman & Gelade, 1980; Wheeler & Treisman, 2002; Wolfe, 1999; Wolfe & Bennett, 1997). This notion has been taken as evidence of a minimal role for visual memory in representing the external visual world. For example, the change blindness phenomenon describes situations under which changes to a visual scene go unnoticed during a visual disruption, such as a blink or saccade (French, 1953; Grimes, 1996; Gur & Hilgard, 1975; Hochberg, 1986; Levin & Simons, 1997; O'Regan, Rensink, & Clark, 1999; Pashler, 1988; Rensink et al., 1997; Simons, 1996; Simons & Levin, 1997, 1998; Simons, 2000). Failure to detect changes has been explained by proposing that representations in VWM are volatile unless the remembered object is attended and thus that one must be attending the changing object in order to detect a change (O'Regan, 1992; O'Regan & Nöe, 2001; Simons, 1996, Simons & Levin, 1997). However, subsequent research has demonstrated that VWM representations do not necessarily depend on the continuous allocation of attention and can be retained robustly across shifts of attention to other objects (Allen, Baddeley, & Hitch, 2006; Gajewski & Brockmole, 2006; Hollingworth, 2004; Hollingworth & Henderson, 2002; Johnson, Hollingworth, & Luck, 2008). Thus, VWM may support the retention of information in VWM during active vision as attention and the eyes are directed to other objects.

Passive Maintenance Accounts of VWM

According to the *passive maintenance* view, attention maintains coherent object representations in VWM, but as soon as attention is withdrawn, new perceptual information automatically overwrites the content of VWM (e.g., Rensink et al., 1997; Wheeler & Treisman, 2002). The passive maintenance hypothesis does not imply that no cognitive operations are occurring over the current information in VWM. Indeed as long as one attends to an object, its VWM representation is preserved (Makovski, Sussman, & Jiang, 2008) and can be used to perform visual tasks, such as comparison and change detection. Rather, the term passive used here suggests an inability to actively manage the

content of VWM in the absence of attention, such as in prioritizing information once attention is reallocated to another object.

Evidence suggests that attention is necessary to bind perceptual object representations (Treisman & Gelade, 1980), leading Wheeler and Treisman (2002) and others (e.g., Rensink, 2000a; Wolfe, 1999) to suggest that attention is also necessary to maintain bound object representations in VWM. Wheeler and Treisman implemented a change detection task to examine the role of sustained attention in maintaining coherent object representations in VWM. The memory array consisted of one or more colored shapes to be remembered across a delay and compared to a test array, that was either the same (50% of trials) or changed (50% of trials). On a subset of change trials, all the original features were present (e.g. colors and shapes) but their bindings were changed (e.g., a red circle and a blue square became a blue circle and a red square). In order to successfully detect this change, it would have been insufficient to simply remember all the colors and shapes in the memory array; one must have retained the color-shape bindings (i.e., which color belonged to which shape). Change detection performance in this binding condition was reliably worse than when either two colors or two shapes changed (the 2 feature conditions), but only in a whole-array test condition where the entire memory array was presented at test rather than a single probe item. Wheeler and Treisman suggested that the presence of distractors in the whole array test condition required attentional resources to process, removing attention from the bound objects in memory, and causing the loss of bindings in VWM.

As discussed by Johnson et al. (2008), the Wheeler and Treisman (2002) data must be interpreted with caution. First, it is difficult to evaluate the role attention played in maintaining VWM representations in the Wheeler and Treisman study because they did not directly manipulate the availability of attention during retention. Second, the assumption that the whole-array test condition led to decreased attentional resources for maintaining bound representations is unsupported by previous work that found improved

change detection performance for trials in which the whole-array was presented at test relative to presenting single probe items at test (Jiang, Olson, & Chun, 2000). Third, the percentage of trials in which participants correctly linked features together creating the appropriate bound objects, despite the presentation of the whole-array at test, was 70% or better. This is considerably good change detection performance, given Wheeler and Treisman's assumption that, in this binding condition, attention had been withdrawn causing bindings to come undone. Fourth, the binding condition differed in several important ways from the 2 feature conditions. For example, in the 2 feature condition when only shape changed, the two changed objects appeared at new locations. This caused a change in the overall configuration of the display in the 2 feature condition. However, in the binding condition when objects changed, they simply traded colors with other objects, rather than actually move to previously unoccupied spatial locations. Therefore, there was no change in configuration in the binding condition. Because changes in configuration are easily detected (Jiang et al., 2000; Simons, 1996), configural encoding of the memory array would explain superior change detection performance when shape changed in the 2 feature condition relative to the binding condition. In addition, Wheeler and Treisman's failure to find a set size effect in that condition can also be explained by configural encoding; because regardless of the number of objects in the display, each display may have been encoded as one perceptually grouped object.

The passive maintenance view provides an explanation for change blindness by suggesting that one does not maintain memory representations for items outside the focus of attention (e.g., Rensink et al., 1997; Wheeler & Treisman, 2002). Because the passive maintenance view holds that newly attended perceptual information automatically replaces the memory representations of no-longer attended information, this eliminates the possibility that a change to information outside the focus of attention could be detected. Similar claims have been made in the framework of visual search tasks, in

which previously examined objects are not represented as coherent, bound objects (Horowitz & Wolfe, 1998; Wolfe, 1999).

The passive maintenance view is clearly a prominent theory of VWM, but can it account for the role of VWM in a perceptual comparison task? Because spatial attention is shifted covertly to each object before the eyes fixate it (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995), attention cannot be sustained on the original item as other items are fixated (see Hollingworth & Henderson, 2002). If, as proposed by the passive maintenance view, VWM representations came unbound as soon as attention was directed elsewhere, one could never perform a perceptual comparison between two sequentially fixated objects. Such a system would essentially prohibit the ability of VWM to support real-world vision any time more than one potentially relevant object requires attention, because attending a second item would result in the loss of the bound representation of the original object. This inability to conduct cross-object comparisons significantly reduces the plausibility of the passive maintenance account as a model of VWM.

Robust VWM representations in the absence of attention

Subsequent research has demonstrated that VWM representations do not necessarily depend on the continuous allocation of attention and can be retained robustly across shifts of attention to other objects (Allen et al., 2006; Gajewski & Brockmole, 2006; Hollingworth, 2004, 2005; Hollingworth & Henderson, 2002; Johnson et al., 2008). This raises the possibility that participants can exert strategic control over the content of VWM, preserving task-relevant objects across disruptions and shifts of attention in support of intelligent visual behavior. Gajewski and Brockmole utilized an explicit report procedure to examine the role of attention in preserving feature bindings in VWM. While maintaining a verbal load, participants were shown a ring of six colored shapes. After a delay, their attention was exogenously drawn to a location along the no-longer-present ring. Then a location along the ring was cued, indicating that the

participant was to report either the color, shape or the color-shape combination that was present at that location. The explicit report procedure was implemented to determine the nature of errors. The non-predictive exogenous cue drew attention to the cued location. If attention was necessary to maintain feature bindings in VWM, drawing attention away from the memory representation via the cue during the retention interval should have resulted in worse memory for the conjunction of features relative to memory for the features themselves. If bound object representations were maintained in VWM, on trials in which there was a memory error, neither of the features should have been remembered. However, if memory reverted to unbound individual features in the absence of attention, errors should have involved the correct features but without information about their binding. Consistent with the former view, both color and shape were either remembered together or forgotten together (i.e., as bound objects). Contrary to the passive maintenance view, this research suggests that in the absence of attention object representations in VWM are maintained as bound representations rather than as individual features.

Further evidence that attention does not play a special role in maintaining feature bindings has been shown using the hallmark VWM task, the change-detection task. Johnson et al. (2008) presented participants with 4 objects; each consisted of a distinct color and oriented bar surrounded by a circle. Participants were required to remember either two features of this memory array, such as the color or orientation of two of these objects, or the bindings of the specific color and orientation information on each object. During the retention interval, the participants completed an attention-demanding visual search task, such that the participant would no longer be able to attend to the visual representation of the memory array between presentation and test. If, consistent with Wheeler and Treisman (2002), attention was necessary to maintain the bound object representations, memory for the bound objects would have been impaired relative to memory for the individual features. However, Johnson et al. found similar performance

for both the individual and bound features, suggesting attention does not play a distinguishing role in maintaining bound object representations relative to individual features in VWM.

In contrast to the passive maintenance view, additional research has indicated that people can accumulate object information in visual memory during online scene viewing, as the eyes are directed from one object to the next (Hollingworth, 2004; Hollingworth & Henderson, 2002). In examining the contributions of VWM and VLTM during scene viewing, Hollingworth cued participants' eyes to various objects embedded in a scene. After fixating a series of objects, participants performed a two alternative forced-choice token or discrimination memory test for one of the fixated objects. The serial position of the tested object was manipulated across trials. The most robust memory performance was found for the last two objects in the sequence. Performance was also well above chance for objects fixated earlier in the sequence. This two-object recency advantage suggests the involvement of the limited-capacity VWM during online scene viewing. It is therefore likely the capacity of VWM during natural scene viewing is limited to 1 or 2 complex objects (see also Alvarez & Cavanagh, 2004). Above-chance performance for items outside the 1 or 2 object capacity of VWM indicated a VLTM contribution to natural scene viewing. In fact, Hollingworth (2005) demonstrated that objects presented in a scene are remembered above-chance when the memory test is delayed for 24 hours. These results cannot be accommodated by the passive maintenance hypothesis, because robust memory performance was found for objects that were no longer attended when the test took place. Although this work showed that object representations can be preserved after the withdrawal of attention in both VWM and VLTM, it did not examine whether participants can strategically control object memory, prioritizing task-relevant objects for retention.

Sensitivity of VWM to the demands of visual behavior

Object information is preserved after the withdrawal of attention, but is that maintenance related to the demands of the particular visual task? Task-specific maintenance of VWM would suggest that VWM is not just a passive maintenance store but is managed strategically in the immediate service of a task. In the flower picking example, is the content of VWM controlled by the particular perceptual and memorial demands of comparing flowers? Specifically, if one is choosing flowers on the basis of color, and color information is preferentially maintained in VWM, this would be evidence that the content of VWM is indeed managed according to the needs of the current task.

Support for this claim comes from Hayhoe, Besinger, and Ballard (1998), who examined fixation patterns during block-copying tasks to determine the visual information acquired, and presumably stored, at each moment along the task (see also Ballard, Hayhoe, & Pelz, 1995). Participants copied a model pattern of colored blocks on a computer by dragging blocks from a resource space on the left side of the screen to the corresponding location in a work space on the right side of the screen. Changing the color of a block in the model during a saccade to that block either before picking up a block from the resource space or after picking up a block from the resource space but before placing it in the work space resulted in two distinct changes. While both changes resulted in a longer fixation on the block, changing the block after pickup resulted in greater increase on fixation time (103 ms increase compared to a 43 ms increase when the change occurred before pickup). Because a change to the block was registered, as indicated by reliably higher fixation time across both conditions, these results suggest that a representation of the block was maintained in VWM between fixations. Additionally, the effect of the change was larger when the changed object was currently being manipulated, supporting the extraction and storage of different visual information at different points along the task. Accordingly, Hayhoe (2000) suggested that separate

fixations support online visual behavior by extracting only relevant information for the moment-by-moment task. Hayhoe proposed that all relevant information is not extracted at once, but rather the model is fixated to determine the color block necessary, then once that block is picked up, the model is again fixated to acquire the relative location to place the block in the workspace. These results support a strategic maintenance account of VWM by which the content is managed according to the immediate task demands.

To determine the extent to which task demands effect the acquisition of new information in VWM, Droll et al. (2005) used a block sorting task in which participants were shown five blocks, comprised of four features (color, width, height and texture). The participants were given a pick-up cue, indicating a feature, and were instructed to pick up any block that possessed the relevant feature, regardless of its other features. They then carried the block to a put-down area, where they were required to place the block based on a feature that might differ from the pick-up feature. Participants were told that it was possible for any of the features of the block they were carrying to change, and if they noticed this change, to place the block in a virtual trash bin. This secondary task was used to assess what information was stored to conduct the primary task. Droll et al. found that changes to features were detected more often when the feature was relevant to the primary task, though overall rates of detection were very low. Participants were more likely to notice the change when it occurred along a feature dimension relevant for sorting. On trials in which participants did not notice the change, they tended to sort the blocks along the pre-changed feature values, rather than determining the new feature value, even when they fixated the block after the change. In other words, participants used the feature originally encoded in VWM (e.g., red), rather than updating VWM and sorting based on the new feature (e.g., blue) despite fixating the changed block during the put-down task. These results indicate a maintenance operation by which the content of VWM may be updated only when the task requires this process to occur. Simply

attending to an item did not necessitate the re-organization of VWM to include the changed information.

In addition to maintaining task-relevant features in VWM and updating the content of VWM only as needed, current research supports the flexible weighting of task-relevant information in VWM. In the above block-copying tasks by Hayhoe and colleagues (2000; Ballard et al., 1995; Droll et al., 2005; Hayhoe et al., 1998), the relevant features were stored in VWM and the task dictated that other features were entirely insignificant. However, in natural scene viewing, multiple features are relevant, yet some are more critical to the task than others. For instance, when establishing object correspondence across saccades, one dimension, such as surface feature information, may be more relevant to the task (fixate the pink flower among blue flowers), however another dimension, such as spatiotemporal information (e.g., the locations of the flowers), is also applicable to the task of fixating the proper object amongst other objects.

To test the relative contributions of surface feature and spatiotemporal information in establishing object correspondence across saccades, Richard et al. (2008) instructed participants to fixate a fixation cross to the left of two objects (see Figure 1). One of the objects was cued and the participant generated a saccade to the cued object. Across the saccade, the two objects shifted vertically such that the eyes landed in between the two objects. The shift itself could not be detected directly, because vision is suppressed across saccades (Matin, 1974). Participants were then required to correct gaze to the target object using the identifying information stored in VWM. The authors measured the role of both surface feature and spatiotemporal information in establishing object correspondence when values along the alternate dimension were either consistent or inconsistent with the preview of the target object. The measure of performance was saccade latency, or the duration of fixation prior to the corrective saccade, during which memory was used to determine the proper target and the corrective saccade was computed and initiated. When the task required correspondence based on surface feature

information (e.g., fixate the red disk, which happened to be on the top), redirecting gaze to the target object (the red disk) was impaired by inconsistent spatiotemporal information (the red disk is now on the bottom). The reverse was also true; when the task required correction based on spatiotemporal information (e.g., the top object, which happened to be red), correction was impaired when the surface feature information was inconsistent (the top object was now blue). These results indicate that both dimensions were maintained in VWM. However, the relative contribution of these two sources of information was governed by the task demands, such that one source of information dominated object correspondence. If the feature that defined the saccade target was its location, spatiotemporal information dominated correspondence. However, if the feature that defined the saccade target was color or identity, surface feature information dominated correspondence. These findings suggest that particular sources of information are preferentially encoded and retained in VWM across the saccade, optimizing the content of VWM in service of the current task.

Implementation of strategic control in VWM

Visual memory for objects can be preserved and is not automatically overwritten by new perceptual information (e.g., Hollingworth, 2004; Johnson et al., 2008). In addition, the content of VWM is optimized for the current visual task (e.g., Droll et al., 2005; Richard et al., 2008). This research sets the stage for examining how that memory is managed so as to support intelligent visual behavior. Although there has been relatively little work examining the mechanisms of strategic control in VWM, initial evidence suggests there could be at least three mechanisms by which the content of VWM is controlled: (1) attention controls initial encoding into VWM, (2) attention protects VWM representations from decay and interference, and (3) prioritization is effectively reallocated to relevant items from no-longer-relevant items.

Attentional control of initial encoding into VWM

Attention controls the content of VWM, because attention is critical for the consolidation of perceptual information into VWM (Averbach & Coriell, 1961; Hollingworth & Henderson, 2002; Irwin & Gordon, 1998; Schmidt, Vogel, Woodman, & Luck, 2002; Sperling, 1960). Evidence that cuing attention to particular items transfers that information into working memory was first found in the original iconic memory studies by Sperling and Averbach and Coriell. In these studies, participants were shown an array of letters and were asked to report either the entire array or a particular subset of the array. The subset was designated by either a tone indicating a row (Sperling, 1960) or a circle or bar indicating a letter (Averbach & Coriell, 1961). When participants were required to report the entire array, performance was optimal for arrays of 4-5 items or less. And when participants were cued to specific rows or items, performance was also highly accurate for up to 4 or 5 cued items (working memory capacity). These early studies utilized this cuing method to demonstrate that even when cues appeared after the offset of the array, the entire array was available for a brief period of time (a demonstration of iconic memory). They were also the first to demonstrate that cuing attention to items controlled the consolidation of that information into working memory. Subsequent studies confirmed this link between attentional cuing and VWM using stimuli that were not likely verbally encoded (Palmer, 1988, 1990; Palmer & Ames, 1992; Scott-Brown & Orbach, 1998).

Ensuing research has supported the general claim that the consolidation of information in VWM is governed by attention. This is true when voluntarily attending to a particular spatial location, such as one side of an array of letters (Irwin & Gordon, 1998), and involuntarily, such as when attention precedes an eye movement (Deubel & Schneider, 1996; Hoffman & Subramaniam, 1995; Kowler, Anderson, Doshier, & Blaser, 1995; Shepherd, Findlay, & Hockey, 1986). Both conditions were examined by Irwin and Gordon who presented participants with a central fixation cross and a tone, indicating

which direction they would execute an eye movement once an array of 10 letters and two flanking saccade targets appeared on the screen. When participants initiated a saccade, the letter array disappeared and, after a delay, a bar probe appeared indicating the test location and target (participants had to report the array location, numbered 1-10, and the letter previously occupying that location). Throughout the experiment, participants were instructed to attend to one side of the display, being told that items on the ‘high-probability’ side were 5 times more likely to be tested. Under conditions of voluntary attention, accuracy was higher for items on the ‘high-probability’ side compared to the ‘low-probability’ side on trials in which the saccade target was on the opposite side. This suggests that voluntarily attending to a particular side of the array improved memory for those items, despite that a saccade was executed to the other side. Under conditions of involuntary attention, when cued to make an eye movement to the ‘low-probability’ side of the array, memory for items on that side of the array was improved. Increased performance for items on the ‘low-probability’ side, when participant’s strategy was to attend the opposite side of the display, due to executing a saccade to that side is evidence that simply executing a saccade to a location shifts attention, and thereby increases the memory representation of information at that location.

Support that attention governs the consolidation of information into VWM was also found in cuing paradigms, both when participants were informed that cues were predictive and when they were told they were not predictive (Schmidt et al., 2002). Schmidt et al. presented participants with predictive and non-predictive cues in a VWM task. Each trial began with a cue, followed by an array of six colored squares, and a delay interval. Then memory was tested with a color square presented at a location along the array and participants responded whether it was the same color square that previously occupied the corresponding array location. Participants were either in the predictive or non-predictive cue group and were consequently instructed that the cue was valid on 2/3 of trials (predictive cue group) or 1/6 of trials (non-predictive group). Despite these

instructions, both groups showed better memory performance for cued items than non-cued items, suggesting that cuing attention played a role in transferring perceptual representations into VWM. However, as discussed by Schmidt et al., these studies do not address whether participants strategically control the entry of information into VWM. Although they illuminate that exogenously orienting attention to an item consolidated that item into VWM when the participant had no strategic incentive to do so, participants also had no strategic incentive *not* to consolidate that item.

While current research suggests an automatic link between attention and consolidation into VWM (e.g., Olson, Moore, & Drowos, 2008; Schmidt et al., 2002; but see Yotsumoto & Sekular, 2006), it is possible that entry into VWM could be further controlled by task relevance. Even for attended objects, participants may be able to exert finer control over entry into VWM. For instance, if one is examining a garden in search for the most appealing flower, one might attend to one flower and immediately decide it is not an option based on its extremely small size or lack of color. There is no need to consolidate this item into VWM for later retrieval, because it has already been excluded as a possibility. This example demonstrates that simply attending to an item does not necessitate its consolidation into VWM based on task demands. But is there a compulsory link between attention and consolidation in VWM?

To examine whether the relationship between attention and the consolidation of information into VWM is obligatory, Olson et al. (2008) presented participants with novel shapes, appearing sequentially at fixation, ensuring that every item was attended. However, some of the items were targets (signified by a box around the shape) and the rest of the items were distractors. The participants' task was to remember the target objects (and disregard the distractor objects) to compare to a test image at the end of the trial and determine if the probe was one of the targets presented. On trials in which the probe was not a target object, it was either an entirely novel object or a distractor object. The central question was whether participants did indeed, despite explicit instructions

against doing so, encode distractors into VWM. The logic of the Olson et al. manipulation was that if distractors were encoded into VWM, despite instructions that they were irrelevant, on some trials the participant would inaccurately respond that a distractor probe was a target (i.e., a false alarm); and this would presumably occur on a higher proportion of trials than when probed with an entirely novel object. If participants were able to entirely block attended distractors from VWM, this would support a strong gating theory, under which VWM content is controlled by preventing the entry of attended but irrelevant information. Olson et al. found distractors did intrude into memory, except in one experiment in which all objects were presented simultaneously and participants were able to strategically attend to the locations of relevant items. These results were taken to suggest an obligatory relationship between attention and the consolidation of objects into VWM.

The Olson et al. (2008) results must be interpreted with caution. In Experiment 4, targets and distractors were presented simultaneously, with a white box surrounding the target. Under these conditions, when participants were not required to fixate distractors, accuracy on lure trials (correctly identifying that a probe distractor was not a target) was significantly improved. These results were interpreted by Olson et al. as suggesting that when attention could be used to select only relevant information (presumably via fixating only the target object), relative to the sequential presentation condition that required attending each item, non-relevant information was not consolidated into VWM. However, one cannot determine whether targets were fixated and distractors were not, because eye movements were not monitored.

In Experiment 5 (Olson et al., 2008), eye movements were discouraged in the simultaneous presentation task by reducing the size of the stimuli, presenting them near fixation and shortening their duration to 100 ms. Under these conditions, the distractors did intrude into memory again, suggesting that executing saccades and fixating individual items differentiated whether irrelevant items will be excluded from VWM. These two

experiments (and others Hollingworth & Henderson, 2002; Nelson & Loftus, 1980; Williams, Henderson, & Zacks, 2005) suggest that actively executing eye movements, likely to fixate relevant objects, is strongly correlated with later memory for such items. Therefore, it is not surprising that distractors were encoded when they were obligatorily fixated in Experiments 1-3. It is in fact likely that much of the items we fixate are encoded into VWM, as indicated by the transsaccadic memory task by Irwin and Gordon (1998) above.

Research has also indicated that despite attending to an item, control can be exerted over the initial encoding of information into VWM. Yotsumoto and Sekular (2006) presented participants with either one or two compound gratings, sequentially at fixation (see Figure 2). Then one or two test probes were sequentially presented and participants made yes-no judgments as to whether the probes were one of the previously presented stimuli. On trials in which there were two gratings presented during the memory phase, there were two test probes sequentially presented. Participants responded to whether the first probe matched the first memory grating and then whether the second probe matched the second memory grating. The critical manipulation required participants to view but ignore the second compound grating. This ignore condition was blocked so participants could anticipate the need to ignore the second grating. Eye position was monitored to assure participants did not close or avert their eyes to avoid fixating the ignored grating. Performance in this ignore condition was compared to blocks in which either one or both gratings were to-be-remembered. Performance in the ignore condition and the one-grating condition did not differ significantly, and both were reliably better than the two-grating condition. These results suggest that the irrelevant stimulus was successfully ignored, because if both the first memory grating and the ignore grating were maintained in VWM, performance would have been similar to the two-grating condition rather than the one-grating condition. These results suggest that

attended information is not necessarily encoded into VWM when it can be tagged as irrelevant before its presentation.

Why did Yotsumoto and Sekular (2006) find that attended items could be blocked from VWM when Olson et al. (2008) found they could not be blocked? One possible explanation described by Olson et al. was anticipatory ignoring. In the Yotsumoto and Sekular task, trials in the ignore condition were blocked such that participants knew the second object presented would be irrelevant. In the Olson et al. task, distractor items were presented sequentially but not at a fixed interval in the trial, so participants did not know when relevant and irrelevant items would be presented in the sequence. In Experiment 3, Olson et al. did manipulate the timing of the cue, by either presenting the box indicating a target object 500 ms before the target or presenting the box simultaneously with the target as in their previous experiments. The authors found no significant difference between pre-cue trials and simultaneous cue trials, concluding distractors intruded into VWM regardless of foreseeing an item's status of relevant or irrelevant. In any case, this distinction does not apply to blocking irrelevant items from VWM during natural scene viewing, because one likely does not know before fixating an item that it is irrelevant to the task, or it would not be fixated in the first place.

A second key distinction between the Yotsumoto and Sekular (2006) and the Olson et al. (2008) studies is the manner in which inclusion of irrelevant information in VWM was measured. The Yotsumoto and Sekular task measured the ability to correctly identify the probe as a match or mis-match to a memory grating, and performance in the ignore condition was compared to conditions in which one or two memory grating was presented. This comparison did not require the ignored grating (i.e., the irrelevant stimulus) to be presented at test. In the Olson et al. task, distractors (i.e., the irrelevant stimuli) were occasionally presented at test, to determine the false alarm rate of detecting the distractor as a target. Therefore, in the Olson et al. study, it may have been the case that participants were responding to the distractor item because they remembered the

probe item from the trial, not because it was necessarily encoded into VWM as a prioritized object. For example, as mentioned above, it is likely that simply having fixated distractor objects may have led to greater memory performance for those items (Hollingworth & Henderson, 2002; Nelson & Loftus, 1980; Williams et al., 2005), whether or not they were prioritized in VWM as target items.

Protection of VWM Representations

A second mechanism by which the content of VWM can be controlled is through the protection of task-relevant information in VWM during retention. A number of studies have found that sustained attention to an item in VWM by means of cuing appears to protect it from interference (Griffin & Nobre, 2003; Landman, Sperkreijse, & Lamme, 2003; Makovski et al., 2008; Matsukura, Luck, & Vecera, 2007). In a change-detection task, Griffin & Nobre found a significant cuing effect for items maintained in VWM. Participants were presented with a memory array of four colored Xs. The memory array was either preceded or followed by an 80% valid central arrow cue indicating the location likely to be tested. Then a colored X appeared at one of the locations previously occupied by a memory array item and participants were asked to respond whether the test X was the same color as the X that had previously occupied the corresponding location. Results showed participants were faster and more accurate on valid trials, with decreasing performance on neutral and then invalid trials respectively. This pattern of results was similar across both cuing conditions (before or after the memory array) suggesting that attention can be employed to protect memory representations during retention as effectively as allocating attention to a currently visible stimulus.

The protection afforded by cued objects described by Griffin and Nobre (2003) may have occurred because of a reduction in decision noise. Specifically, because an attentional cue during a retention interval indicated which item was to be tested, there may have been no need to compare the memory item to multiple items at test, leading to better performance. Makovski et al. (2008) examined this possibility by presenting only

one item at test, thus eliminating the need for multiple comparisons. If under these conditions, a cue still improved change detection performance, then the cue did not operate simply to reduce the number of comparisons made at test. Makovski et al. presented participants with circular arrays of either four objects or six colors for 1,000 ms, followed by a 100 ms blank delay interval. Then participants were either cued to one location along the array followed by a single probe test or just presented with a single probe test. Change detection performance was higher on trials with a valid cue, despite the fact that both conditions involved only one item at test, requiring only a single comparison. These results suggest that rather than reducing decision noise during the comparison process (because both types of trials only required one comparison), the cue during the maintenance interval likely directed attentional resources to the cued object's representation in VWM allowing protection of that representation.

Cuing attention to an item during VWM retention improves memory performance; but what is the mechanism by which this occurs? There are two main accounts of how attention could be used to control object representations already consolidated into VWM. First, attention could serve to prioritize certain VWM representations by protecting them from interference or decay (Griffin & Nobre, 2003). Alternatively, better memory performance for cued objects could be due to setting a particular order according to which items in memory are compared with test items in VWM. To distinguish these two views, Matsukura et al. (2007) presented participants with a modified change detection task in which a set of color patches appeared on the left and right side of the screen (see Figure 3). They were then cued to a side of the display previously occupied by color patches and, after a delay, were shown either a set of color patches on the left or right and were required to report if any of the color patches had changed from the original display. Matsukura et al. divided the experiment into single-cue and double-cue trials. On single-cue trials, the tested side of the display could have been the cued side (valid trial) or the non-cued side (invalid trial). On double-cue trials,

the delay was followed by a second (100% valid) cue pointing to either the same side as the first cue or the opposite side, followed by a delay and test. The logic of the double-cuing manipulation is that one side is originally cued as to-be-remembered, but on some trials, opposite side is cued, indicating the need to prioritize that second side for later test. Under these circumstances, participants are required to reallocate prioritization from the originally cued side to the second side within a memory representation. Importantly, when the second cue occurs, the objects are not visible; so this reallocation of prioritization has to occur as a shift within a memory representation. Under this procedure, the protection account proposes that only the originally cued side will be protected from degradation, such that if the second cue pointed to the opposite side, little information would be available to report, causing poor performance on double-cue trials. Alternatively, the prioritization account proposes that the cue determines the priority of sides in the memory representation, so when the second cue signaled the opposite side, priority would then be assigned to that side. This ordering of items would then result in equally accurate performance for both single- and double-cue trials. Consistent with the protection account, participants shifted attention to the side of the display indicated by the first cue, but were unable to access memory for the items presented on the side indicated by the second cue. These findings suggest that attention plays a role in protecting specific VWM representations from degradation.

Cuing seems to operate to protect items already consolidated in VWM. Such protection could either be protection from interference between items in VWM or protection from the interference generated by subsequent perceptual input. Makovski et al. (2008) attempted to distinguish these two possibilities by varying the set size of the memory display in a change detection task. Under these conditions, if attentional cuing protects items in VWM by reducing subsequent perceptual interference, rather than from other items in VWM, the effect of the cue should be equal across all set sizes because the test stimulus always consisted of only one object (i.e., the subsequent perceptual input

was equal). Alternatively, if attentional cuing reduced interference from other items in VWM, the cuing benefit would be greater for larger set sizes when competition for VWM resources increases. When presenting participants with memory arrays of one to six objects, the authors found that the size of the cuing advantage did not differ for set sizes above one. The results suggest that the attentional cue served to protect the cued item from perceptual interference generated by the test display, rather than from other items in VWM.

However, the demands on memory during natural scene viewing, such as disruptions caused by shifts of attention, saccades and occlusion, make protection of information in VWM considerably more challenging than the sequence of events examined in these tasks. In real-world scene viewing, one sequentially attends to a series of objects, and it is unlikely that one could sustain attention to a particular remembered object. So, the type of sustained attentional protection observed in these studies would not necessarily be sufficient to protect items across shifts of attention and the eyes. This issue is illustrated by the cuing manipulation paradigms implemented in these studies. In these experiments, a memory array is followed by the presentation of a cue during a blank inter-stimulus interval (ISI) and then a change detection task. There is no additional perceptual input from which the memory representation is protected other than the test array. The Makovski et al. (2008) work manipulated the set size of the memory array and found similar cuing benefits when equating the perceptual interference generated by the test array; but the test array does not replicate the interference generated by large-scale perceptual changes of eye movements. In real-world scene viewing and perceptual comparison tasks, not only must one protect items in VWM from the global perceptual disruption generated by fixations on subsequent objects, one must also do so while shifting attention to objects other than the object one is attempting to retain.

Reallocation of VWM resources from no-longer-relevant information

A third major component in managing the content of VWM is the successful removal of prioritization from no-longer-relevant items and reallocation of protection to new items. Support for the successful reallocation of prioritization in VWM comes from Landman et al. (2003) who used a double-cuing procedure to determine if the prioritization afforded by attending a cued item during retention could be reallocated to a second item. Participants were shown a circular array of horizontally and vertically aligned bars. The trial consisted of a circular array for 500 ms, then a delay interval during which one or two cues was presented. Following the delay, the array reappeared and on 50% of trials one bar had changed in orientation. Participants were instructed to respond whether any of the rectangles had changed orientation. They were also instructed that the cue (a line pointing from center fixation to a location along the circular array) appearing during the retention interval indicated the location of the changed bar if there was indeed a change on the trial. Participants were told that on trials in which there were two cues (which could not be predicted because they were randomly combined with trials containing only one cue), the second cue was the valid cue and the previous cue was irrelevant. The results showed similar change detection performance in single-cue and double-cue trials, indicating the efficient reallocation of prioritization from an originally relevant object to a second relevant object in VWM.

Landman et al. (2003) further suggested that because it appeared possible to prioritize an originally cued object in VWM and then reallocate prioritization to the memory representation of a second cued object (which was not originally prioritized), attention was not required to maintain the second object in VWM. The authors reasoned that had attention been necessary to maintain the representation of an object in VWM, the representation of the second object would not have been available for prioritization. This is consistent with current research indicating attention is not necessary to maintain VWM representations (e.g., Hollingworth, 2004; Johnson et al., 2008).

The finding by Landman et al. (2003) that prioritization could be reallocated differed from those of Matsukura et al. (2007); who found that information of non-cued items was unavailable for the reallocation of prioritization upon the presentation of a second cue. Matsukura et al. argued that Landman et al. may have found robust change detection performance for both single- and double-cue trials because their paradigm did not ensure participants utilized the cues. They argued that the Landman et al. stimuli of a circular array of lines may have been perceptually grouped into one easily remembered object. If the array was perceptually grouped into one object, this would mean that the task may have been easily accomplished by attending the whole array rather than using the cue to focus on one bar. Therefore, rather than having to shift protection along a memory representation upon presentation of a second cue, participants may have easily retained the entire perceptually grouped array as one object, and no shift would have been necessary. This strategy would have eliminated the need to use the cues, leading to similar performance (at ceiling) in both cue conditions. It is plausible that protection of items during a blank ISI is more complicated with more complex stimuli (e.g., the color squares used by Matsukura et al.), explaining the inability to reallocate prioritization to new items on double-cue trials in the Matsukura et al. study. Though in the Landman et al. study, ignoring the cues (particularly the first cue) would not have been an advantageous strategy because only 25% of trials had two cues; the other 75% of trials had only a single cue. Therefore, on most trials the first cue was indicative of the tested bar. In addition, the cues were always valid; so the simplest strategy would be to utilize the cues. If the difference between stimuli in these two studies explains the difference in results, such a discrepancy only serves to illuminate the necessity to examine the influence of perceptual interference generated by real-world scene viewing to determine how the content of VWM is strategically managed.

Inhibition of no-longer-relevant information in working memory

The few studies on the reallocation of protection in VWM suggest that the complexity of the stimuli may affect successful reallocation. Recent research in the verbal working memory literature indicates that reallocating prioritization in working memory is also influenced by successfully inhibiting no-longer-relevant information. Traditionally, verbal working memory research has utilized working memory span tasks, which measure individual and group differences in working memory capacity, as a window into working memory based on their repeated ability to predict performance on various cognitive tasks (Lustig, May, & Hasher, 2001). For example, one working memory span task requires that participants read unrelated sentences for comprehension while trying to remember the last word of each sentence (Daneman & Carpenter, 1980). The participant's memory span score is calculated by the number of words they can successfully recall. Individuals with high span scores are repeatedly found to perform better on various cognitive tasks than those with low span scores. However, memory span tasks likely require the management of both currently active information from the current trial and no-longer-relevant information from previous trials (Dempster & Corkill, 1999; May, Hasher, & Kane, 1999). Indeed, Hasher and colleagues (Lustig et al., 2001; May et al., 1999) varied the degree of proactive interference in working memory span tasks and found reducing the amount of no-longer-relevant information produced similar performance among participants with high and low span scores. These results suggest that scores on working memory span tasks are more an indicator of participants' successful management of no-longer-relevant information rather than their working memory capacity. This evidence highlights the importance of inhibiting no-longer-relevant information in the successful management of verbal working memory. To anticipate, the present study also finds evidence of inhibition of no-longer-relevant information within the visual working memory domain.

Summary

Originally introduced in 1960 (Miller, Galanter, & Pribram, 1960), the term working memory was proposed based on the concept that information must be briefly retained, while directly accessible, during cognitive tasks. In the early 1970's, VWM was recognized as a visual working memory system distinguished from the fleeting, high-capacity iconic memory and visual long term memory (Phillips, 1974). Despite a great deal of research dedicated to VWM since then, little work has focused on how the content of VWM is managed in order to enable intelligent behavior, or the actual *work* of working memory (Luck, 2008; Hollingworth, 2008).

Existing work on the function of VWM indicates that VWM representations can be retained robustly across shifts of attention to other objects (e.g., Hollingworth, 2004; Johnson et al., 2008), the content of VWM is optimized for the current visual task (e.g., Droll et al., 2005; Richard et al., 2008), attention governs the entry of items into VWM (e.g., Olson et al., 2008; Schmidt et al., 2002; but see Yotsumoto & Sekular, 2006) and protects VWM representations from interference (e.g., Makovski et al., 2008; Matsukura et al., 2007). One limitation of existing work on the strategic control of VWM is that cuing manipulations have been implemented during a blank ISI between memory and test displays of a change detection task, in the absence of significant additional perceptual input. As discussed above, in real-world perceptual comparison, a particular object must be retained in VWM despite the potentially disruptive effects of sensory processing during the fixation of other objects. Initial evidence that participants can prioritize items in VWM despite subsequent perceptual interference comes from a study by Makovski et al. (2008), in which the authors equated perceptual input following the memory array and found no effect of the number of items in the memory array. They concluded that prioritization in VWM operates to protect items from subsequent perceptual interference (i.e., the test array). However, the interference created by a test array of objects is likely

to be quite minor compared with the effects of shifting gaze to objects in a scene, which generates broad changes in perceptual input with each new fixation.

In this paper, I seek to understand strategic control over the content of VWM, focusing on how efficiently people can prioritize task-relevant objects in VWM during complex scene viewing (which requires sequential shifts of attention and the eyes to other objects) and the mechanism supporting such prioritization. Because the successful performance of real-world tasks requires managing the content of VWM, understanding strategic control in VWM is central to understanding how VWM functions in real-world cognition. At a general level, I examine whether, and how, people can strategically control the content of VWM during scene viewing, retaining task-relevant objects in VWM even as attention and the eyes are directed to subsequent objects. I address five specific questions: First, how efficiently can people prioritize task-relevant objects in VWM during complex scene viewing, considering that retention must survive perceptual disruptions generated by orienting attention and the eyes to multiple objects in the scene? Second, is this prioritization immune to perceptual interference caused by subsequent perceptual processing? Third, what is the mechanism enabling this control? Does it operate over the encoding stage, the maintenance stage, or both? Fourth, is this prioritization flexible in the sense that it can be reallocated to additional objects if subsequent items are deemed relevant? Fifth, what is the fate of de-prioritized objects?

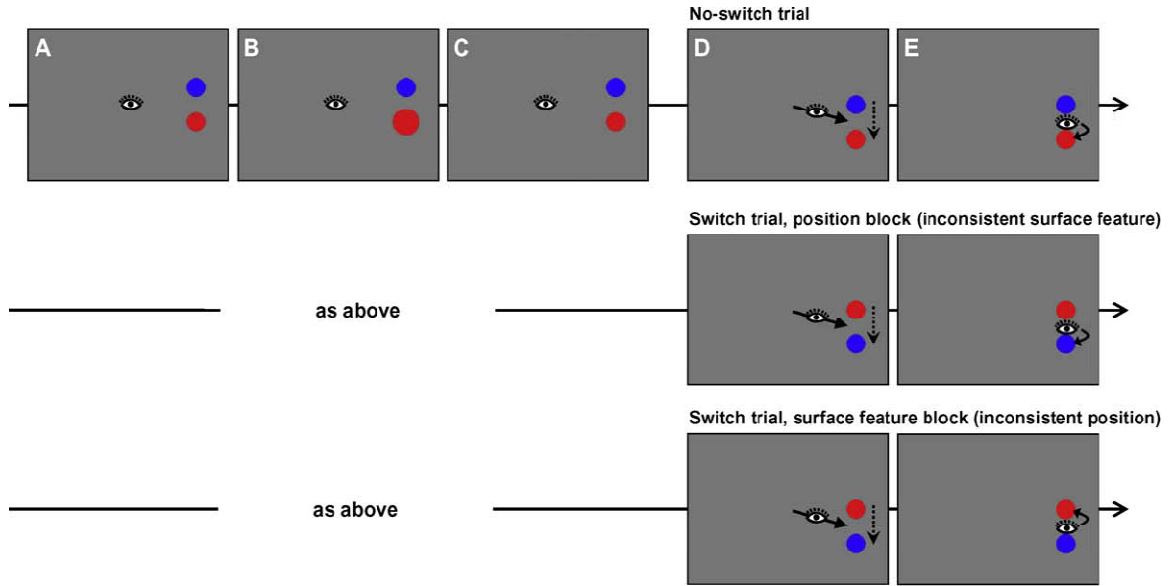


Figure 1. Sequence of events in Richard et al. (2008). During the saccade to the cued object, the two objects shifted either up or down $\frac{1}{2}$ object position (in these examples the objects were shifted down), causing the eyes to land in between the two objects. Thus memory of the saccade target was needed to correct gaze to the appropriate target.

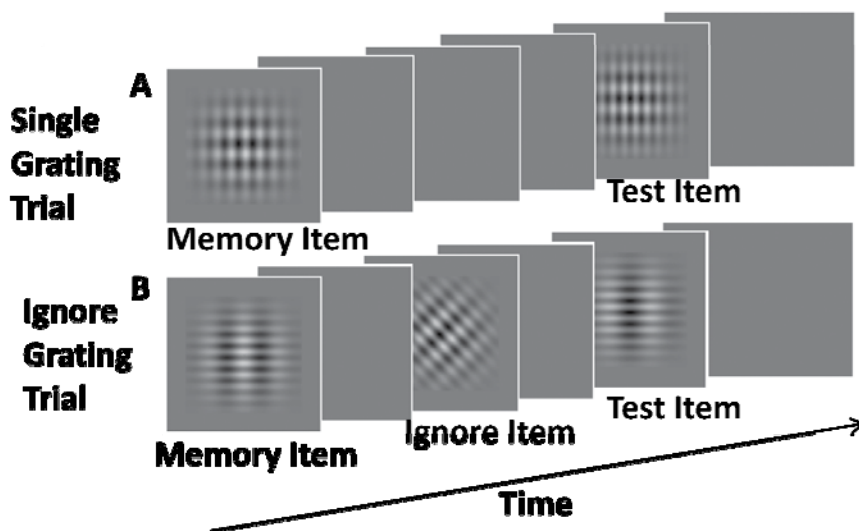


Figure 2. Sample compound grating stimuli used in Yotsumoto and Sekular (2006). (A) Single grating condition trial: a single grating followed by a test grating. (B) Ignore grating condition trial: two compound gratings, the second is to-be-ignored, followed by a test item to be compared to the first grating.

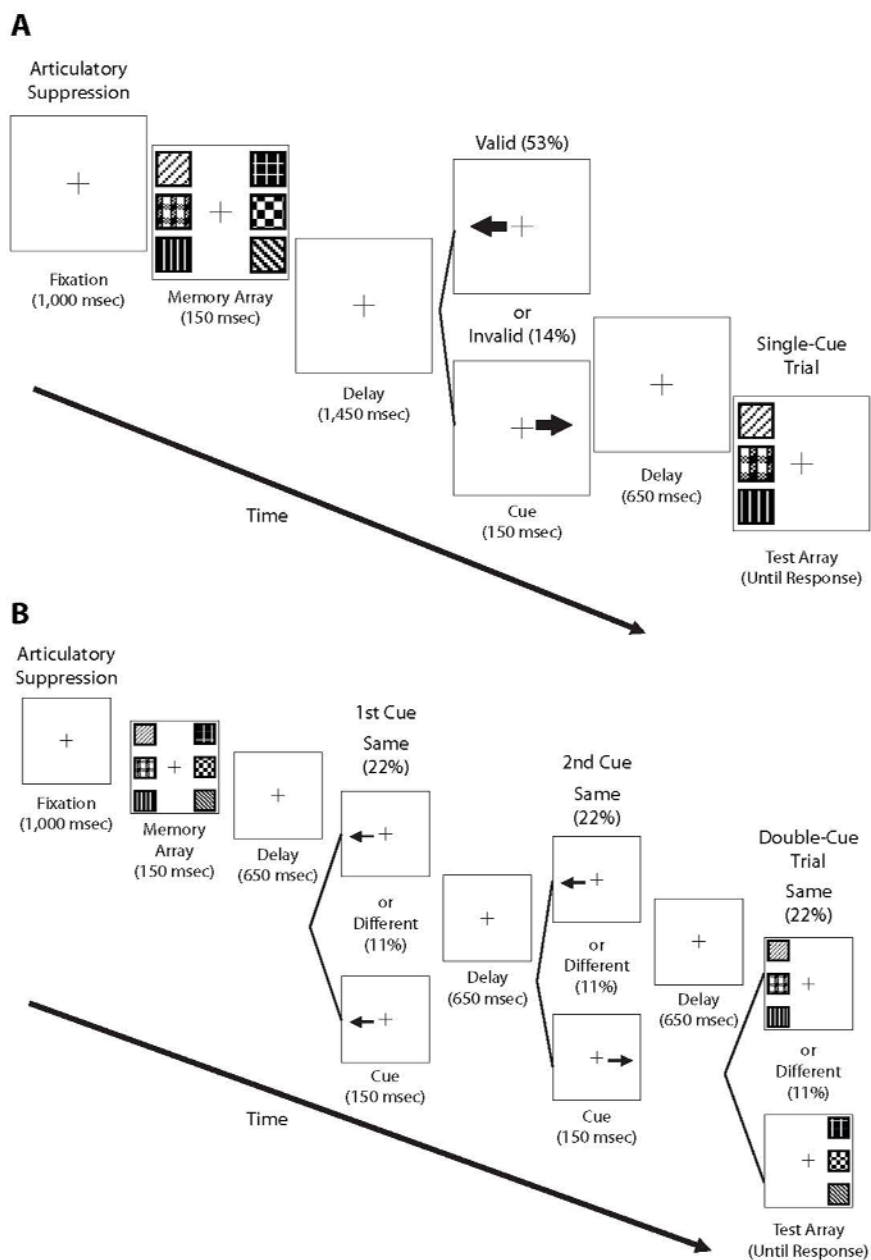


Figure 3. Sequence of trial events on (A) single-cue trials and (B) double-cue trials from Experiment 3 by Matsukura et al. (2007).

CHAPTER II

STRATEGIC PRIORITIZATION IN VWM

Experiment 1

I first examined whether participants can strategically control the content of VWM during scene viewing, retaining task-relevant objects in VWM even as attention and the eyes are directed to subsequent objects. To this end, I developed a paradigm in which participants viewed a series of objects in a scene and had to retain one of the objects in memory for a test at the end of the trial.

The scene in which the objects appeared depicted a workshop (see Hollingworth, 2004). On each trial, participants first saw the background scene (Figure 4). Then, a set of objects was presented sequentially within the scene. Each object was presented for 1,000 ms, after which it was removed. The removal of one object coincided with the presentation of the next object in the series. There were 10 possible objects that could appear in the sequence. Two token versions of each object were created (e.g., two different hammers, two different screwdrivers, etc.). These are displayed in Figure 5. On each trial, between 6 and 10 objects were presented in the sequence (randomly chosen without replacement from the set of 10). The token version of each object was chosen randomly.

A sample portion of the study sequence is displayed in Figure 6. Participants were instructed to generate a saccade to fixate each object as it appeared in the scene, to remain fixated on that object while it was visible, and to shift gaze to the next object in the sequence as it appeared within the scene. At the end of this study sequence, one test object was displayed within a green box in its original position in the scene, and the participant responded to indicate whether this object was the same token version of the object that had been presented during the study sequence (e.g., the same screwdriver) or a different token version. Thus, the basic method was a change detection task, in which the

to-be-remembered stimuli were presented sequentially within a real-world scene. The token change detection task ensured that the method probed memory for the visual details of the objects (Hollingworth, 2003, 2004; Hollingworth & Henderson, 2002).

An auditory cuing manipulation was used to examine participants' ability to prioritize task-relevant objects for retention in VWM. The appearance of each object in the study sequence coincided with an auditory tone. One object in the sequence was cued by a high-pitched tone as 'to-be-remembered'. All other objects were presented with a low-pitched tone. At the end of the sequence, the high-pitched tone (cued) object was six times more likely to be tested than a low-pitched tone (non-cued) object. The central issue in Experiment 1 was whether participants could preferentially retain the cued object, prioritizing the retention of that object despite the need to make a series of fixations on other objects in the study sequence. Memory for the cued object was compared against object memory at that same serial position in a neutral control condition in which no object was cued. In addition, memory for the cued object was compared with memory for other objects in the sequence. Finally, I compared memory for the cued object at different serial positions within the sequence to assess whether cued objects early in a sequence were remembered less accurately than cued objects late a sequence, indicating some degree of interference.

Method

Participants. Forty participants from the University of Iowa community completed the experiment. They received course credit or were paid. All participants reported normal vision.

Stimuli. A workshop scene was created from a 3-D model (see Hollingworth, 2004). The 10 objects that could appear within the study sequence were: bucket, watering can, wrench, lantern, scissors, hammer, aerosol can, electric drill, screw driver and fire extinguisher. Two token versions of each object were created (see Figure 5). The token versions typically differed from each other in the visual details of the object. For

example, one screwdriver had a blue and yellow handle and the other had a green and black handle. Token versions were created to closely match in relative size and orientation. Both token versions appeared in the exact same location within the scene (e.g., when the blue-handled screw driver appeared in the scene, it was in the same location as the green-handled screw driver when it appeared in the scene). The objects were rendered in *3D Studio Max* so that when they appeared, they were naturally integrated within the scene (see Figure 5). The same background workshop scene and object set was used on every trial. It has been demonstrated that repeating the same background scene and object set within an experiment does not necessarily introduce significant proactive interference (Hollingworth, 2004; Irwin & Zelinsky, 2002). Scene images subtended 16.9° by 22.8° visual angles at a viewing distance of 80 cm. Target objects subtended 3.3° on average along the longest dimension on the picture plane.

Apparatus. The stimuli were displayed on a 17-in CRT monitor with a refresh rate of 120 Hz. Eye position was monitored by a SR Research Eyelink 2000 video-based eye tracking device sampling at 1,000 Hz. A chin and forehead rest was used to maintain a constant viewing distance of 70 cm and minimize movement of the head. The right eye was tracked. The experiment was controlled by E-prime software. The computer running E-prime received real-time gaze position samples from the eye tracking device and compiled eyetracking data and the participants' manual responses collected by a serial-response button box.

Procedure. After calibrating eye position, all trials began with participants fixating a small green box in the center of the background workshop scene for 750 ms. None of the objects was visible. During this time, four consonants were presented via the computer speakers. The letters were randomly drawn from the following set of ten consonants: C, G, H, J, K, L, Q, R, T, V. The consonants were created digitally at a sampling rate of 44.1 kHz by the same female native English American speaker. Participants were instructed to remember the consonants. This verbal WM load

minimized the possibility that the objects present in the scene would be encoded verbally (Baddeley, 1986; Besner, Davies, & Daniels, 1981; Murray, 1968). The workshop scene was then presented for an additional 1,000 ms. The number of objects presented on a given trial (between six and ten) was randomly determined. Between six and ten objects from the object set were randomly selected and individually presented in the scene. The appearance of the first object co-occurred with the disappearance of the green central box. Each object appeared embedded in the scene for 1,000 ms and then disappeared simultaneously with the appearance of the next object in the sequence. The appearance of a new object and the disappearance of the currently fixated object was the cue to move the eyes to fixate the new object. The purpose of removing each object from the scene after it had been presented was to control the amount of time the participant could fixate and encode each object. If all objects had remained on the screen, it would have been possible for the participant to either revisit cued objects or continue to fixate them after another object appeared. Eye movements were monitored to ensure participants complied with the instructions. The experimenter observed gaze position during each trial and corrected the participant if the participant failed to shift gaze to each object in turn.

After all of the six to ten objects were presented, the original background workshop scene with the central green box was displayed for 1,000 ms and participants directed their gaze back to the center of the scene. Then, one of the objects appeared in its original location with a green box around it. The test object was either identical to the object presented during the trial or a token version of that object (e.g., a white bucket rather than a green bucket). Participants were required to respond whether the test object was the 'same' or 'changed' by button press on a response box. Half of all trials were 'same' trials and half were 'changed' trials. The test object remained on the screen until the participant responded.

On each trial, 100 ms following the onset of every object, either a low- or a high-pitched tone played for 500 ms. The tone indicated the likelihood that the object would be

tested at the end of the trial. Cuing conditions are depicted in Figure 7. A low-pitched tone suggested that the item was not likely to be tested. A high-pitched tone (cue) indicated that the object was ‘to-be-remembered’ and likely to be tested. On 80% of the trials, one object in the sequence was cued by a high-pitched tone. On the remaining 20% of trials (neutral condition) none of the objects was cued (i.e., all were accompanied by a low-pitched tone). When the object was accompanied by a high-pitched tone, it was the object tested on 60% of trials. On the remaining 40% of trials in this condition, the tested object was one of the other four objects appearing before the test (10% each). Thus, when cued, the cued object was six times more likely to be tested than any of the other objects. On trials in which there was a high-pitched tone, it accompanied the second or third object before the test. In other words, the high-pitched tone was always followed by one or two items before the test. Participants were unable to predict when the ‘to-be-remembered’ object would occur, because they never knew how many objects would be in the trial, as each trial consisted of a random number of six to ten objects in the series.

After the participant responded ‘same’ or ‘changed’ to the token discrimination test, one consonant was presented auditorily. The consonant was either a member of the set of four consonants presented at the start of the trial or a different fifth consonant. Participants used the same buttons from the token discrimination test to signify if this test consonant was the ‘same’ as one of the consonants presented at the beginning of the trial or ‘changed’. An error in the programs of Experiments 1 and 2 created inaccurate feedback for the secondary verbal memory test on approximately 10% of trials. This error only affected feedback during the experiment and not data collection. This was corrected in Experiment 3. Mean accuracy on the secondary verbal memory test was 91.7%.

The participant’s response to the test consonant terminated the trial. The next trial was initiated by the experimenter after checking calibration of the eye tracker. The experiment consisted of 12 practice trials, drawn randomly from the full experimental design, and 100 experiment trials. Eighty of the trials were divided equally into the two

cuing conditions. Of the 40 trials in each cue condition, 24 trials were valid cue trials, and the remaining 16 trials were invalid trials, equally divided among the other four test locations. The neutral condition consisted of 20 trials with 4 trials at each of the five test locations. Trials from the different conditions were randomly intermixed. The entire session lasted approximately 50 min.

Results

Effects of cue. I first examined the question of whether participants were able to prioritize task-relevant objects for retention in VWM and protect these from the perceptual interference generated by fixating subsequent objects. The results are illustrated in Figure 8. Performance for the cued item was compared with performance at the same serial position in the neutral condition. Token change performance for cued items was reliably higher than items in the same serial positions in the neutral condition. Accuracy was reliably better for an item at serial position 2 (one item intervening the target item and token test) when it was validly cued (86.6%), relative to trials in the neutral condition where there was no cue and serial position 2 was tested (73.8%), $t(39) = 3.73, p < .001$. Accuracy was also reliably better for an item at serial position 3 (two items intervening the target item and token test) when it was validly cued (81.7%), relative to trials in the neutral condition where there was no cue and serial position 3 was tested (67.5%), $t(39) = 3.79, p < .001$. Improved performance for cued items relative to trials with no cue suggests that cued items were effectively prioritized in VWM as attention and the eyes were directed to intervening objects.

The data were also examined for an advantage for the particular cued object relative to other serial positions within the serial sequence. When serial position 3 was cued, there was a significant decrease in performance at serial position 2 (70.6%) relative to the last object in the sequence (83.8%), $t(39) = 2.93, p < .01$, and relative to the cued position (81.7%), $t(39) = 2.86, p < .01$. Similarly, when serial position 2 was cued, There was a significant decrease in performance at serial position 3 (64.4%) relative to the last

object in the sequence (86.3%), $t(39) = 4.78, p < .01$, and relative to the cued position (86.6%), $t(39) = 5.77, p < .01$. This drop in performance for adjacent non-cued items suggests that a limited set of VWM resources is strategically deployed to protected cued items at the cost of other items in the sequence.

Effects of serial position. In the neutral condition, there was a reliable effect of serial position, $F(4,195) = 13.28, p < .001$. This effect of serial position is consistent with the serial position effect found by Hollingworth (2004). I also examined the data for evidence of perceptual interference from objects intervening between a cued object and the test. I did so by examining whether objects cued earlier in a sequence were remembered less accurately than objects cued later in a sequence. When validly cued, accuracy at serial position 2 (86.6%) was reliably higher than at serial position 3 (81.7%), $t(39) = 2.81, p < .01$, indicating a degree of interference by subsequent perceptual processing, even for a cued object.

Together, the results of Experiment 1 suggest that task-relevant objects can be effectively prioritized in VWM during a task that required sequential shifts of attention and the eyes. However, this prioritization is not absolute, as there was a moderate amount of forgetting for cued objects earlier in the sequence compared with later in the sequence.

Eye tracking data were analyzed offline using dedicated software to determine fixation patterns across the experiment. Saccades were defined using a velocity criterion of eye rotation $> 30^\circ$ per second. Object scoring regions were rectangular and had an area approximately 20% greater than the objects themselves. Gaze duration, the sum of all fixation durations from the entry into an object region to the exit from that region, was reliably higher for cued objects relative to objects in the same serial position in the neutral condition. When serial position 2 was cued, gaze duration (855 ms) was longer than serial position 2 in the neutral condition (811 ms), $t(39) = 3.42, p < .01$. When serial position 3 was cued, gaze duration (873 ms) was longer than serial position 3 in the neutral condition (837 ms), $t(39) = 3.29, p < .01$. This raises the possibility that

participants were capitalizing on sensory persistence following the disappearance of relevant objects, causing longer gaze durations to result in higher accuracy for cued items. To determine whether there was a relationship between longer dwell times on cued objects and change detection performance, I conducted a gaze duration by accuracy regression analysis for the cued objects and found no significant relationship between gaze duration and accuracy ($r < .01, p = .92$). Thus, although cued objects were fixated longer than non-cued objects, longer fixation does not appear to account for the memory advantage observed for cued objects. The remaining experiments in this study included an object mask following the offset of each object to ensure that effects of cuing could not be caused by differences in the length of encoding processes.

Discussion

The Experiment 1 results demonstrate that participants can effectively prioritize task-relevant items for retention in VWM. Cued objects were consistently remembered more accurately than other objects in the scene. This is the first demonstration that people can strategically control the content of VWM in a task that replicates the demands of real-world perceptual comparisons (i.e., across shifts of attention and the eyes to other objects). Such prioritization is likely to play an integral role in visual behavior during everyday tasks.

The results also exhibited a general recency effect, as indicated by a reliable effect of serial position. This recency effect is consistent with the involvement of VWM in maintaining recently attended objects (Hollingworth, 2004). In previous studies (for review see Hollingworth, 2008), object retention over the course of scene viewing appears to be supported by both VWM and visual long-term memory (VLTM). Although one can be fairly sure that the objects contributing to the recency advantage are being maintained in VWM, one cannot eliminate the possibility that there is a VLTM contribution to the enhanced memory representation of cued objects. However, if there is a VLTM contribution, it is VLTM over the course of no more than a few seconds and in

the service of immediate task performance. Thus, I can say that prioritization of cued items is *functioning* as a working memory, even if I cannot ensure that maintenance is dependent exclusively on the VWM system.



Figure 4. Background workshop scene used in all trials (from Hollingworth, 2004).



Figure 5. Token versions of the ten manipulated objects displayed in their corresponding locations in the scene. Only one of the ten manipulated objects was visible at a time during a trial.



Figure 6. A sample portion of the sequence of events from Experiment 1. The numbers indicate the serial position before test. The tones indicate the tone accompanying each object. All objects were accompanied by a low-pitched tone and, in some trials, one of the objects was cued by a high-pitched tone.

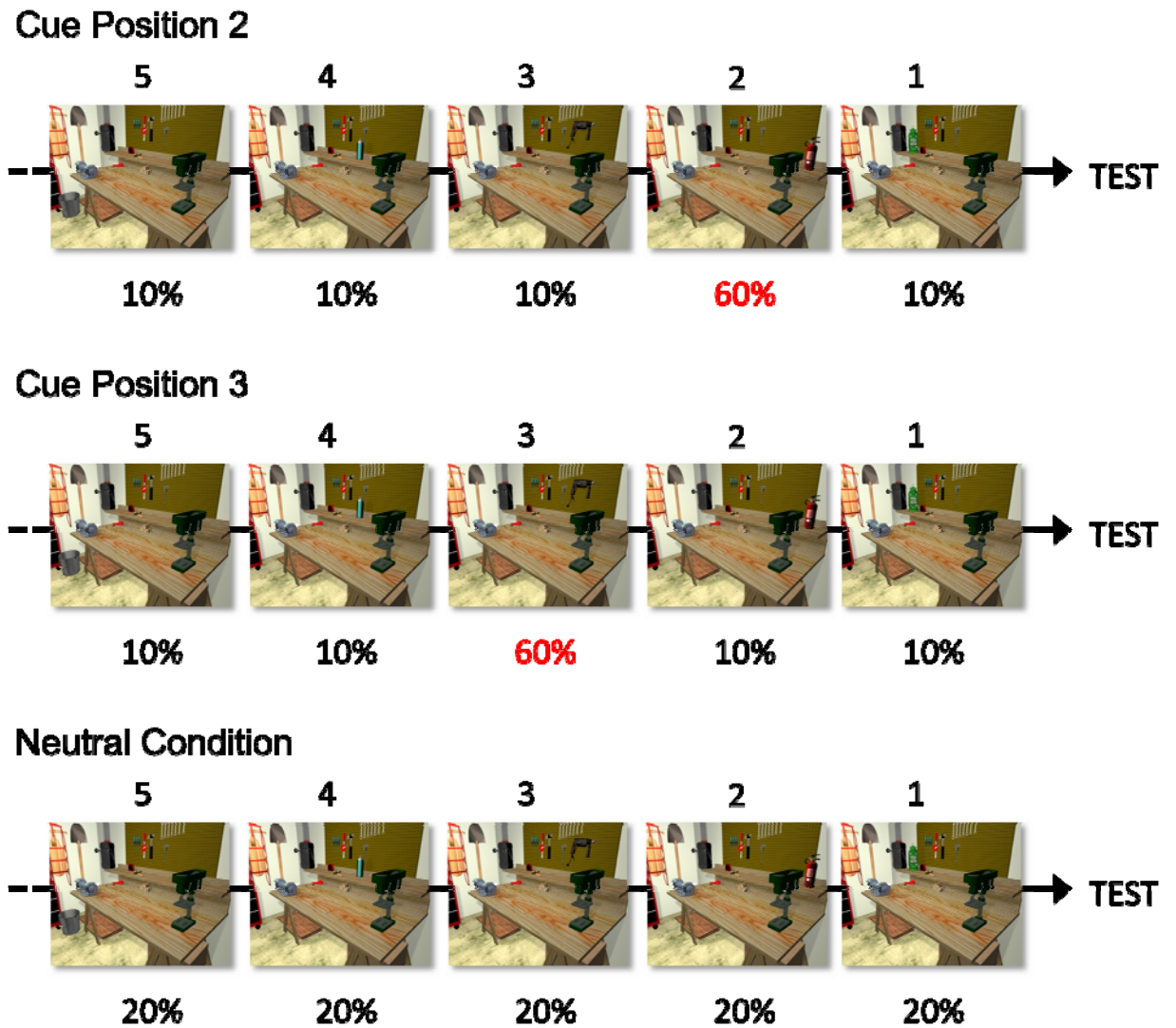


Figure 7. Cue conditions from Experiment 1. The percentages indicate the proportion of trials in which each respective serial position is tested, as a function of cue condition.

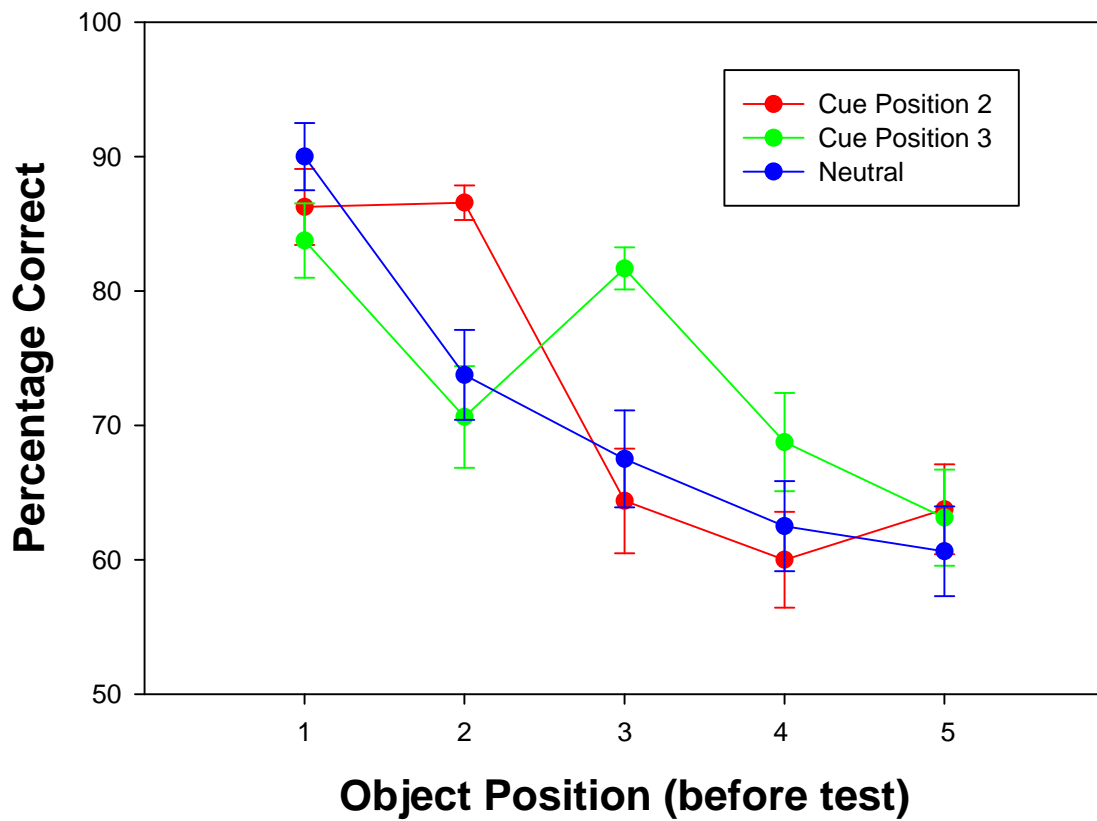


Figure 8. Experiment 1 data.

CHAPTER III

THE ROLE OF SUBSEQUENT PERCEPTUAL PROCESSING IN PRIORITIZATION

Experiment 2A

In Experiment 1, superior performance for cued objects later in the sequence compared with cued objects earlier in the sequence could indicate some degree of interference in VWM caused by subsequent perceptual processing, even for a task-relevant object. However, one limitation of Experiment 1 is that participants had at least some incentive to encode non-cued objects in the sequence, as non-cued objects were tested on 40% of trials. Thus, participants may not have maximized their prioritization of the cued object, sacrificing memory for the cued object in order to encode at least some information from other objects in the sequence. In Experiment 2, the method of Experiment 1 was modified so that all cues were 100% valid. Thus, participants had no incentive to encode information about non-cued objects and could maximize retention of the cued object. All of the last five serial positions in the sequence could be cued by the high-pitched tone. If participants were to show decreasing performance as the number of objects intervening between the cued object and test is increased, this would suggest that the protection of items from subsequent interference is not perfect and that there is some degradation of the VWM representation from subsequent perceptual input.

To ensure that the advantage for cued objects was not caused by differences in the processing time for cued and non-cued objects, each object presentation was followed by an object mask to limit perceptual processing to the period that the object was visible (i.e., to eliminate any sensory persistence).

Method

Participants. Sixteen new participants from the University of Iowa community completed the experiment. They received course credit or were paid. All participants reported normal vision.

Stimuli. The stimuli were identical to Experiment 1 with the following exceptions. The object mask (depicted in Figure 9) was composed of a patchwork of small colored shapes and completely covered each of the objects. Each object mask was rectangular and had an area approximately 20% greater than the objects themselves.

Procedure. The procedure was identical to Experiment 1 with the following exceptions. The experiment consisted of 10 practice trials followed by 80 experiment trials. Each of the last 5 serial positions was validly cued on 16 trials. The presentation of every object was followed by an 1,100 ms object mask at the location of that object (see Figure 9). The mask was then followed by the presentation of the next object. Following the last object of the trial, the object mask was followed by the blank scene with the central fixation box for 1,000 ms and then the test object until response. Mean accuracy on the secondary verbal memory test was 84.2%.

Results

The token change detection accuracy results are presented in Figure 10. Performance at all five serial positions was relatively high, only slightly decreasing as the number of intervening objects between cue and test increased. Token change accuracy from serial position one to five was 97.7%, 95.3%, 93.8%, 94.1% and 89.1%, respectively. There was a reliable effect of serial position, $F(4,75) = 3.96, p < .01$, indicating some loss of information as the number of intervening objects increased. Note, however, that the drop in memory performance for cue position 5 (earliest) and cue position 1 (latest) was less than ten percentage points, and performance at cue position 5 was nearly 90% correct. This moderate drop in performance was observed despite the fact that four objects intervened between the cued object and test in the cue position 5

condition, whereas no objects intervened between cued object and test in the cue position 1 condition. In addition, the retention interval for the cued object was 11.5 s in the cue position 5 condition but only 3.1 s in the cue position 1 condition.

Eye tracking data were analyzed to determine fixation patterns across the experiment. There was no main effect of serial position, $F(4,75) = .86, p = .494$. Although the mask that appeared after each object ensured that longer dwell times on cued objects could not enable longer encoding of those objects, I nevertheless examined the relationship between gaze duration and memory performance to ensure that there was no relationship between longer dwell times on cued objects and token change performance. Again, there was no significant relationship between gaze duration and accuracy for cued objects ($r < .01, p = .92$). In summary, the results of Experiment 2A demonstrate that with no incentive to remember subsequent items, participants can protect cued objects very efficiently, with only minimal interference from perceptual processing on subsequent fixations.

Experiment 2B

Experiment 1 showed evidence of strategic protection of cued items relative to a baseline condition in which no objects were cued. In Experiment 2A, I removed any incentive to encode non-cued objects by including a valid cue on every trial. Experiment 2B was identical to Experiment 2A, except that a baseline condition with no high-pitched tone cue was added. This manipulation allowed for a within subjects comparison of a 100% valid cue condition (as in Experiment 2A) and a neutral baseline condition (as in Experiment 1).

Method

Participants. Sixteen new participants from the University of Iowa community completed the experiment. They received course credit or were paid. All participants reported normal vision.

Stimuli. The stimuli were identical to Experiment 2A.

Procedure. Experiment 2B replicated Experiment 2A with the addition of a neutral baseline condition in which no object was cued by a high-pitched tone. Each experiment session included 80% validly cued trials, evenly distributed over each of the last 5 serial positions. The remaining 20% of trials were neutral with no high-pitched tone cue, also evenly distributed over the last 5 serial positions. There were 10 practice trials and 100 experiment trials. Mean accuracy on the secondary verbal memory test was 85.0%.

Results

Results from Experiment 2B are shown in Figure 11. The results replicated Experiment 2A, I observed significantly improved performance at every serial position in the valid cue condition relative to the neutral baseline condition. At each serial position, accuracy was higher in the valid cue condition than in the neutral condition: position 1, $t(15) = 4.20, p < .01$; position 2, $t(15) = 3.17, p < .01$; position 3, $t(15) = 3.90, p < .01$; position 4 $t(15) = 3.19, p < .01$; and position 5 $t(15) = 7.49, p < .01$. There was a reliable effect of serial position in both the neutral condition $F(4,75) = 4.61, p < .01$ and the valid cue condition $F(4,75) = 3.09, p < .05$, but note that the difference between serial positions 1 and 5 was more than doubled in the neutral condition (28.1 percentage points) relative to the valid cue condition (11.7 percentage points).

Eye tracking data were analyzed to determine fixation patterns across the experiment. There was a main effect of serial position, $F(4,60) = 2.75, p < .05$. There was no main effect of cue type (100% valid cue, no-cue neutral), $F(1,15) = 2.26, p = .153$. There was also no interaction between cue type and serial position, $F(4,60) = .98, p = .428$. There was a significant relationship between gaze duration and accuracy for cued objects ($r = .05, p < .05$). To unpack the relationship between gaze duration and accuracy, I ran separate regressions on the 100% valid cue and no-cue neutral conditions. The gaze duration by accuracy regression was significant along the 100% valid cue condition (r

=.05, $p < .05$) but not the no-cue neutral condition ($r = .009$, $p = .785$). This is unsurprising, given the extent to which these two conditions differed: in the 100% valid cue condition, participants knew they would be tested on the fixated object; whereas in the neutral condition, none of the objects was cued.

Discussion

With no incentive to remember subsequent items, participants could maintain cued objects in VWM with little interference from subsequently fixated objects. This prioritization resulted in significantly more robust memory representations for cued items relative to non-cued items fixated across the trial. These results provide evidence for a highly effective maintenance operation over items in VWM which protects relevant objects from interference created by subsequent perceptual processing. Such maintenance is imperative to intelligent visual behavior in order to maintain relevant information in VWM in service of an ongoing visual task.

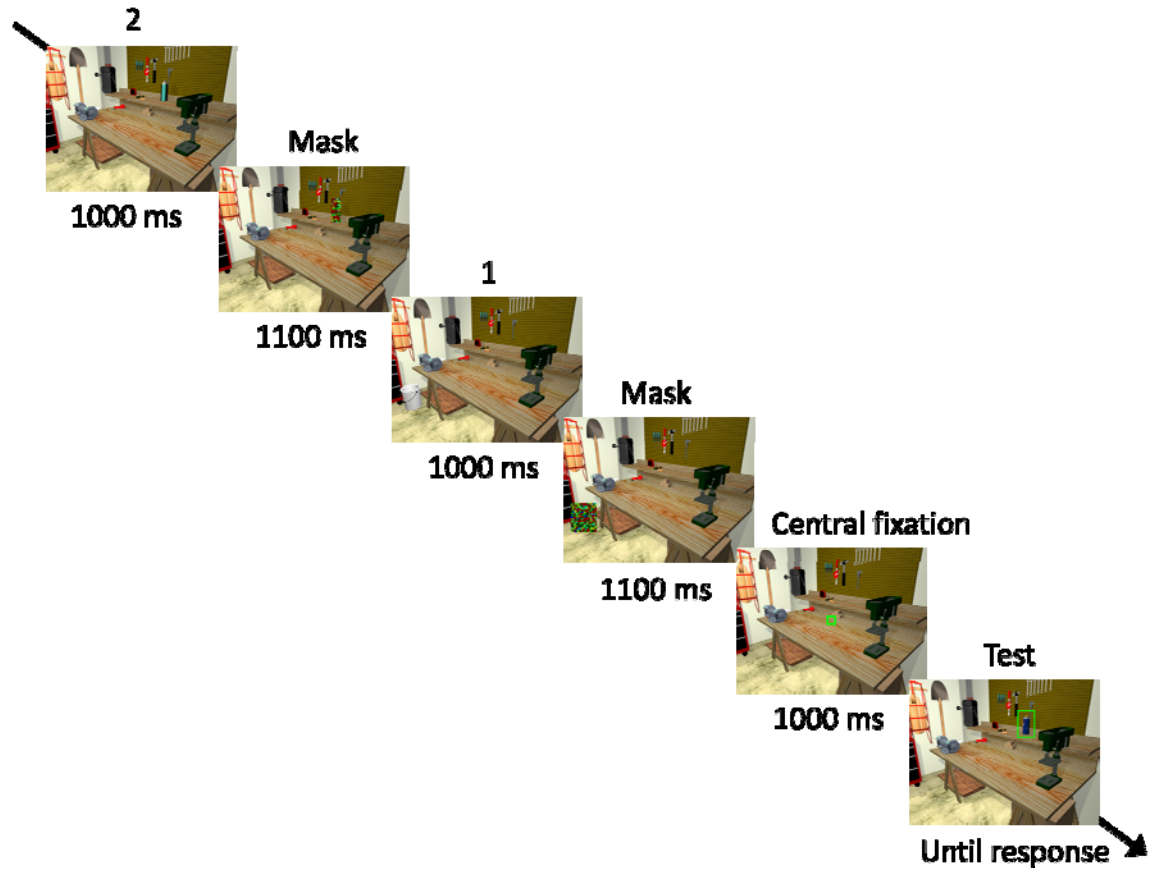


Figure 9. The final portion of the sequence of events in an Experiment 2A trial. The last two serial positions are illustrated, followed by a mask.

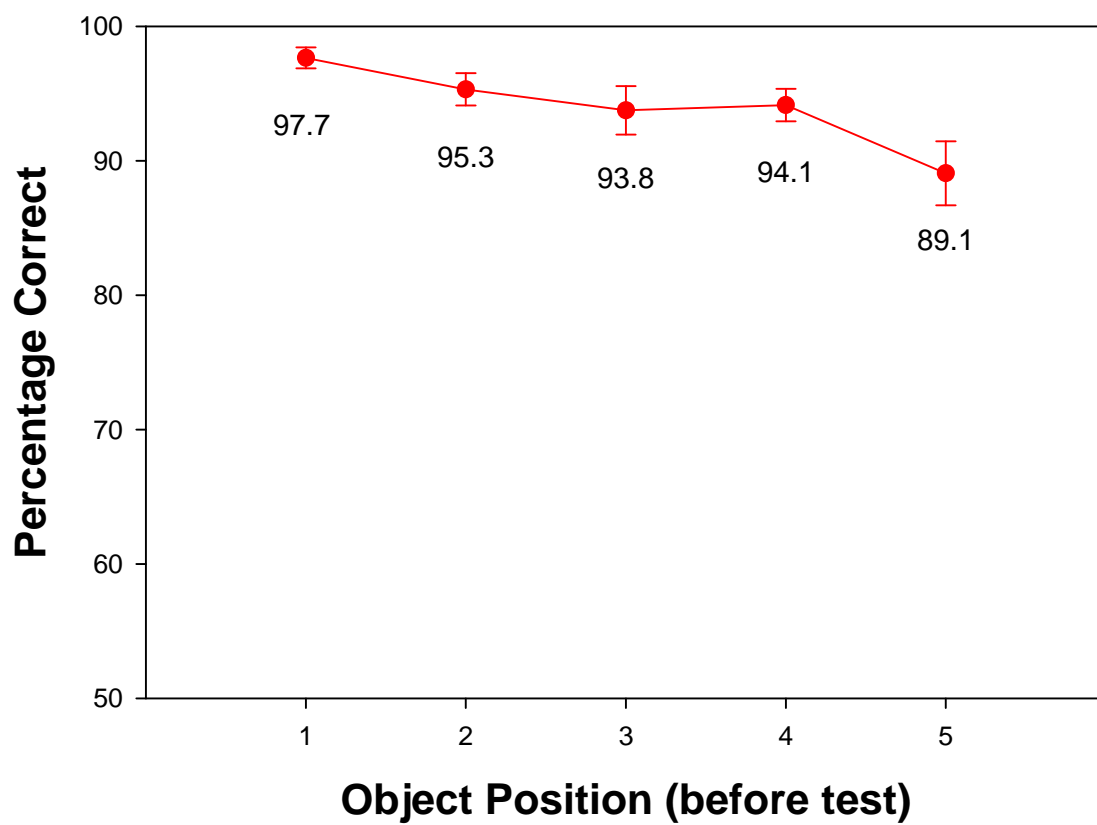


Figure 10. Experiment 2A data.

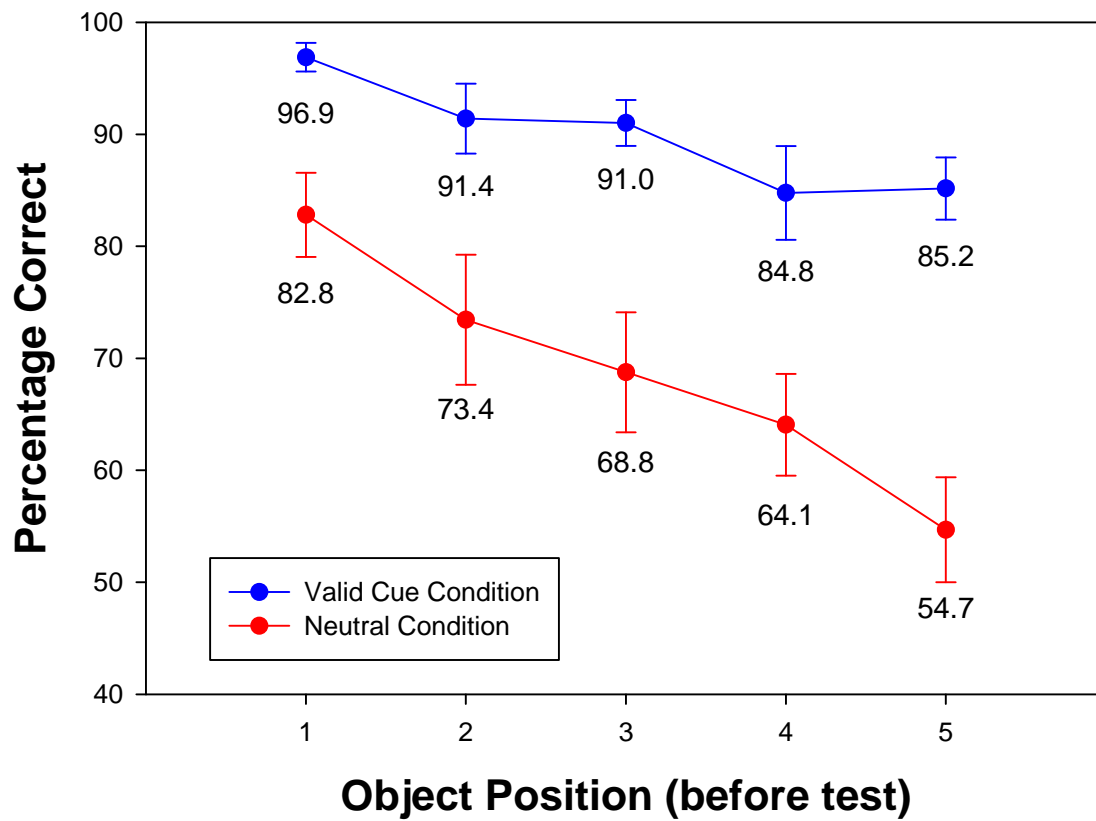


Figure 11. Experiment 2B data.

CHAPTER IV

ENCODING VERSUS PROTECTION

Experiment 3

In Experiment 3, I examined three possible explanations of the prioritization found in Experiments 1 and 2. Specifically, items in VWM may be prioritized via (1) more robust encoding of cued objects, (2) protection of cued objects from subsequent interference/ decay, or (3) some combination of these two factors. To test these hypotheses, I contrasted two cuing conditions (depicted in Figure 12). In the simultaneous cue condition, the cue was presented while the object was visible (as in the previous experiments), 100 ms after the appearance of the object. In the post-cue condition, the cue was presented 100 ms after the mask onset. In the post-cue condition, prioritization of the cued object could only occur by protection from subsequent interference or decay, because the cue was presented only after the object had been masked. Specifically, if the object is not cued until after it has been masked, then there logically cannot be any differences between cued and non-cued objects in the encoding of object information into VWM. If prioritization is achieved by preferential encoding, then performance should be impaired in the post-cue condition relative to the simultaneous cue condition. Alternatively, if prioritization is achieved by protection from subsequent interference, performance in the post-cue condition need not be impaired.

Method

Participants. Sixteen new participants from the University of Iowa community completed the experiment. They received course credit or were paid. All participants reported normal vision.

Stimuli. Stimuli were identical to Experiment 2A.

Procedure. The procedure was identical to Experiment 2A, with the following exceptions. Experiment 3 was divided into two blocks: the simultaneous cue block (the tone played shortly after the appearance of the object) and the post-cue block (the tone played shortly after the onset of the mask), depicted in Figure 12. In the simultaneous cue block, the tones were played 100 ms after the onset of the objects, as in Experiments 1 and 2. In the post-cue block, the tones were played 100 ms after the onset of the mask. The tone that occurred during the mask signaled the status (likely to be tested, not likely to be tested) of the object currently covered by the mask. Participants were given the relevant cuing instructions at the beginning of each block. The serial positions that could be tested were limited to the last three objects before test (rather than the last five). Each block consisted of 6 practice trials and 42 experiment trials. All cues were valid, and there was no neutral condition. In both blocks, each of the three last serial positions in the sequence was validly cued and tested on 14 trials. Mean accuracy on the secondary verbal memory test was 92.2%.

Results

The central issue in Experiment 3 was whether memory accuracy would be impaired in the post-cue condition relative to the simultaneous cue condition. The data are illustrated in Figure 13. There was no main effect of cue type, $F(1,15) = .60, p = .453$; indicating no difference in performance for items cued while visibly present compared with items cued after the object had been obscured by a mask. There was a reliable effect of serial position, $F(2,30) = 3.94, p < .05$; though the difference between serial positions 1 and 3 was only 5.4 percentage points in the simultaneous cue condition and 4.9 percentage points in the post-cue condition. There was no interaction between cuing condition (simultaneous cue, post-cue) and serial position, $F(2,30) = .50, p = .61$.

If the prioritization of cued items were caused by differences in encoding, then we should have observed superior performance in the simultaneous cue condition in which relevant items were cued while visible. The absence of an advantage for the simultaneous

cue condition suggests that the prioritization of task relevant objects is implemented primarily after an object has been consolidated in VWM.

Eye tracking data were again analyzed to determine fixation patterns across the experiment. Gaze duration was reliably longer in the post-cue condition than the simultaneous-cue condition at serial position 1 (993 vs. 861 ms), $t(15) = 3.52, p < .01$, but not at position 2 (1042 vs. 1018 ms), $t(15) = 0.56, p = .29$, or position 3 (1046 vs. 982 ms), $t(15) = 1.24, p = .12$. Unlike Experiments 1 and 2, There was a significant relationship between gaze duration and accuracy for cued objects ($r = .10, p < .01$).

To unpack the relationship between gaze duration and accuracy, I ran separate regressions on the simultaneous cue and post-cue conditions. The gaze duration by accuracy regression was significant along the simultaneous cue condition ($r = .16, p < .01$) but not the post-cue condition ($r = .05, p = .23$). These analyses show that the reliably longer dwell time found at serial position 1 in the post-cue condition did not result in significantly better accuracy. Rather, the significant relationship found between gaze duration and accuracy for cued objects was driven by trials in the simultaneous cue condition. However, it is unlikely that gaze duration affected performance, because trials in this condition actually showed shorter dwell times relative to the post-cue condition. Additionally, all objects were followed by an object mask, eliminating an advantage of lingering at the object location to capitalize on sensory persistence.

One plausible explanation for the difference in gaze duration between the simultaneous and post-cue conditions is that in the former, participants had longer to establish the protection of the cued object before the onset of the next object in the sequence. That is, in the simultaneous condition, the SOA between the cue and the onset of the next object was 2,000 ms, whereas in the post-cue condition, the SOA was only 1,000 ms. In the latter case, participants may have delayed the saccade to the next object in the sequence (producing longer gaze duration on the cued object region), because they required additional time to establish protection of the cued object.

Discussion

In Experiment 3 I examined how the prioritization observed in Experiments 1 and 2 is implemented. The results from the present experiment suggest prioritization is achieved by the protection of task-relevant objects from subsequent interference rather than by preferential encoding. These results support a strategic maintenance account of VWM management, with a strong top-down component whereby task-relevant information is strategically protected after encoding. This finding extends previous work supporting the protection of VWM representations during retention (Griffin & Nobre, 2003; Makovski et al., 2008; Matsukura et al., 2007) by demonstrating that a protection mechanism operates over VWM content in the face of multiple shifts of attention and the eyes to other objects and despite the significant perceptual disruptions generated by these events.

Simultaneous-Cue Condition: Tone occurred 100 ms after OBJECT onset



Post-Cue Condition: Tone occurred 100 ms after MASK onset



Figure 12. Illustration of event timing from Experiment 3. In both conditions, the object was visible for 1,000 ms and the mask was visible for 1,100 ms. In the simultaneous cue condition, the tone occurred 100 ms after the onset of the object. In the post-cue condition, the tone occurred 100 ms after the onset of the mask.

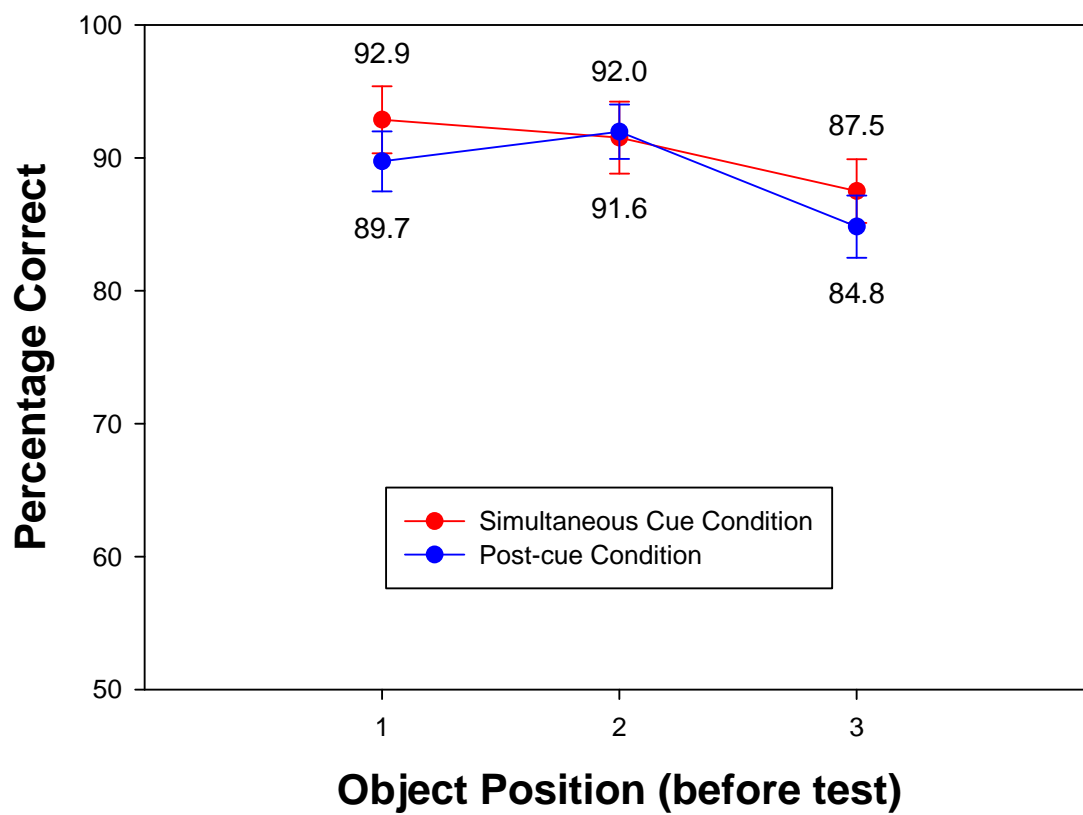


Figure 13. Experiment 3 data.

CHAPTER V

STRATEGIC REALLOCATION OF PROTECTION

Experiment 4

The previous three experiments have examined whether one can efficiently protect information in VWM from subsequent perceptual interference, and the results have indicated that this is indeed the case. However, protection of VWM content must also be flexibly controlled in support of intelligent visual behavior. Items in VWM must both be maintained when relevant and released when no-longer-relevant. Referring back to the original example of selecting flowers from the garden, it is often the case that one item is temporarily prioritized, but later needs to be replaced with another item (such as a more appealing flower). This flexible control is the hallmark of a working memory system, as working memory is essentially a holding area for relevant information in service of cognitive tasks. Although the flexible management of VWM content is imperative to its classification as a working memory system, little work has specifically addressed the flexible management of VWM content.

In Experiment 4, I examine how efficiently protection in VWM can be reallocated from no-longer-relevant objects to newly relevant objects. In Experiment 4, either 1 or 2 objects were cued on each trial. When two objects were cued, the most recently cued object was always tested. The present paradigm differs from previous studies on reallocation in the following manner. Previous studies used double-cuing paradigms in which a memory array was presented, and then during a delay interval, one or two cues indicated a location along the memory array for test (e.g., Makovski et al., 2008; Matsukura et al., 2007). Then participants were presented with a test array and asked to indicate if an item had changed. The double-cuing paradigm has been employed to address whether participants are able to access the memory representation of non-cued items in order to reallocate protection to a second item, despite having already allocated

attention to the item indicated by the original cue. In the present method, participants shift attention and the eyes to objects embedded within a scene and are cued to each item as that item is fixated. Under these conditions, the new high-priority item is visible when it is cued. This design allows the present experiment to examine whether participants are able to reallocate protection of the VWM representation of the first cued item to the second cued item. If the results show similar memory performance for the most recently cued item despite the number of cues in a trial (one or two), this would suggest that participants were able to effectively reallocate protection from the originally cued item to the subsequently cued item within the time course of only one trial. If accuracy for the second cued object is impaired on two-cue trials, relative to the cued item on one-cue trials, this would suggest a system in which reallocation of protection is imperfect and cannot be completed within the time-course of a few seconds during active vision.

Method

Participants. Sixteen new participants from the University of Iowa community completed the experiment. They received course credit or were paid. All participants reported normal vision.

Stimuli. Stimuli were identical to Experiment 2A.

Procedure. The procedure was identical to Experiment 3 with the following exceptions. The experiment consisted of two types of trials, one in which only one item was cued during the trial (one-cue trials) and one in which two items were cued during the trial (two-cue trials). Participants were informed that the most recently cued item would be tested. In other words, on two-cue trials, the most recent cue was always the item tested, and the previously cued item was then irrelevant. This design ensured that participants could not simply ignore the first cue, because they could not know whether or not there would be a second cue in the trial. Strategically, participants had to assume the cued item was the relevant item, unless there was a subsequent cue in the trial. In both conditions, the tested item was always one of the last three serial positions. This design

allowed for the comparison of equivalent serial positions between the two cuing conditions. On two-cue trials, the serial position of the second cued item was always 1,2, or 3 before test. The number of intervening objects between the first and the second cued item was 0, 1 or 2. Therefore, there were 9 possible two-cue combinations: when the second cue was at serial position 3, the first cue was at serial position 6, 5 or 4; when the second cue was at serial position 2, the first cue was at serial position 5, 4 or 3; and when the second cue was at serial position 1, the first cue was at serial position 4, 3 or 2. Trial order was determined randomly to ensure that participants would be unable to predict if a second cue would follow the first and when it would occur. The one-cue and two-cue conditions were equally weighted, with 36 trials in the one-cue condition, evenly distributed among the three possible cue locations, and 36 trials in the two-cue condition, evenly distributed among the nine possible two-cue combinations. Mean accuracy on the secondary verbal memory test was 93.2%.

Results

The results from Experiment 4 are illustrated in Figure 14. I first examined the data to assess whether there was a difference between the one-cue and two-cue conditions in each respective serial position. There was no main effect of cue type, $F(1,15) = .32, p = .582$, and no interaction between cue type and serial position, $F(2,30) = .71, p = .501$, indicating no difference in memory performance for the first or second item cued. There was a reliable effect of serial position, $F(2,30) = 8.17, p < .01$; though there was only a 6.2 percentage point difference between serial positions 1 and 3 in the two-cue condition ($F(2,45) = 2.16, p = .127$) and a 9.0 percentage point difference in the one-cue condition ($F(2,45) = 8.88, p < .01$). The similarity between the one-cue condition and two-cue conditions at all three serial positions, suggests items that are the second cued item in a sequence are protected as efficiently, or nearly as efficiently, as a single cued item.

Eye tracking data were analyzed to determine fixation patterns across the experiment.

There was no main effect of cue type, $F(1,15) = 1.85, p = .194$; serial position, $F(2,30) = 2.92, p = .069$; or an interaction between cue type and serial position, $F(2,30) = 2.68, p = .085$. There was no significant relationship between gaze duration and accuracy ($r = .02, p = .613$).

Discussion

The results of Experiment 4 suggest a flexible system of maintenance in VWM, in which protection can be reassigned to subsequent high-priority items. The task required not only the protection of a task-relevant item but also the flexible reallocation of that protection to a different item. This experiment provides evidence that protection can be effectively reassigned to a new item within the brief time course of one trial, regardless of the number of intervening objects (at least within the range tested here). A system that can assign protection to a new item along the time course of a few seconds is imperative for enabling intelligent visual behavior.

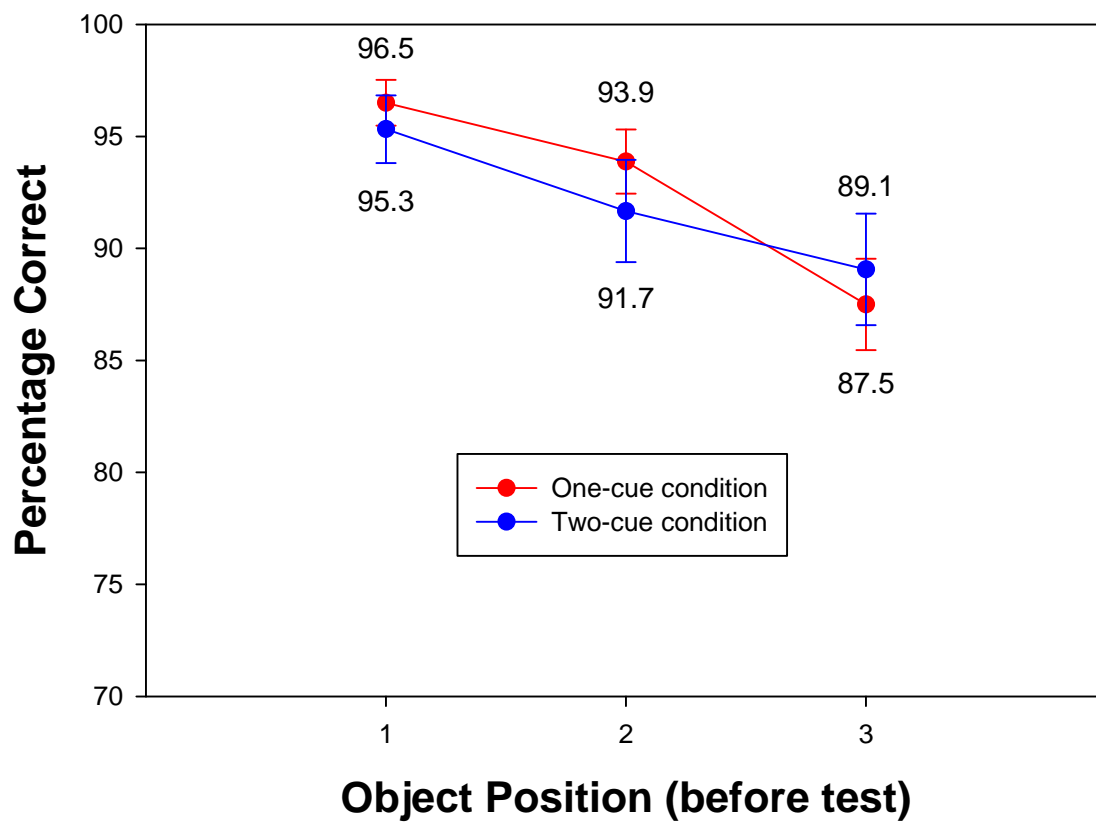


Figure 14. Experiment 4 data.

CHAPTER VI

EFFECTS OF PROTECTION REALLOCATION

Experiment 5

In Experiment 4, participants were able to efficiently reallocate protection from one object to another as task conditions changed. In Experiment 5, I examined the fate of a de-prioritized object. On the one hand, after protection has been reallocated to a different object, the originally prioritized object might be effectively purged from VWM. In this case, memory for a previously prioritized object might be no more accurate than memory for objects that were never prioritized in the first place. On the other hand, the originally prioritized object might continue to be prioritized within VWM, or the original act of prioritization might have generated a more robust representation of the originally prioritized object (e.g., in VLTm) that can persist despite reallocation of prioritization to a different object. In this case, memory for a previously prioritized object would be more accurate than memory for objects that had never been prioritized. Under conditions in which the originally prioritized item is no longer relevant, an optimal system would effectively purge irrelevant information from VWM. In Experiment 5, I examine the fate of the originally cued, de-prioritized object under conditions that prioritization is reallocated to a second object. In this experiment, memory for the originally cued object was tested on a very small proportion of trials, allowing the assessment of memory for the previously prioritized object without providing significant incentive to persist in prioritizing that object.

As in Experiment 4, trials consisted of either one or two cues. In the one-cue condition, only the object at serial position 4 was cued. In the two-cue conditions, the first cue at serial position 4 was followed by a second cue at serial position 2 or 3. In the two-cue condition when the second cue was at serial position 2, there was one intervening item between the first and second cue (at serial position 3). When the second

cue was at serial position 3, there were no intervening items between the first and second cue. Participants were instructed that in the event of a second cue, the second cue indicated the object *most* likely to be tested and the previously cued object was *least* likely to be tested of all the objects in the trial. These instructions encouraged participants to utilize the latter cue and neglect the previously protected object. Participants could not anticipate whether each trial would have one or two cues, so they had strong incentive to utilize the first cue unless it was followed by a second cue.

In order to determine the fate of the de-prioritized object, Experiment 5 included the following principal analyses. First, on two-cue trials, memory for the first cued (de-prioritized) object was compared with memory for the second cued object to determine if they enjoy similar protection in VWM (resulting in similar performance) or if the original item has been purged from VWM (demonstrated by superior performance for the second cued item).

Second, memory for the de-prioritized object was compared with the equivalent serial position 4 in the one-cue condition, establishing the difference in memory performance when the same serial position is cued for retention (one-cue condition) versus cued and then later de-prioritized (two-cue condition).

Third, I examined whether having kept the original object preferentially in VWM left any stronger trace in memory for that object than for objects that were never prioritized in the first place. This was accomplished by comparing memory performance for the de-prioritized object to adjacent serial positions that were not cued for prioritization.

Finally, the data were examined to address whether the length of time that the originally cued object was prioritized before being replaced by a second item influenced retention of either the de-prioritized item or the new item. Comparing the length of time the originally cued item was prioritized was accomplished by comparing memory performance between the two-cue conditions, when the second cue was at position 3

there were no intervening items between the two cues and when the second cue was at position 2 there was one intervening item. If performance for the de-prioritized item differs based on the length of time it was prioritized, this would suggest that removing protection from the originally prioritized object is less efficient when the original object was prioritized for a longer period of time. If performance for the second item differs based on the length of time the original item was prioritized, this would suggest reallocating protection to a second item is less efficient as a function of the duration of prioritization of another object.

Method

Participants. Twenty-four new participants from the University of Iowa community completed the experiment. They received course credit or were paid. All participants reported normal vision.

Stimuli. Stimuli were identical to Experiment 2A.

Procedure. The procedure was identical to Experiment 4 with the following exceptions. Each trial consisted of 5 or 6 total objects, randomly selected. The experiment again consisted of one-cue and two-cue trials. All of the last 5 serial positions were tested. Across both conditions, the first cue was at serial position 4. In the one-cue condition, this was the only item cued. In the two-cue condition, the second cue was either at serial position 3 (this condition is described hereafter as *cue position 3*), with 0 intervening items between the first and the second cue, or at serial position 2 (*cue position 2*), with 1 intervening item between the first and the second cue. Participants were instructed that a high-pitched tone indicated the object most likely to be tested, but if a second high-pitched tone occurred on a trial, that second cued object was now *most* likely to be tested and the previously cued object was then *least* likely to be tested of all the objects.

The experiment consisted of 136 experiment trials and 12 practice trials randomly selected from the total design. Half of the 48 trials in the one-cue condition were valid

trials, the other 24 trials were evenly distributed between the other 4 serial positions. The remaining 88 trials were evenly distributed among the two-cue conditions (cue position 2 and 3). Half of the trials in the two-cue conditions were valid, 9% probed the originally cued item, and 41% were invalid trials probing one of the 3 non-cued locations. In two-cue trials in which the first cue was at serial position 4 and the second cue was at serial position 3, serial positions 1, 2 and 5 were the 3 non-cued locations. In two-cue trials in which the first cue was at serial position 4 and the second cue was at serial position 2, serial positions 1, 3 and 5 were non-cued locations. Mean accuracy on the secondary verbal memory test was 89.3%.

Results

The results are displayed in Figure 15. Before continuing to the main analyses, I had to ensure that participants did indeed attempt to prioritize the first cued object. In the one-cue condition, performance for the initially cued object (serial position 4) was reliably higher than performance at serial position 3 in that condition, $t(23) = 2.95, p < .01$. Participants successfully prioritized the item at serial position 4 when that item was the only object cued in a trial, and thus we can be confident that in the two-cue conditions, participants initially prioritized the object at serial position 4.

I first examined the fate of the de-prioritized object by examining whether memory performance for the de-prioritized object was impaired relative to the second, validly cued item. In the cue position 3 condition, performance at the originally cued position 4, was significantly lower relative to the second, validly cued position 3, $t(23) = 2.53, p < .01$, indicating reliability decreased performance for the de-prioritized object. In the cue position 2 condition, performance at the originally cued position 4 was reliably worse than the second, validly cued position 2, $t(23) = 3.37, p < .01$, again demonstrating more robust memory representation for the second cued item relative to the de-prioritized object. These data suggest that prioritization was successfully reallocated to the second cued object.

Second, a comparison of serial position 4 between the one-cue condition and the collapsed two-cue conditions indicated that memory for the de-prioritized item was significantly impaired relative to a cued item in the same serial position that was not followed by a second cue, $t(23) = 2.84, p < .01$. Thus, when the object at serial position 4 remained prioritized, the memory representation for the object at serial position 4 was significantly better than when protection was reallocated to a second object. This result also highlights the limited capacity of resources in VWM and the limited capacity for prioritization: The prioritization of the second cued object was achieved at the expense of memory for the first cued object. This effect was extremely large in absolute terms. For example, memory performance at serial position 4 was ~75% correct in the one-cue condition but was barely above chance in the cue position 2 condition (less than 60% correct), suggesting almost complete purging of the previously prioritized object.

Third, I examined memory for a de-prioritized object relative to objects that were never prioritized in the first place. When the second cued object was at serial position 2, there was no reliable difference between memory performance for the de-prioritized object (serial position 4) and non-cued items at serial position 3, $t(23) = 1.56, p = .066$; and 5, $t(23) = 1.43, p = .082$. Similarly, when the second cued object was at serial position 3, there was no reliable difference between memory performance for the de-prioritized object (serial position 4) and non-cued items at serial position 2, $t(23) = 0.96, p = .174$; and 5, $t(23) = 1.27, p = .108$. However, in each of these cases, the numerical trend was toward lower performance for a de-prioritized object compared with non-cued objects at flanking serial positions. In particular, when the second cue appeared at serial position 2, accuracy collapsed across the two serial positions (3 and 5) flanking the de-prioritized position (4) was reliably higher than accuracy at the de-prioritized position, $t(23) = 1.70, p = .05$. There was also a trend toward greater inhibition of the de-prioritized item as a function of the length of time it was prioritized, exhibited by lower accuracy at the de-prioritized position when the second cue was at position 2 (59.4%)

relative to when the second cue was at position 3 (64.6%), $t(23) = .93, p = .182$. These results suggest that the de-prioritized object was effectively suppressed, such that memory for this item was reduced compared with items that had never been prioritized. There is also a non-significant trend that this inhibition was actually greater, the longer the item was prioritized.

Finally, I examined whether the length of time an object was prioritized before the second object was cued influenced retention of the second cued object. A comparison of memory performance for the second cued item between trials in which the two cues were intervened by 1 object (77.1%), versus 0 objects (76.3%), $t(23) = 0.35, p = .366$, suggests that protection assigned to the second item was not affected by the duration of the original object prioritization.

Eye tracking data were analyzed to determine fixation patterns across the experiment. I first assessed gaze duration for the first cued item (serial position 4) across the one-cue condition and the collapsed two-cue conditions. Indicative of participants' strategy to utilize the first cue, gaze duration at serial position 4 differed by less than 11 ms between the one- and two-cue conditions: 870 ms in the one-cue condition, 859 in the two-cue conditions, $t(23) = .71, p = .241$. These results emphasize the striking finding that, in the two-cue conditions, there was ultimately no superior memory trace for items at serial position 4 relative to non-cued items, despite being fixated for essentially the same duration as items at serial position 4 in the one-cue condition, which were remembered at significantly better rates than non-cued items.

Next, I examined gaze duration for the second cued item, determining if there was a difference between gaze duration for the first cued item and the second cued item. As participants fixated the second cued item, they received a cue indicating the need to both de-prioritize the originally cued item and reallocate protection to the second cued item. However, this process did not result in significantly longer gaze durations on the second cued item. In the cue position 3 condition, gaze duration for the second cued item (865

ms) was not reliably longer than gaze duration for the originally cued item (856 ms), $t(23) = .57, p = .287$. In the cue position 2 condition, gaze duration for the second cued item (856 ms) was not significantly longer than gaze duration for the originally cued item (863 ms), $t(23) = .48, p = .319$. Strikingly, when the participant was already protecting an item and was then cued to a second item, the gaze duration on the second cued item was no longer than gaze duration on the first cued item. These findings support the conclusion from Experiment 3 that prioritization occurs by the protection of task-relevant objects from subsequent interference rather than by preferential encoding.

Discussion

The results from Experiment 5 indicate that when protection is reallocated from one relevant item to a second relevant item, there is no persisting memory advantage for the de-prioritized object. The originally protected item appears to have been effectively eliminated from memory, and even suppressed relative to non-cued items. Having held the originally cued object in memory preferentially in VWM does not seem to leave any stronger memory trace than for objects that were never prioritized in the first place. In fact, there was a trend toward greater inhibition for a de-prioritized object when it had been prioritized for a longer length of time.

These findings demonstrate the hallmark of working memory, flexible control. In the domain of visual working memory, participants appear to have exquisite strategic control over VWM contents, such that they can strategically eliminate, and possibly inhibit, a previously relevant object. There are at least two possible mechanisms supporting the removal of information from VWM. First, protection from de-prioritized items may be released, allowing them to be overwritten by new perceptual information, as suggested by the passive maintenance view (e.g., Rensink et al., 1997; Wheeler & Treisman, 2002). On the other hand, information may exit VWM by actively purging no-longer-relevant object representations. These possibilities will be further examined in the General Discussion.

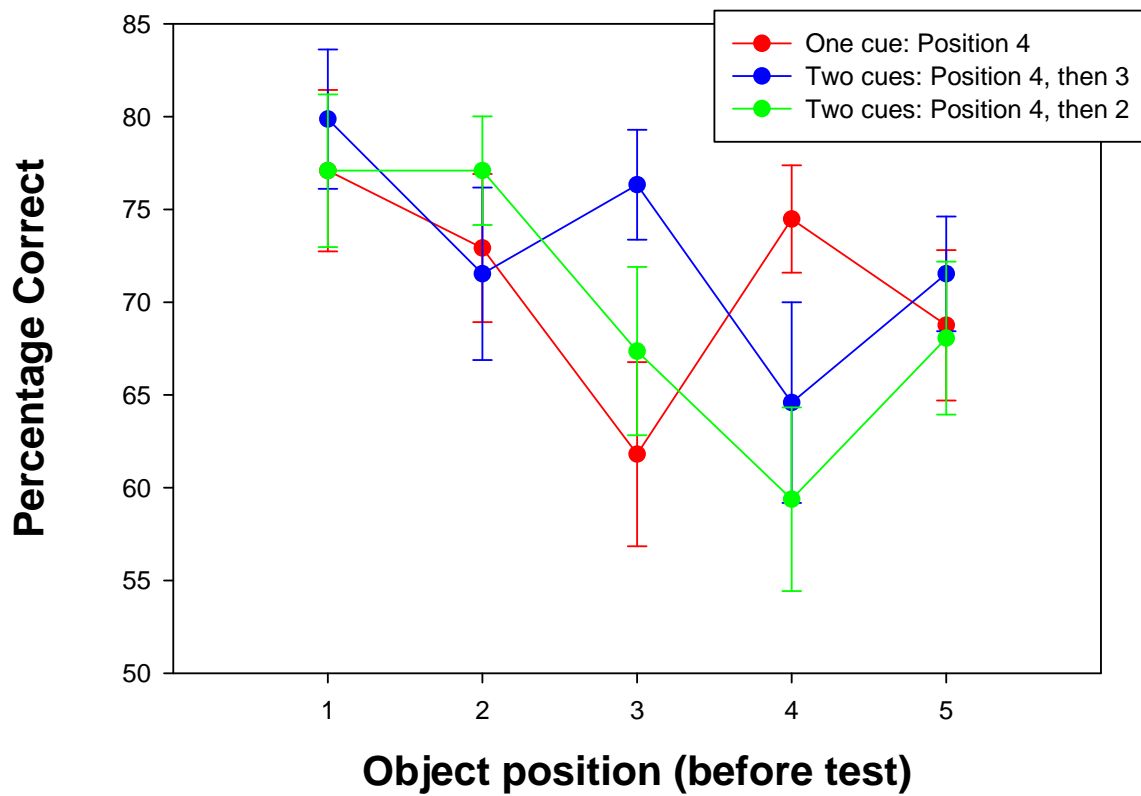


Figure 15. Experiment 5 data.

CHAPTER VII

GENERAL DISCUSSION

Intelligent visual behavior requires sequential shifts of attention and movements of the eyes, which introduce visual disruptions and gaps in perceptual input. To establish some degree of perceptual continuity, a brief visual memory is needed that is sufficiently robust to span these disruptions. A large body of research suggests that the visual working memory (VWM) system plays precisely this role in visual cognition. For example, when generating a saccade to an object, VWM is used to retain properties of the saccade target across the disruption and change caused by the saccade itself, so that after the eyes land, the visual system can establish whether the intended object has been fixated (Hollingworth et al., 2008; Richard et al., 2008). Clearly, VWM plays a key role in supporting everyday visual behavior. In order to support such tasks, VWM must be subject to significant strategic control. Yet the processes of strategic control over VWM have received relatively little empirical attention.

Early theories of visual function proposed that the maintenance of objects in VWM required sustained attention, and that after the withdrawal of attention, objects in VWM were overwritten by new perceptual input (e.g., Rensink et al., 1997; Wheeler & Treisman, 2002). This conceptualization of VWM does not allow for strategic control of VWM in dynamic tasks, such as holding the target template in memory during search. However, current research indicates that new perceptual information does not necessarily overwrite VWM representations after the withdrawal of attention from the remembered object (e.g., Hollingworth, 2004; Johnson et al., 2008). These findings suggest that VWM representations are robust enough that people could exert strategic control over the content of VWM, preserving task-relevant objects across disruptions and shifts of attention in support of intelligent visual behavior. In fact, recent evidence suggests that the content of VWM is managed according to the needs of the current task, such that

information relevant to the ongoing visual task is weighted more heavily in VWM (e.g., Droll et al., 2005; Richard et al., 2008).

To date, empirical evidence has suggested that control over VWM is implemented via multiple processes: 1) Attention controls the entry of items in VWM (e.g., Olson et al., 2008; Schmidt et al., 2002; but see Yotsumoto & Sekular, 2006); 2) Task-relevant VWM representations can be selectively protected from decay and interference (e.g., Makovski et al., 2008; Matsukura et al., 2007); and 3) VWM resources can be reallocated from no-longer-relevant objects to newly relevant objects (Landman et al., 2003). However, the management of VWM content during scene viewing is considerably more challenging than the circumstances examined by the current research. In real-world scene viewing, one sequentially attends to a series of objects, and it is unlikely that one could sustain attention to a particular remembered object. So, the type of sustained attentional protection observed in these studies is unlikely to be sufficient to protect items across shifts of attention and the eyes.

The present study is the first to examine how the content of VWM is managed during natural scene viewing. In order to address this issue, I presented participants with a series of objects presented sequentially within a workshop scene. The appearance of one object co-occurred with the offset of the previous object. Participants were instructed to fixate each object as it appeared in the scene. After a varied number of objects were presented, a test object appeared in its original location within the scene. Participants responded whether the test object was the same token version of the object that had been presented during the study sequence (e.g., the same fire extinguisher) or a different token version. The appearance of each object within the scene was followed by a tone indicating whether the item was likely to be tested (high-pitched tone) or unlikely to be tested (low-pitched tone). This method enabled the examination of participants' ability to prioritize relevant items in VWM.

The present paradigm differs from previous methods looking at strategic control,

because it implements a scene viewing task closely replicating typical visual behavior. Previous studies have employed cuing paradigms in which a memory array was presented, followed by a blank delay and a test. During the blank delay interval, one or two cues indicated relevant objects. The key distinction between such paradigms and the present study is that selective prioritization during a blank retention interval minimizes factors that are likely to make prioritization difficult, such as shifts of attention and the eyes to other objects and new perceptual input created by these dynamic events. In the present study, strategic maintenance of VWM representations was studied across shifts of attention and movements of the eyes while participants directed the eyes to a series of objects. These disruptions are precisely the events that VWM would need to span in order to establish perceptual continuity and support real-world visual behavior.

In Experiment 1, I examined the extent to which participants could effectively protect memory representations of cued items, despite the subsequent perceptual interference generated by fixating additional items in the scene. Participants were presented with six to ten objects, and on most trials, one of the objects was cued by a high-pitched tone as ‘to-be-remembered’. The cued object was either the second-to-last object before test (one object intervening the cued item and test) or the third-to-last object before test (two objects intervening the cued item and test). In a neutral condition, none of the objects was cued, allowing for a baseline measure of memory performance for the change detection task. The last five serial positions were tested. On trials in which there was a cue, the cued object was tested on 60% of trials, and the other 4 serial positions were each tested on 10% of trials. In the neutral condition, each of the 5 test positions was tested on 20% of trials. The results showed that token change detection performance for cued items was reliably higher than for items in the same serial positions in the neutral condition, indicating that cued items were effectively prioritized in VWM as attention and the eyes were directed to intervening objects. The data were also examined for an advantage for the particular cued object relative to other serial positions within the

sequence. There was a decrease in change detection accuracy for non-cued items within the trial sequence, suggesting that a limited set of VWM resources was strategically allocated to prioritizing cued items at the cost of other items in the sequence. I also found evidence of perceptual interference from objects intervening between a cued object and the test. Objects cued earlier in the sequence were remembered less accurately than objects cued later in the sequence, indicating a degree of interference by subsequent perceptual processing, even for the cued object. The findings from Experiment 1 indicate that task-relevant objects can be effectively prioritized in VWM during a task that requires sequential shifts of attention and the eyes, but prioritization is not absolute, as cued objects earlier in the sequence were remembered less accurately than those later in the sequence.

In Experiment 2, I examined whether the moderate forgetting in Experiment 1 for cued items earlier in the sequence was the result of interference in VWM generated by fixating subsequent items or the result of participants' strategy to encode non-cued objects in the event that they were tested. To encourage participants to maximize prioritization of the cued item, all cues in Experiment 2 were 100% valid. As in Experiment 1, the last 5 serial positions were tested. Under these conditions, performance on the token change detection was relatively high across all 5 serial positions. Accuracy decreased from the most recently fixated serial position 1 to position 5 by less than 10 percentage points. These results suggest that without incentive to remember non-cued items, participants efficiently prioritized cued objects with only minimal interference from subsequent perceptual processing. Experiment 2B included a neutral baseline in which none of the objects was cued. This manipulation allowed for a within-subjects comparison of a 100% valid cue condition and a neutral baseline condition. Reliably superior performance in the valid cue condition relative to the neutral baseline condition was observed at every serial position. The results of Experiments 2A and 2B suggest a highly efficient maintenance operation over objects retained in VWM, one that is capable

of protecting relevant objects from the perceptual interference created by subsequent perceptual processing.

In Experiment 3, I examined the mechanism of this protection, distinguishing between an encoding and a protection explanation. The encoding explanation suggests that objects in VWM are prioritized via more robust encoding of cued objects. The protection explanation holds that objects are prioritized in VWM by protecting cued items from subsequent perceptual interference. To discriminate these hypotheses, participants were presented with two cuing conditions. In the simultaneous cue condition, the cue was presented while the object was visible, 100 ms after the appearance of the object. In the post-cue condition, the cue was presented 100 ms after the mask onset. In this condition, the object could only be prioritized via protection, because the target object was not designated until after it was masked. If prioritization is achieved by preferential encoding, performance in the simultaneous cue condition should have been superior to the post-cue condition, because in the latter, relevant objects were not cued while visible. The results showed no significant difference in memory performance between the two cuing conditions. This suggests that the mechanism of prioritization does not benefit from the opportunity to preferentially encode features of the cued object. It is therefore likely that prioritization operates primarily by the protection of task-relevant objects in VWM from subsequent interference.

In Experiment 4, I examined whether protection of VWM content could be flexibly controlled such that prioritization could be strategically reallocated to a second cued item. To address this issue, trials consisted of either one or two cues. In the event that there was a second cue, participants were instructed that the second cued item was now 'to-be-remembered' and most likely to be tested. A comparison between the ultimately relevant object (the cued item in one-cue trials and the second cued item in two-cue trials) exhibited no significant difference in memory performance between the

two conditions. These results indicate that protection within this flexible VWM maintenance system can be reassigned to new, high-priority items.

In Experiment 5, I examined the fate of the originally cued, de-prioritized object when protection is reallocated to a second item, as in Experiment 4. To test this, Experiment 5 was divided into three cuing conditions. In the one- and two-cue conditions, the first cue was always at serial position 4 (the fourth object before test). In the two-cue conditions, a second cue followed at serial position 3 or 2. Participants were instructed that when there were two cues in a trial, the second cued item was to replace the old item as ‘to-be-remembered’ and the originally cued item was *least* likely to be tested of any object in the sequence. This gave participants strategic incentive to utilize the latter cue and neglect the previously protected object. The results showed that memory performance for the originally cued item on two-cue trials was reduced to levels similar to that of non-cued items, effectively removing the privileged memory trace from VWM originally afforded to that object. In fact, there was a trend toward lower performance for a de-prioritized object compared with non-cued objects at flanking serial positions, consistent with some inhibition of the originally cued object. The results from Experiment 5 indicate that when protection is reallocated from one relevant item to a second relevant item, there is no persisting memory advantage for the de-prioritized object. Rather than leaving a stronger memory trace for de-prioritized items, it appears that having held an object in memory and subsequently reallocating protection to another object may actually result in the inhibition of that item.

The successful management of VWM is imperative for any visual task involving the maintenance of perceptual representations during a short period of time and despite disruptions to perceptual input. Here I demonstrated that the content of VWM is managed in the following manner. During a task requiring active vision, items in VWM are prioritized according to task-relevance with little perceptual interference generated by fixating subsequent objects. For instance, it is indeed the case that one can maintain a

representation of one flower while scanning the garden for other appealing flowers with little perceptual interference generated by subsequent flowers, despite the many disruptions to visual input generated by this search. Such prioritization is likely implemented after the encoding of an object into VWM via protection of the memory representation of the item of interest. These findings are consistent with recent research (Makovski et al., 2008; Matsukura et al., 2007) proposing that attentional cuing operates by protecting the cued item from subsequent perceptual interference. However, the present experiments actually manipulated the degree of subsequent perceptual interference in a simulated scene-viewing task in which participants shifted attention and the eyes to subsequent objects, inducing typical disruptions of perceptual input. If task demands change and prioritization needs to be switched to a different object (e.g., a new, “best candidate” flower is found), this prioritization can be withdrawn from the originally protected item and reallocated to a subsequently relevant object. Prioritization is indeed withdrawn from the previously relevant item, and that item is effectively removed from VWM. Memory performance for de-prioritized items returns to similar, or even lower, levels compared with memory for items that were never cued. This strategic management of the content of VWM represents a flexible working memory system that can be controlled strategically to adapt to the changing demands of a task.

Visual working memory was originally conceptualized as a passive buffer for visual information (Phillips, 1974). This notion has persisted for several decades in passive maintenance accounts of VWM function, such as those reviewed above (e.g., Rensink et al., 1997; Wheeler & Treisman, 2002). However, the present results suggest exquisite strategic control over the content of VWM, with participants demonstrating the ability to flexibly and selectively protect certain items in VWM and the ability to selectively purge no-longer-relevant items from VWM. Throughout the history of VWM research there has been variation in the terminology used to describe this system. Some researchers have used the term VWM, whereas other have used the term “visual short-

term memory”. This variation in terminology reflected the fact that up until this point, it was not clear if this system was a relatively passive buffer (i.e., a *short-term* memory) or a more controlled visual store in the direct service of the current task (i.e., a *working* memory). Based on these results, one can now say that the system is more accurately described as a working memory, retaining visual information flexibly in service of an ongoing task.

Modes of maintaining information in working memory

The present results exhibit elevated memory performance for the most recently fixated items, relative to other non-cued serial positions, across all five experiments. This recency advantage is a standard effect for sequentially presented stimuli and was originally established in the verbal working memory domain. Early theories of memory principally presented participants with a list of words and then instructed them to recall the list of items. These studies found that the first few items in the list and the most recently presented items in the list were remembered at higher rates than items in the middle of the list (Baddeley, 1976; Balota & Engle, 1981; Corballis, 1966; Murdock, 1962). The higher performance for the first items is termed the *primacy effect*. The advantage for the last items, particularly the final item in the list, is termed the *recency effect*. The modal model, a highly influential model of memory, explained these effects via the role of control processes over memory storage (Atkinson & Shiffrin, 1968; Glanzer, 1972). Atkinson and Shiffrin suggested that two memory stores, the short-term store (STS) and the long-term store (LTS) were linked, such that transfer into LTS was dependent upon time spent in the STS. Accordingly, they suggested that the primacy effect was the result of the extended duration the original items in a list spent being rehearsed in the STS and the consequential likelihood they were transferred into the LTS. Atkinson and Shiffrin also suggested that the most recently presented items are the most likely to be actively maintained in the STS, producing the recency effect. Indeed, experiments have shown that when working memory can no longer be allocated to the

last few items in the list due to a secondary task, such as counting backwards for 30 seconds, the recency effect is eliminated (Baddeley & Hitch, 1974; Glanzer & Cunitz, 1966, Postman & Phillips, 1965; but see Bjork & Whitten, 1974; Neath, 1993). And recency effects persist despite variations in the number of items on a list (Murdock, 1962). These results suggest that recency effects reflect the active maintenance of items in working memory.

Subsequently, the recency effect was observed in the visual domain using stimuli of abstract visual patterns that could not have been encoded verbally (Broadbent & Broadbent, 1981; Phillips, 1983; Phillips & Christie, 1977; Wright, Santiago, Sands, Kendrick, & Cook, 1985). In one experiment, Phillips and Christie presented participants with a sequential string of eight abstract block patterns for 1250 ms, followed by a short delay (250 ms) before the next item. Participants were then given a change detection task for each item presented. The result found a robust recency effect (97% accuracy for the last item presented in the test string) and significantly lower, but still above-chance, performance for the rest of the items presented. These results suggest that two distinct memory systems account for the recency effect (VWM) and above-chance pre-recency performance (VLTm). These findings are consistent with the claims of Hollingworth and colleagues, who argued that superior performance for the last two items fixated in a scene indicated a VWM contribution to online scene viewing limited to approximately two objects (Hollingworth, 2004, 2005; Hollingworth & Henderson, 2002).

Support for this association between recency effects and working memory has also been found in patients with anterograde amnesia (Baddeley & Warrington, 1970). Patients with anterograde amnesia exhibit impaired pre-recency performance but intact recency performance. Reciprocally, patients with working memory deficits have been shown to have intact pre-recency performance but impaired recency performance (Shallice & Warrington, 1970). This double dissociation is strong evidence that working memory is the memory system supporting recency performance.

In addition to primacy and recency effects, studies have also shown improved performance at various locations in strings of verbal stimuli. The *salience effect*, or the *von Restorff effect*, is exhibited by better memory for a verbally encoded item that is cued by a distinguishing feature (e.g., the only item on a grocery list that is highlighted) and is more likely to be remembered than other items (Crowder, 1976; Fabiani & Donchin, 1995; Huang & Willie, 1979; Murdock, 1960; Neath, 1998, 2000; von Restorff, 1933; Wallace, 1965). A similar increase in memory performance is found when placing verbal stress on words (Reeves, Schmauder, & Morris, 2000) and syllables in polysyllabic non-words (Gupta, Lipinski, Abbs, & Lin, 2005). However, in all of these studies, the stress or cue is a feature of the input. Such effects do not necessarily address strategic prioritization, implemented by the participant, in order to control the content of working memory.

In the present study, I observed a recency advantage, but there was no evidence of a primacy advantage. The recency advantage replicates the recency effect found in a similar paradigm where objects were sequentially attended in a scene (Hollingworth, 2004). The absence of a primacy advantage could have derived simply from the fact that the first item in the sequence was never tested in the present experiments. However, the first item was tested in Hollingworth (2004), and there was still no evidence of a primacy advantage. In fact, primacy effects are almost never observed in serial memory experiments using visual stimuli that cannot be encoded verbally (Shaffer & Shiffrin, 1972). As indicated above, primacy effects are thought to stem from rehearsal of items in a STS (Atkinson & Shiffrin, 1968). The absence of primacy effects in visual tasks may therefore reflect the fact that visual stimuli are not explicitly rehearsed in VWM (Shaffer & Shiffrin, 1972).

In Experiment 5, I examined the fate of de-prioritized objects and found no persisting memory advantage for the de-prioritized object relative to other non-cued items. In fact, the numerical trend was toward lower performance for de-prioritized

objects relative to non-cued objects at flanking serial positions. This result is difficult to reconcile with traditional models of working memory systems claiming that items maintained longer in a STS are more likely to be transferred into LTM (Atkinson & Shiffrin, 1968). The originally cued object in Experiment 5 should have been retained prominently in VWM until the second cue was presented. Yet, this period of active maintenance does not appear to have generated a memory representation more robust than that of other items in the sequence. Any interpretation of this effect must be highly speculative at this point, especially as there is no equivalent in the verbal memory literature of the two-cue method used in Experiment 5. However, one possibility is that the mechanism of maintenance in VWM, sustained activation of object features in brain regions responsible for visual perceptual processing (Castel, Pratt, & Craik, 2003; Hyun & Luck, 2007; Luck, 2008; Woodman & Luck, 2004; Woodman et al., 2001), does not have the same consequences for LTM consolidation as the active rehearsal of verbal stimuli. Such an account would also be consistent with the general lack of primacy effects in visual serial memory tasks.

Alternatively, there might be direct inhibition of de-prioritized objects in VWM. Assessing the fate of de-prioritized objects and the mechanism by which de-prioritization occurs depends on determining whether memory for these objects just returns to baseline levels or is suppressed to levels below baseline. The results from Experiment 5 suggest a trend toward worse change detection performance for de-prioritized items relative to non-cued items. However, in Experiment 5 this trend is the result of contrasting performance for the de-prioritized object and the immediately adjacent serial positions. It is difficult to draw firm conclusions from this comparison about whether the memory representation for a de-prioritized object is eliminated to baseline (i.e., equivalent to non-cued items) or inhibited (i.e., impaired relative to non-cued objects) because performance at these positions may be affected by prioritizing the adjacent item.

To determine whether the memory representation of the de-prioritized object is

returned to levels similar to other non-cued items or actually inhibited relative to items that were never prioritized, a baseline measure of memory for non-cued items is necessary. This baseline could be integrated into the Experiment 5 paradigm by adding a neutral condition in which none of the items are cued. The equivalent serial position in this neutral condition can be compared to the de-prioritized item to determine whether the memory representation of the cued item is returned to baseline (i.e., similar to the neutral condition) or inhibited (i.e., impaired relative to the neutral condition). This manipulation is currently under investigation and preliminary results suggest that performance for the de-prioritized object is actually lower than the equivalent serial position in the neutral condition, suggesting that de-prioritized objects are in fact inhibited relative to other non-cued items.

Overwriting no-longer-relevant information in VWM

The results of Experiment 5 demonstrate that prioritization of items in VWM can be withdrawn, leaving no privileged memory trace from previously trying to remember that item. This finding raises the issue of how no-longer-relevant information leaves VWM. Current theories of VWM maintenance have suggested that prioritization results via protecting relevant information from subsequent perceptual interference (Makovski et al., 2008; Matsukura et al., 2007). However, these paradigms did not directly manipulate perceptual interference. For instance, Makovski et al. concluded that VWM protects prioritized items from subsequent perceptual input (i.e., the test array). This conclusion was drawn by manipulating set size and determining protection does not operate to reduce inter-item interference. Makovski et al. did not directly manipulate perceptual interference. The present study also does not directly manipulate perceptual interference because participants are continually presented with new perceptual input, as the task requires them to sequentially fixate a series of objects within a scene. Thus, the manner by which information leaves VWM is an important topic for future research.

As discussed above, irrelevant information could be actively purged from VWM.

Alternatively protection of no-longer-relevant items could be released without necessarily directly purging the items from VWM, allowing new perceptual information to overwrite them. In this view, de-prioritized items might remain in VWM until there was subsequent perceptual input to displace them. These alternatives could be discriminated by modifying the double-cuing paradigm used by Matsukura et al. (2007) and Makovski et al. (2008) and varying the extent to which the second cue, indicating the de-prioritization of the original object, is followed by subsequent perceptual interference (e.g., an object mask). Specifically, participants would be presented with one or two cues, and informed that in the event of a second cue, the second cue indicates the object most likely tested and the first cued object is *least* likely to be tested. After the cue(s), half of the trials would include an object mask before memory for objects is probed via a change detection task. The de-prioritized items would be probed on a small proportion of trials to determine if there is better change detection performance for de-prioritized items not followed by a mask compared to de-prioritized items that are followed by a mask. If memory performance for the de-prioritized object is less accurate when the second cue is followed by an object mask, this would suggest that no-longer-relevant items leave VWM via overwriting by subsequent perceptual information following the release of protection of those items. However, if participants can directly purge the originally cued, de-prioritized item on trials in which there is no subsequent perceptual interference as efficiently as when there is subsequent perceptual interference, this would suggest that de-prioritized items can be explicitly removed from VWM rather than having to wait to be replaced by subsequent perceptual information.

Although the mechanism of replacement in VWM has yet to be determined, it is likely that the loss of information from VWM is an all-or-none operation, terminating suddenly and completely. Recent evidence suggests that forgetting in VWM is likely to occur via a “sudden death” of VWM representations (Zhang & Luck, in press), consistent with all-or-none explanations of working memory encoding (Zhang & Luck, 2008),

attentional selection (Sergent & Dehaene, 2004), and recognition memory (Quiroga, Mukamel, Isham, Malach, & Fried, 2008; Yonelinas, 1994). This view is an alternative to the traditional conception that VWM representations gradually decay, reducing in precision over time (Cornelissen & Greenlee, 2000; Lee & Harris, 1996; Paivio & Bleasdale, 1974). Zhang and Luck (in press) assessed the precision of VWM representations after various delays, hypothesizing that if VWM representations decay over time, their precision would also decline over time. They implemented a short-term recall paradigm in which participants were first shown a memory array of 3 colored squares. Then after a 1, 4, or 10 s delay, participants were presented with a color wheel surrounding the screen and 3 outline squares at the same locations as the original memory array. One of the squares was cued by a thicker outline and participants were required to designate the location on the color wheel indicating the color of the cued square. The precision of the VWM representation of the cued item was determined by the distribution of responses around the actual color value of that item, such that a wider distribution indicated less precision. The authors found that after the 4 s delay, although the probability that an item was maintained in VWM decreased, there was little to no change in the precision of the representation of those items that continued to be maintained. These results suggest an all-or-none transition of information out of VWM. The all-or-none transition is consistent with the results of Experiment 5, in which probing memory for the de-prioritized object indicated that information eliminated from VWM appears to have been completely eliminated.

Capacity limitation of VWM maintenance

I have examined the extent to which information is prioritized within VWM, the mechanism responsible for that protection and the ability to reallocate prioritization, returning de-prioritized objects to similar memory levels as non-cued items. While these results support a system of maintenance in which protection is completely withdrawn from an originally cued item in order to protect a new item, there are two possible

explanations for this efficient reallocation. First, participants may have intentionally withdrawn prioritization from the de-prioritized object to the newly relevant object due to the task instructions. Second, protection may have been withdrawn from the first de-prioritized object because the prioritization of two objects exceeded capacity. In general, it is currently unclear whether more than one object can be prioritized at a time. The capacity of strategic prioritization of VWM representations is an important topic for future research.

The capacity of protection in VWM could be addressed using the present paradigm and implementing three cuing conditions: 1) a one-cue condition; 2) a two-cue condition; and 3) a no-cue, neutral condition. In the event of a two-cue trial, rather than be instructed to reallocate protection from the original object to the second object as in the present study, participants would be instructed to protect *both* items. Then at test, participants will be probed equally for either of the two items in the event that two items were cued. Therefore, participants' strategy would be to protect all cued items.

Two principal analyses would then be conducted to address the capacity of prioritization in VWM. First, if two items can be protected efficiently in VWM, change detection performance for both cued items in the two-cue condition should be significantly better than the equivalent serial positions in the neutral condition. The current studies show that participants can protect one item in VWM without diminishing the recency effect, suggesting that at least two items can be stored in VWM during online scene viewing (the cued item and the most recently fixated item). Evidence that both items in the two-cue condition are effectively prioritized would be consistent with estimations of complex object capacity to be around 1-2 objects (Alvarez & Cavanagh, 2004; Hollingworth, 2004; Hollingworth & Henderson, 2002). Second, change detection performance for the cued items from the one-cue and two-cue conditions will be compared to determine if both the two cued items are protected as robustly as the single cued item in one-cue trials. Within the two-cue condition, memory performance for the

first and second cued items will be compared to determine if superior performance exists for the second item, indicating some degree of displacement in VWM of the original item.

Conclusion

The strategic management of VWM is critical to support everyday visual tasks. The flexible maintenance of VWM is the hallmark of a working memory system in which items in memory are managed in specific support of ongoing tasks. Visual tasks involving shifts of attention and the eyes would not be possible without top-down control of VWM. Here, I illuminated several key properties of strategic control over VWM content during real-world scene viewing. First, task-relevant objects are prioritized in VWM despite subsequent perceptual interference. Second, this prioritization is implemented via protection of memory representations. Third, prioritization can be effectively reallocated from a no-longer-relevant object to a new object. Fourth, a de-prioritized object is efficiently eliminated from VWM, leaving a memory trace that is no more robust than memory for non-cued items. Future research will examine the extent of the inhibition of the de-prioritized object, the manner by which subsequent perceptual processing plays a role in releasing protection from VWM content, and the capacity of this protection. This strategic control provides the flexible and efficient management of VWM necessary to support intelligent visual behavior.

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