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Attentional templates in visual search

Valerie M. Beck
University of Iowa

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ATTENTIONAL TEMPLATES IN VISUAL SEARCH

by

Valerie M. Beck

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Thesis Supervisor: Professor Andrew Hollingworth

Graduate College
The University of Iowa
Iowa City, Iowa

CERTIFICATE OF APPROVAL

PH.D. THESIS

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

Valerie M. Beck

has been approved by the Examining Committee for
the thesis requirement for the Doctor of Philosophy degree
in Psychology at the August 2016 graduation.

Thesis Committee: ___________________________
Andrew Hollingworth, Thesis Supervisor

____
Eliot Hazeltine

____
Cathleen Moore

____
J. Toby Mordkoff

____
Shaun Vecera

ABSTRACT

An attentional template based on a feature in visual working memory (VWM) can be used to bias attention toward feature-matching objects in the visual field. Attentional guidance based on a single feature is highly efficient and has been well characterized. It is debated, however, whether multiple features can be used to guide attention simultaneously. Some argue that only a single feature in VWM can be elevated to an "active" state and influence perceptual selection. To evaluate whether multiple features can guide attention simultaneously, eye movements were recorded while participants completed both traditional and gaze-contingent visual search tasks. Participants demonstrated guidance by multiple features by switching between relevant colors frequently and without delay. Furthermore, relevant objects of different colors actively competed for saccadic selection. These results provide compelling evidence that multiple attentional templates are able to guide selection simultaneously.

Although it was originally proposed that a feature in VWM could also be used to bias attention away from irrelevant items ("template for rejection"), the evidence thus far has been mixed. Some studies report that participants were faster to find a target item after being cued with a distractor feature, suggesting participants were using this feature to avoid matching items, while other studies report a cost and find that participants actually attended to cue-matching items even though they are irrelevant. The current work demonstrates that some evidence in support of feature-guided avoidance can be explained by spatially recoding the cued feature information. Furthermore, when shown a distractor color at the beginning of a trial, participants frequently fixated a matching object early in the trial, but avoided matching objects later in the trial. Other work has

suggested that this initial attentional capture by a cue-matching object facilitates later avoidance, but the current data do not support a functional relationship of this nature. In sum, it may not be possible to implement an exclusionary template directly as feature-guided avoidance, but it may be possible to implement indirectly by converting the irrelevant feature information into relevant feature or spatial information.

PUBLIC ABSTRACT

Each time you search for your phone, you bring an image to mind of what your phone looks like and your attention is guided toward similar objects. Now imagine you are searching for your phone and your wallet – can you search for both objects at the same time? Some say no. I examined this by asking people to search for two colors simultaneously while I recorded their eye movements. I found that people frequently switched between the two colors, and that eye movements were made to each color in a similar manner, suggesting that people could search for two things simultaneously.

Alternatively, what if you changed your phone case but you do not remember the color of the new case, only that it is different from the old case which was red. Can you use this “not red” information to help you search and avoid looking at red objects? To examine this, I asked people to search for a particular shape while avoiding any red shapes. I found that people frequently looked at a red item right away, but were able to avoid red items once they knew more about the non-red objects. This suggests that people can avoid particular objects once they know the colors or locations of the remaining objects.

Determining whether people can search for two things simultaneously or avoid searching for irrelevant things is critical for understanding and improving real-world search tasks such as luggage screening, reading x-ray images, and satellite image analysis.

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CHAPTER 1: INTRODUCTION

1.1 Visual Search

Every day we perform any number of visual search tasks: looking for keys on a table, a book on a shelf, or a friend in a crowd. In each of these scenarios, there is an enormous amount of information in the visual scene, but we are somehow able to limit our search to plausible objects. Several different factors, such as likely location or memory of last interaction, can influence where a person chooses to look for something, but here I will focus on how knowledge of specific features influences attentional guidance and results in different search patterns. Say you are looking for *An Introduction to the Event-Related Potential Technique* somewhere on the bookshelves in your office. Being familiar with the book, an image comes to mind of the bright red spine. This knowledge can help you to limit your search to books with red spines, rather than searching randomly or inspecting each book spine in order along the shelves. In this example, the feature red is likely to have been activated in visual working memory (VWM), served as an attentional template, and guided your attention to possible candidate books. Specifying how this process works is critical to understanding and possibly improving real-world visual search tasks such as diagnostic radiology (e.g., Drew et al., 2013), security screening (e.g., Biggs, Cain, Clark, Darling, & Mitroff, 2013), and satellite image analysis (e.g., Peters, Iyer, Itti, & Koch, 2005), but is also important for understanding the basic architecture of the interaction between VWM and attentional guidance.

Intuitively, it seems like we can easily limit our search to items that match the object in memory (search target), but intuition can be misleading. In one of the earliest studies, participants were instructed to find a specific two-digit number (e.g., 39) in an array of other two-digit numbers (Green & Anderson, 1956). When they were also given information about what color the number would appear in, they were faster to locate this target number than when they had no information about what color it would be. In fact, participants were almost as fast at searching through this subset of color-matching numbers (e.g., 20 out of 60 total) as when the entire array contained the same number of items (e.g., 20 total). These data support our intuition, and suggest that participants were able to restrict their search to items matching the target color.

In the decades since Green & Anderson's (1956) study, visual search behavior has been studied extensively and has been fairly well characterized. The response time (RT) benefit from limiting search to items matching a known target feature has been replicated many times using varying combinations of target and distractor features. Search for a single feature (e.g., color) is more efficient than search for a combination of features (e.g., color and orientation) or a spatial configuration (e.g., "T" among "L"s; Wolfe, 1998). Additionally, the magnitude of this RT benefit depends on both target-distractor similarity and distractor heterogeneity, with low target-distractor similarity/low distractor heterogeneity producing the greatest benefit, and high target-distractor similarity/high distractor heterogeneity producing the least benefit (Duncan & Humphreys, 1989). In other words, finding a red book on a shelf full of green books would be trivially easy, but finding a particular red book on a shelf full of books in various shades of red would be quite difficult.

Furthermore, participants can make use of this feature information very quickly. When the target feature varies from trial to trial, participants need only a 200 ms delay between presentation of the relevant feature and appearance of the search array for their search performance to be as efficient as when the target feature remained the same across trials (Wolfe, Horowitz, Kenner, Hyle, & Vasan, 2004). Additionally, search is more efficient when the feature cue is an exact match to the target stimulus, though a feature cue that is a different size or presented at a different orientation still yields more efficient search than an uninformative cue (Vickery, King, & Jiang, 2005). In sum, visual search can be highly efficient, and efficient search can be configured very quickly. Although many other factors such as saliency (e.g., Itti & Koch, 2000), context (e.g., Chun & Nakayama, 2000), and reward history (e.g., Navalpakkam, Koch, & Perona, 2009), among others, can influence visual search performance (for reviews, see Eckstein, 2011; Nakayama & Martini, 2011), the studies presented here will focus on feature-guided visual search.

When feature information is used to guide search, it is frequently described as an “attentional template” or “search template”: an internal representation of the relevant feature(s) that can interact with perceptual selection and guide attention toward relevant objects. Does this attentional template reside exclusively in VWM? There is some evidence that attentional guidance can be controlled by feature information in an “activated long-term memory” (ALTM; Cowan, 1995, 2001) representation (Drew & Wolfe, 2014; Wolfe, 2012). However, the tasks used to support this involve memorizing a large set of possible target items and then searching for the same set repeatedly. Day-to-day visual search tasks typically require searching for a single item or, at most, a small number of items (e.g., phone, keys, wallet), which would not necessarily tax the capacity of VWM. Whether an attentional template is maintained in VWM or ALTM seems to depend primarily on whether the template feature(s) change from one search to the next (as in day-to-day search tasks) or remain constant (Woodman, Luck, & Schall, 2007). The type of stimuli and task demands used in the studies reported here are consistent with those used in studies supporting a VWM attentional template account (Carlisle, Arita, Pardo, & Woodman, 2011; Gunseli, Meeter, & Olivers, 2014; Woodman & Arita, 2011). From here forward, the discussion will be limited to how VWM representations serve as templates and influence attentional guidance.

1.2 Multiple Templates

If a feature representation in VWM can serve as an attentional template (Carlisle, Arita, Pardo, & Woodman, 2011; Gunseli, Meeter, & Olivers, 2014; Woodman & Arita, 2011), and VWM can typically hold three to four items (Cowan, 2001; Luck, 2008), then it could plausibly follow that multiple representations in VWM should be able to guide attention simultaneously. However, some models of working memory propose that only a single item in memory can be in the "focus of attention" and made available for other processes (McElree, 2006; Oberauer, 2002). Consistent with this account, Olivers, Peters, Houtkamp, and Roelfsema (2011) have proposed that, although multiple items can be held in VWM, only a single VWM representation can be elevated to an "active" state that is able to influence attentional guidance. The remaining items are left in an "accessory" state and are not able to influence attentional guidance.

Evidence in favor of this *single-item template hypothesis* (SIT) comes primarily from a series of attentional capture studies. Downing and Dodds (2004) asked participants to perform both a search task and a memory task with the expectation that maintenance of the memory item might interfere with search performance if all items in

VWM automatically interact with perceptual selection. Each trial began with the presentation of two novel shapes: one presented above fixation (the “search target”) and one presented below fixation (the “memory target”). Then, after a delay, a search array appeared and remained visible until the participant indicated whether or not the cued search target was present. After another delay, a memory probe appeared and participants were asked to indicate whether the probe was the same or different from the cued memory item. On 50% of trials, the memory item could appear as a distractor in the search array. If both the search target and memory item representations were influencing attentional guidance, longer RTs should have been observed when the memory item appeared as a distractor in the search array than when it did not.

However, Downing and Dodds (2004) found that a memory item, when included as a distractor in the search array, did not significantly increase search RTs (even though it was ultimately retrieved accurately for the memory test), suggesting that participants’ search was guided only by the search target. The authors interpreted these results as evidence in favor of separate stores within VWM, with one of the stores maintaining representations that are sequestered until required by current task demands. These results have since been interpreted as consistent with Olivers et al.’s (2011) SIT hypothesis: only the search target was “active” for the search task and the memory item was “active” only during the memory task. However, since Downing and Dodds (2004) never demonstrated attentional capture by the complex novel shapes they used in this task when the object was maintained in the hypothesized “active” state, it is unclear whether their paradigm was sufficiently sensitive to detect interference from a memory-matching distractor during a search task.

In a similar study, Houtkamp and Roelfsema (2006) examined whether a secondary search target interfered with performance on an initial search task if it was included as a distractor in the search array. In this task, each trial began with presentation of two objects – one on the left and one on the right – that served as search targets for two upcoming search tasks. After a delay, the first search array appeared on the left side of the screen, and participants were instructed to search for the item that had previously appeared on the left side of the screen ("left target"). Once that target had been reported present or absent, the second search array appeared on the right side of the screen, and participants were instructed to search for the item that had previously appeared on the right side of the screen ("right target"), indicating whether it was present or absent. On half of the trials, the right target could appear as a distractor in the left search array (termed the "memory item", because it had to be held in memory in order to perform the second search task) and, independently, the left target could appear as a distractor in the right search array (termed the "former target"). The authors ran several versions of this task, while recording eye movements or using articulatory suppression, using line drawings of real-world objects, colors, and fractal stimuli.

If both search targets were maintained in a state that influenced attentional guidance, search RTs should have been slower when the "memory item" was included in the first search array, and slower search RTs might also have been observed when the "former target" was included in the second search array (though there was really no reason to continue maintaining the "former target" in memory during the second search task, so discussion here will be limited to results from the first search task). Houtkamp and Roelfsema (2006), however, found very little evidence of interference from the “memory item” during the first search task. Across stimulus sets, there was no significant effect of memory item presence on search RTs on target present trials, but there was some evidence of interference on target absent trials. On the other hand, participants fixated the memory item significantly more often than other distractor items on target present trials with color stimuli, and, although not reliable, the search RTs were higher when the memory item was present, suggesting that the memory item representation was in fact influencing attentional selection, at least on some trials.

In general, Houtkamp and Roelfsema (2006) concluded that, although multiple items could be held in VWM, they do not automatically influence selection, and one representation can be prioritized over others for attentional guidance. These conclusions stop short of a strong SIT hypothesis, consistent with their finding of capture by the currently task-irrelevant memory item under some circumstances. Subsequently, however, these data have been interpreted as supporting the SIT hypothesis that only a single VWM representation can guide attention at any particular time (Olivers et al., 2011). In any case, the paradigm used by Houtkamp and Roelfsema (2006) was suboptimal for examining possible attentional guidance by multiple VWM representations. First, because the search targets and subsequent search arrays appeared in separate hemifields in the Houtkamp and Roelfsema (2006) task, this may have supported the prioritization of the left target for the left array only and the right target for the right array only. Other work has demonstrated that different attentional control settings (e.g., different relevant colors) can be applied to separate regions in space (Adamo, Pun, Pratt, & Ferber, 2008) or different RSVP streams (Moore & Weissman, 2010). Second, the evidence providing the strongest support for the SIT hypothesis in

Houtkamp and Roelfsema (2006) came from experiments using easily nameable line-drawings of common objects, raising the possibility that the “memory item” was converted to verbal label, a format that would be expected to minimize capture. Finally, and similarly to Downing and Dodds (2004), Houtkamp and Roelfsema (2006) did not demonstrate that the experiments with line drawing stimuli were capable of generating attention capture from a memory item maintained in the hypothesized “active” state. In sum, although the data presented in Houtkamp and Roelfsema (2006) lend some support to the idea that VWM representations can be in different states, an “active” state can influence attentional selection and an “accessory” state that does not, they do not conclusively support the claim that attentional guidance is limited to a single VWM representation.

Furthermore, while investigating the automaticity of memory-driven attentional capture, Olivers (2009) found that a memory-matching distractor interfered with search performance only when the search target did not vary from trial to trial. Participants were instructed to hold a color in memory, search for a disk with a notch in the top or bottom, then respond to a memory probe. In the “consistent mapping” condition, the search target could be any color (except the color held in memory) and was the only disk with a notch in the top or bottom (all distractors had a notch in the left or right). In the “varied mapping” condition, the target color was presented at the same time as the color to hold in memory and all disks had a notch in the top or bottom so participants had to use the color information to determine which disk was the search target. In both conditions, a memory-matching distractor was present on half of the trials. When the search target varied and the target feature was also cued at the beginning of the trial (essentially increasing the memory load to two items, as in Downing & Dodds, 2004; and, Houtkamp & Roelfsema, 2006), presence of a memory-matching distractor did not interfere with search performance, suggesting that the search target feature was able to influence attentional guidance but the memory feature was not. Conversely, when the search target did not vary, presence of a memory-matching distractor in the search array interfered with search performance. Consistent with previous studies (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006), the results from Olivers (2009) suggest that the search target feature was prioritized over the memory feature and only a single item in VWM was able to influence attentional guidance.

van Moorselaar, Theeuwes, and Olivers (2014) examined the relationship between memory load and attentional capture by varying the number of items held in memory while participants performed a search task. They used a task similar to that used in Olivers (2009) except that they varied the number of items held in memory, and participants were asked to report whether the target object contained a vertical or horizontal line (distractors also had vertical or horizontal lines). If only a single item can actively influence attentional guidance, as proposed by the SIT hypothesis, then a memory-matching distractor in the search array should produce interference when there is a memory load of one, but should decrease as the memory load increases (smaller probability of the corresponding memory item being in an “active” state by chance as the memory load increases). van Moorselaar et al. (2014) did find reliable interference with a memory load of one, but this interference was not observed with a memory loads of two, three, or four. With a memory load of one, the authors suggest that the single VWM representation was automatically prioritized and able to influence attentional guidance.

With a memory load of two or more and no clear priority for one item over any of the others, however, they argued that none of the VWM representations were able to influence attentional guidance.

To examine the role of prioritization on attentional capture, van Moorselaar et al. (2014) used a constant memory load of two items and tested memory for each at the end of the trial. Critically, on half of the trials they indicated which of the two colors in memory would be tested first (assigning priority to that item) and on the other half the test order was unknown. When the test order was known, they found reliable capture by items matching the first color to be tested, but not by items matching the second color to be tested. When the test order was unknown, they again found no reliable capture by items matching either color in memory. Consistent with Hollingworth and Hwang (2013), who found that a memory-matching item in a search array did not capture attention when the corresponding memory item was deprioritized though still retained, these results suggest that, although multiple items were maintained in VWM, one item was prioritized such that it influenced attentional guidance whereas the other item did not. Although these results support multiple states within VWM ("active" versus "accessory" representations), they do not conclusively demonstrate that attentional guidance is limited to a single VWM representation.

Thus, several studies appear to support a single "active" item, but there are several concerns that need to be addressed. First and foremost, examining whether multiple VWM representations can guide attention by evaluating capture by a memory-matching distractor is not the most direct approach, and this may be a better test of automaticity rather than ability. When a single item is held in VWM, it may be automatically elevated to an "active" state and able to influence attentional guidance, whereas when multiple items are held in VWM, they may remain in "accessory" states, unable to influence attentional guidance, unless one is prioritized over the others (Hollingworth & Hwang, 2013; van Moorselaar et al., 2014). This initial assignment of states within VWM does not necessarily preclude the ability to elevate multiple representations to an "active" state such that they influence attentional guidance simultaneously. Elevating multiple representations to an "active" state may be effortful, though, and therefore not automatic. That is, when the task demands guidance by a single target representation (as in the studies supporting the SIT hypothesis), it may be possible to assign additional memory items to the "accessory" role so as to exert efficient control over attention and avoid capture. However, if the task demands guidance by multiple items, then it may be possible to maintain multiple active template representations in VWM. Thus, a better test of the architectural relationship between VWM and attentional guidance would be to explicitly instruct participants to use multiple features to guide visual search. Initial studies examining guidance by multiple features found that guidance by multiple features was less efficient than guidance by a single feature (Menneer, Barrett, Phillips, Donnelly, & Cave, 2007; Stroud, Menneer, Cave, & Donnelly, 2011). However, these studies used the same target features for the entire experimental session, and the template representations were likely to be maintained in LTM (Carlisle et al., 2011; Woodman et al., 2007). Thus, it is unclear whether guidance by multiple VWM representations is possible.

Moreover, there is no clear architecture constraint that would limit attentional guidance to a single VWM representation. Feature information for items maintained in

VWM can be reliably decoded from activity in visual-sensory cortex for a single item (Harrison & Tong, 2009; Serences, Ester, Vogel, & Awh, 2009) and multiple items (Emrich, Riggall, Larocque, & Postle, 2013). This active maintenance of feature information in visual-sensory cortex could interact with processing of new visual information and bias attention toward items matching the features currently maintained. However, Olivers et al. (2011) have suggested that a gating mechanism might exist elsewhere (possibly in prefrontal regions) that would limit the interaction between VWM and attentional guidance to a single "active" representation. A recent study found reduced connectivity between prefrontal regions and occipital areas under a high memory load (three items) compared with a low memory load (one item; Soto, Greene, Chaudhary, & Rotshtein, 2012), but again relied on interference between items in memory and search performance so it is unclear whether the results are indicative of a gating mechanism or the automaticity of attentional guidance by a single versus multiple VWM representations. Conclusively evaluating whether this gating mechanism exists is beyond the scope of this dissertation, but directly examining the nature of attentional guidance by multiple VWM representations can constrain whether this kind of gating mechanism is necessary and, ultimately, determine whether the SIT hypothesis can be accepted or should be revised.

Last but not least, measures such as accuracy and manual response time may not be sensitive enough to evaluate whether participants are able to use multiple features to guide attention simultaneously or are "activating" and "deactivating" VWM representations as needed. A better approach would be to use an online measure of the moment-to-moment deployment of attention among objects to evaluate how attentional guidance is deployed during the course of the trial. Some studies have evaluated guidance by multiple features in VWM by recording brain activity using the event-related potential (ERP) technique (Grubert & Eimer, 2012, 2015, 2016), but ERP paradigms are better suited to examining the deployment of attention to one or two objects rather than a whole search array. Furthermore, these ERP studies also kept the target features constant for the entire experimental session, so it is unclear whether they examined guidance by VWM or LTM. Recording eye movements while participants perform a search task would provide an online measure of attentional guidance using standard search arrays.

1.3 Negative Template

Woodman and Luck (2007) originally proposed that VWM representations could be used flexibly to either bias attention toward matching items ("template for selection") or bias attention away from matching items ("template for rejection"). Similar to many of the studies described in the previous section, Woodman and Luck (2007) asked participants to hold a colored square in memory, search for a Landolt-C target (outlined square with a gap in the top or bottom) among various colored Landolt-Cs with a left or right gap, then respond to a memory probe. In previous studies that reliably found attentional capture by a memory-matching item (e.g., Experiments 1-3 in Soto, Heinke, Humphreys, & Blanco, 2005), the memory-matching distractor could sometimes contain the target feature (tilted line) so there was some incentive for participants to strategically begin their search with that item when it was present in the search array. To remove this incentive, Woodman and Luck (2007) constrained their paradigm so that a memory-matching distractor never contained the target feature (top or bottom gap). Thus, participants should be motivated to avoid any memory-matching items in the search array.

If the contents of VWM automatically bias attention toward matching items, then the presence of a memory-matching distractor should slow search performance compared to trials without a memory-matching distractor. If, on the other hand, a VWM representation can be used to avoid matching items when they are known to be irrelevant, then search performance could even be faster on trials with a memory-matching distractor (eliminating one item from search) compared to trials without a memory-matching distractor. In their initial study, Woodman and Luck (2007) found numerically faster response times when the search array contained a memory-matching distractor, but they were not reliably faster than for arrays without a memory-matching distractor. It is possible, though, that being able to eliminate only a single memory-matching item from search did not sufficiently motivate participants to strategically avoid the memory-matching item.

Woodman and Luck (2007) increased the incentive to avoid memory-matching distractors by increasing the proportion of search array items that matched the color in memory. As before, each trial began with presentation of one colored Landolt-C with a gap in the left or right to hold in memory. In this version, the search array was expanded from six items (each a different color) to twelve, but now there were two items drawn in one color, four items drawn in a second color, and six items drawn in a third color. The three colors for each trial were selected randomly without replacement from the set of seven colors used previously. Again, the target item was never the same color as that held in memory, but now, because the color in memory was always used as a distractor color, the number of memory-matching items in the search array could be two, four, or six. If attention is automatically biased toward memory-matching items, participants should be slower to respond to the target item as the number of memory-matching items increases. If, however, participants are able to selectively avoid memory-matching items, they should be *faster* to find the target item as the number of memory-matching items increases. Participants were, in fact, reliably faster to respond to the target item when there were six memory-matching distractors compared to when there were only two or four, suggesting that they were able to avoid searching memory-matching distractor items.

However, several studies have produced evidence that is inconsistent with this finding (Folk, Remington, & Johnston, 1992; Hollingworth & Luck, 2009; Hollingworth, Matsukura, & Luck, 2013; Olivers, 2009; Soto et al., 2005; Soto, Humphreys, & Heinke, 2006b). Perhaps the best example comes from a study by Olivers, Meijer, and Theeuwes (2006) who consistently found evidence of attentional capture by a memory-matching distractor, even though it could never be the search target. In their task, each trial began with the presentation of a colored disk with the instruction to hold the color in memory for a later test. After a delay, a central search array appeared and participants were instructed to locate the grey diamond and report whether it contained an “M” or “N”. All remaining items in the search array were grey disks that each contained an horizontally oriented hourglass (|×|) that included features common to both “M” and “N” so that search would be guided by the shape information rather than the feature to report. On 50% of trials, one of the disks appeared in the same color as the memory item (25%) or in an unrelated color (25%). When a memory-matching distractor was present in the search array, Olivers et al. (2006) found reliably greater search RTs than when an unrelated colored distractor or no colored distractor was present. They found the same pattern of interference using shapes instead of color in the memory task (with a luminance-defined search target), and with a combination of color and shape (with a size-defined search target), but not when the memory test preceded the search array, suggesting that the interference observed in the search task depended on maintenance of the memory item in VWM. In sum, this robust RT cost due to presence of a memory-matching distractor during search conflicts with the RT benefit found by Woodman and Luck (2007).

In addition, although the Woodman and Luck (2007) manipulation was a clever way to vary the proportion of memory-matching distractors while keeping the heterogeneity of the search array constant, there may be another possible explanation for the observed pattern of results. Participants might have begun by searching the color with the fewest number of items, then proceeded to the next largest set, then the next. Such an approach could have been strategic, since it would be easier to keep track of previously attended items within the smaller groups, or nonstrategic, since the items in the smaller groups would have been more salient (i.e., lower average similarity to neighboring items, Wolfe, 1994). If they adopted this approach, participants would avoid searching the six memory-matching items not because they were avoiding memory-matching items, but because the largest set of items tended to be searched last.

With this possible alternative explanation in mind, the observed pattern of results is ambiguous. Slower response times when only two memory-matching distractors were present could have been due to the fewer number of items excluded from search or could have been due to participants' attending one or both of these items initially, locating the target item later. Faster response times when six memory-matching distractors were present could have been due to the greater number of items excluded from search or could have been due to participants' beginning search with the colors that had fewer items and typically locating the target before searching the six memory-matching distractors. Furthermore, even though the memory-matching items never had the target feature, it is unclear how strong of an incentive this provided to avoid memory-matching items. To examine whether participants can use a feature to avoid matching items, essentially the inverse of feature-guided search, a more direct approach would be to explicitly cue a distractor feature and instruct participants to avoid searching items with that feature.

Arita, Carlisle, and Woodman (2012) implemented this approach. They cued a distractor color as to-be-avoided and compared search performance in this condition against performance with an uninformative cue. Each trial began with presentation of a colored square that could indicate the distractor color (negative cue), target color (positive cue), or a color not present in the search array (neutral cue). After a delay, a circular search array appeared with six items drawn in one color in the left hemifield and six items drawn in another color in the right hemifield. Participants were instructed to find the Landolt-C with a gap in the top or bottom and make a response indicating the gap position. All remaining items were Landolt-Cs with a gap in the left or right. The two colors used in each search array were selected from a total set of three colors (or seven colors in a later version), so participants were unable to predict the target color in the negative cue condition and needed to maintain the negative cue color in memory in order to avoid matching items. Cue condition was blocked and condition order was randomized across participants.

If participants were able to implement feature-guided avoidance, they should have responded more quickly in the negative cue compared to the neutral cue condition. This is precisely what Arita et al. (2012) found. These results seemed to suggest that participants were able to implement a "template for rejection" and avoid searching cue-matching items in the negative cue condition. However, because the two different colors of items were grouped by hemifield, feature information could have been converted into spatial information with minimal effort. For example, when given a red cue in the negative cue condition, if the red items are in the left hemifield when the search array appears, the participant can use this information to shift attention to the relevant, right hemifield. In this manner, the negative cue information could have been converted into a simple spatial template indicating which side of the screen to avoid, or which side to attend. This potential strategy of spatially recoding the feature information is supported by a previous study that found a reliable benefit for cuing a distractor location compared to an uninformative cue (Munneke, van der Stigchel, & Theeuwes, 2008). Since feature cue information in the Arita et al. (2012) paradigm could be converted into relevant spatial information, it is unclear whether their results are indicative of true feature-guided avoidance. To evaluate whether feature-guided avoidance is possible, it will be necessary to decouple feature and spatial information.

Using search arrays that better disassociated feature and location information, Moher and Egeth (2012) examined feature-guided avoidance when array items were drawn in four different colors and the different colors were not segregated by hemifield.

Each trial began with a negative feature cue (distractor color) or neutral cue (grey) followed by a search array. Similar to the paradigm used by Munneke et al. (2008), participants were instructed to indicate whether a “B” or “F” was present in the search array. On negative cue trials, the cue-matching distractor was always “b” or “f” and could be compatible (same identity) or incompatible (different identity) with the target item. Remaining distractor items were “k” and “x” (one uppercase and one lowercase). The four items in the search array appeared equidistant from the center arranged in a diamond shape with objects above, below, left, and right of the center.

If participants could successfully avoid searching the cue-matching distractor, response times on negative cue trials should have been reduced compared to response times on neutral cue trials, and there should have been no difference between trials for which the cue-matching distractor and target identities are compatible or incompatible (replicating the results from Munneke et al., 2008, but with a feature cue instead of a location cue). If, conversely, participants could not avoid attending to the cue-matching distractor, response times on negative cue trials should not have been faster than neutral cue trials, and a compatibility effect should have emerged, such that response times were greater when the distractor and target identities were incompatible compared to when the identities were compatible. Moher and Egeth (2012) found the latter pattern: participants were slower on negative cue than neutral cue trials and were slower to respond when the memory-matching distractor was incompatible with the target than when it was compatible. These results suggest that participants were unable to avoid attending to the cue-matching distractor and are in conflict with the negative cue benefit observed in Arita et al. (2012) and the avoidance of memory-matching distractors observed in Woodman and Luck (2007).

If attentional capture by memory-matching or cue-matching items occurs automatically, then participants should be subject to the effects of capture early in the trial, but might be able to implement avoidance of irrelevant items later on. Moher and Egeth (2012) examined this by presenting placeholders in the same colors and at the same locations of items in the subsequent search array for varying delays (100, 800, or 1500 ms). Additionally, they added a larger set size of twelve items including three items drawn in each of the four colors. If participants are able to implement feature-guided avoidance, they should demonstrate a greater benefit from avoiding a larger number of items. Moher and Egeth (2012) anticipated finding capture by cue-matching distractors at the short delay (100 ms), such that response times would be greater for negative cue than neutral cue trials. They further predicted finding evidence of avoidance at the longer delays (800 and 1500 ms) such that response times would be greater for neutral cue than negative cue trials. Indeed, Moher and Egeth (2012) found evidence of capture at the short delay and evidence of avoidance at the longer delays suggesting participants were not able to implement feature-guided avoidance immediately, but were able to eventually.

Similar to Tsal and Makovski's (2006) "process-all" mechanism, Moher and Egeth (2012) proposed a "search and destroy" mechanism to account for both initial capture by and later avoidance of cue-matching items. Whereas the "process-all" mechanism suggests that all stimuli are initially attended regardless of task demands, the "search and destroy" mechanism suggests that cue-matching items are actively sought out and attended in order to facilitate later avoidance. Thus, Moher and Egeth (2012) have proposed that early capture and later avoidance are functionally related. It is unclear, however, that the avoidance of cue-matching items they observed at longer delays is truly feature-guided avoidance. Because the placeholders conveyed the relevant color information, participants could have attended each of the cue-matching placeholders (1-3 items) during the longer delays and either marked those locations for inhibition or created a spatial template for the locations of potentially relevant items (locations of all colors except the cued color; 3-9 items). The “avoidance” observed at the longer delays could have been evidence of memory for which locations had already been searched (as in Peterson, Beck, & Vomela, 2007) rather than true feature-guided avoidance. Even if there is later avoidance, it is unclear whether it is functionally related to initial capture or if the two phenomena are, in fact, separate processes that co-occur. A more direct approach to examine whether this functional relationship exists would be to use an online measure, such as recording eye movements, to observe how selection unfolds during the course of a trial and whether, on individual trials, later avoidance is dependent on early capture.

Resolving whether it is possible to implement a negative attentional template, resulting in feature-guided avoidance of matching items, is another critical component to understanding the relationship between VWM and attentional guidance. Several studies have demonstrated that attention is automatically directed to VWM-matching items (e.g., Folk et al., 1992), even if they are known to be irrelevant for the current task goals (e.g., Experiment 4 in Soto et al., 2005). However, when a known target feature can be prioritized over a known distractor feature, memory-matching distractors no longer capture attention (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, 2009). If true feature-guided avoidance is possible such that attention is guided *away* from memory-matching items, attentional capture by known irrelevant items should not occur, which would be inconsistent with prior work. Alternatively, if early capture by memory-matching distractors facilitates later avoidance of other memory-matching distractors, then early capture and later avoidance will tend to co-occur. On the other hand, if feature-guided avoidance can only occur via some indirect means, such as converting the negative cue information into relevant features or locations, we may still observe early capture on some trials as this conversion is taking place, but avoidance of memory-matching distractors would not depend on early capture and could be observed in the absence of early capture. Determining the nature of feature-guided avoidance, whether it can be implemented directly or only indirectly, will further illuminate the relationship between VWM and attentional guidance.

1.4 Motivation and Outline of Dissertation

Guidance of attention by a single feature value has been studied extensively, but most studies have focused on the total amount of time it takes to locate and respond to the target item, which is not the most direct method for assessing the selection of individual objects across the trial (Zelinsky, Rao, Hayhoe, & Ballard, 1997). Different search slope functions can reveal how efficient one type of search task is compared to another (e.g., searching for a “Q” among “O”s is more efficient and has a flatter search slope than searching for an “O” among “Q”s; Wolfe, 2001), but they do not allow us to examine attentional guidance at an object-by-object level. In most of the studies included here, I recorded eye movements while participants performed various search tasks so that I could more directly examine how features in VWM influence attentional guidance. Although shifts of attention and eye movements are not perfectly correlated – it is possible to shift attention without making an eye movement – eye movements are preceded by a shift of attention to the saccade location (Hoffman & Subramaniam, 1995), and can serve as a proxy for measuring the deployment of attention more generally.

Because many different factors can influence search performance, several practices were adopted to better isolate the interaction between VWM and attentional guidance. First, the studies described here used easily discriminable colors for target and distractor items, and each item contained a single relevant feature, which should result in relatively efficient search (Duncan & Humphreys, 1989; Wolfe, 1998). Second, the delay between presentation of the cue stimulus and search array was sufficiently long for an attentional template to be established (Vickery et al., 2005; Wolfe et al., 2004). Third, each search array contained enough items to observe how attentional guidance unfolded during the course of a trial. And lastly, because target prevalence can influence search termination thresholds (Fleck & Mitroff, 2007; Hout, Walenchok, Goldinger, & Wolfe, 2015; Peltier & Becker, 2016; Wolfe, Horowitz, & Kenner, 2005) and target absent trials can be difficult to interpret, the studies described here used paradigms for which there was a target item present on every trial and participants reported a secondary feature (e.g., gap location).

In the following chapters, I examine two properties of attentional templates that remain poorly understood: 1) Can multiple VWM representations guide attention simultaneously? 2) Can a VWM representation serve as a negative attentional template and result in feature-guided avoidance?

Chapters 2 and 3 examine whether multiple VWM representations can guide attention simultaneously. In Chapter 2, I first identified markers of switching between attentional templates. Specifically, I examined the pattern of eye movements when the task explicitly encouraged participants to search objects of one color and then switch to objects of another color. I identified “run length” – number of same-color items fixated sequentially – and “switch cost” – delay before initiating a saccade to a new color object – as markers of template switching. Next, I looked for these markers of template switching when participants were asked to search for a target item that could be presented in either of two cued colors. If participants were able to use multiple VWM representations to guide attention, they should switch back and forth between objects in the two cued colors, with no delay when switching from objects in one color to objects in the other. In Chapter 3, I used a gaze-contingent paradigm to directly manipulate selection history and examine whether multiple VWM-matching objects actively compete for saccade target selection.

Chapters 4 and 5 examine whether a VWM representation can serve as a negative template and result in feature-guided avoidance of memory-matching objects. In Chapter 4, I investigated whether results supporting a feature-based negative template could be explained by spatially recoding the feature information. To test this, I first replicated the previous results with their paradigm, then modified the paradigm to manipulate the ease with which participants were able to spatially recode the cue information. In Chapter 5, I examined the implementation of a negative attentional template. Specifically, I recorded eye movements while participants performed a search task after viewing a valid (target color), invalid (distractor color), or neutral cue. I also varied the delay between cue and search array onset to investigate whether a negative attentional template required a greater amount of time to be properly established.

CHAPTER 2: MULTIPLE TEMPLATES IN VISUAL SEARCH

2.1 Overview

Working memory representations play a key role in controlling attention by making it possible to shift attention to task-relevant objects. Visual working memory has a capacity of three to four objects, but recent studies suggest that only one representation can guide attention at a given moment. We directly tested this proposal by monitoring eye movements while observers performed a visual search task in which they attempted to limit attention to objects drawn in two colors. When the observers were motivated to attend to one color at a time, they searched many consecutive items of one color (long run lengths) and exhibited a delay prior to switching gaze from one color to the other (switch cost). In contrast, when they were motivated to attend to both colors simultaneously, observers' gaze switched back and forth between the two colors frequently (short run lengths), with no switch cost. Thus, multiple working memory representations can concurrently guide attention.

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2.2 Introduction

The mechanisms of selective attention fall into two classes, those involved in determining relevant sources of information (*attentional control* mechanisms) and those responsible for enhancing the processing of relevant sources and inhibiting competing sources (*attentional selection* mechanisms; Luck & Vecera, 2002). Multiple factors contribute to attentional control; these factors include bottom-up salience, trial-by-trial priming, associative learning, and long-term knowledge (Chun & Turk-Browne, 2008; Kristjánsson, 2008; Torralba, Oliva, Castelhano, & Henderson, 2006; van der Stigchel et al., 2009). However, the guidance of attention toward task-relevant objects is thought to depend primarily on working memory representations (Soto, Hodsoll, Rotshtein, & Humphreys, 2008). Working memory guidance makes it possible for attention to “change gears” rapidly, because information can be loaded into visual working memory (VWM) in as little as 50 ms (Vogel, Woodman, & Luck, 2006), which leads to changes in the control of attention in 200 ms or less (Vickery et al., 2005; Wolfe et al., 2004).

The typical storage capacity of VWM is three to four items (Cowan, 2001; Luck, 2008). Consequently, one might expect that observers could maintain three to four simultaneous search templates, which would be useful in many natural tasks (e.g., finding either an orange or an apple on the counter). However, several researchers have argued that not all working memory representations are equal (Cowan, 2001) and that only a single object is in a fully active state (McElree, 2001; Oberauer, 2002). This view has led to a theory of attentional control in which only a single VWM representation can control attention at any given time (Olivers et al., 2011). A similar claim is made by Huang and Pashler (2007), whose Boolean-map theory of attention proposed that the visual input can be subdivided into to-be-attended and to-be-ignored regions on the basis of just one feature value.

These proposed limits on VWM control could reflect a fundamental bottleneck in the architecture of the brain. It is possible that, despite the ability to represent multiple objects, only one control signal can be sent from working memory processes to attentional mechanisms that implement visual selection. However, an architectural division of this kind is difficult to reconcile with evidence that VWM and perceptual processes are closely integrated. VWM representations can be stored within the visual system itself (Luck, 2008), including within primary visual cortex (Harrison & Tong, 2009; Serences et al., 2009). If multiple VWM representations are active within the visual system, it should be possible for them to simultaneously control attention. In line with this possibility, a recent study found that observers could search selectively for targets matching two different templates (Stroud, Menneer, Cave, & Donnelly, 2011). However, the targets remained constant over the entire session, which made it likely that attention was guided by long-term memory rather than by working memory. It is also possible that observers switched back and forth between the templates rather than concurrently searching for both targets. Thus, it is unknown whether observers can use two working memory representations simultaneously to guide attention.

The present study addressed this fundamental issue by measuring the pattern of eye movements as observers searched for a target presented in either of two colors. If observers maintain only one search template at a time, they should tend to search many items of one color before switching to search items of the other color, with a brief pause as they switch from one control signal to the other. However, if observers can keep two templates active concurrently, then they should switch back and forth between objects in the two colors, with no delay when switching from objects in one color to objects in the other.

2.3 Experiment 1: Establishing Markers of Template Switching

Before testing observers' ability to search arrays of two different colors concurrently, we examined the pattern of eye movements when the task explicitly encouraged observers to search objects of one color and then switch to objects of another color. That is, Experiment 1 was designed to reveal the signatures of a single attentional template during search.

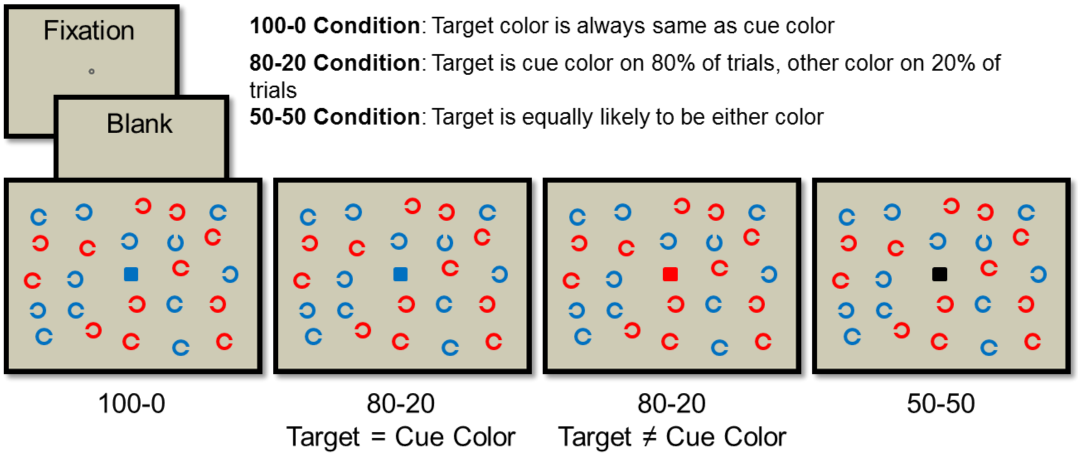
Each search array contained 12 red Landolt Cs, 12 blue Landolt Cs, and a cue square (Figure 2.1). Observers searched for a target C with a gap on the top or bottom and reported the gap location. There were three conditions, in which the predictability of the target color was varied. In the 80-20 condition, observers were told that the target was 80% likely to be the same color as the cue square (which alternated between blue and red, depending on the trial block). These probabilities encouraged observers to search first among objects in the color with the 80% probability of containing the target (the *80% color*) and then, if the target had not been found, switch to objects of the other color (the *20% color*). We also included a 50-50 condition, in which the target was equally likely to be red or blue, and a 100-0 condition, in which the target was 100% likely to be either red or blue, depending on the trial block. The 50-50 and 100-0 condition assessed the limits of attentional control when the color of the target was maximally and minimally uncertain.

In the 80-20 condition, we predicted that observers would fixate many items of the 80% color consecutively, more than would be predicted if observers switched back and forth between items of each color randomly (but with 80% of fixations directed toward the 80% color). We further predicted that observers would switch to the 20% color if they did not find the target in the 80% color, which would require updating the search template and therefore produce a delay in making the next saccade (such a delay would be analogous to switch costs in the task-switching literature; Monsell, 2003).

2.3.1 Method

Observers. Twelve observers (7 female, 5 male; age range = 18-30 years) from the University of California, Davis, completed the experiment. They reported normal color vision and normal or corrected-to-normal visual acuity.

Stimuli and procedure. Stimuli were presented on a CRT monitor at a viewing distance of 70 cm. Each search array contained 24 Landolt Cs – 12 red (8.12 cd/m^2) and 12 blue (8.96 cd/m^2) – presented against a grey background (42.31 cd/m^2; see Figure 2.1). Color coordinates were quantified using the Commission Internationale de l'Éclairage (CIE) 1976 color-space diagram (red: $u' = 0.479$, $v' = 0.514$; blue: $u' = 0.180$, $v' = 0.158$; Wyszecki & Stiles, 1982). Each circle was 0.67° in diameter, had a line width of 0.10°, and a gap measuring 0.07°. Circles were assigned randomly to locations within a 5 x 5 grid (excluding the center location) and jittered within each cell by ±0.96° vertically and ±0.82° horizontally. There was one target circle (in which the gap was on the top or bottom) and 23 distractors (in which the gap was on the left or right).



100-0 Condition: Target color is always same as cue color

80-20 Condition: Target is cue color on 80% of trials, other color on 20% of trials

50-50 Condition: Target is equally likely to be either color

Figure 2.1. Example trial sequence and search arrays for Experiment 1. Observers began each trial by gazing at a central fixation region for 300 to 500 ms. After a blank interval, a cue square and search array appeared. The cue color was the same in every stimulus array for a given block of trials. Each search array contained 24 Landolt Cs – half of which were red, and half of which were blue – presented on a light grey background. In the 100-0 condition, the target was always the cue color. In the 80-20 condition, the target was the cue color on 80% of trials and was the other color on the remaining 20% of trials. In the 50-50 condition, the cue was black, and the target was equally likely to be blue or red.

Observers began each trial by directing their gaze to a central fixation region (a square 1.55° in width) for 300 to 500 ms. Then the cue square (0.65° in width) and search array appeared and remained on screen until the observer’s response. In the 100-0 and 80-20 conditions, the cue square provided a constant reminder of the cued color throughout the search task. The cue square was black in the 50-50 condition. The different cue colors and probability conditions were presented in separate blocks (in counterbalanced order), and observers were informed of both factors at the beginning of each block.

Observers reported the location of the target gap by pressing a button. The gaps in the circles were so small that discriminating them required object fixation, and the task therefore implicitly required observers to translate covert attentional control into overt shifts of gaze. There were two blocks of 42 trials each in the 100-0 and 50-50 conditions and four blocks of 52 trials each in the 80-20 condition. There was a 1,000-ms delay between trials. The first two trials in each block were considered buffer trials and were excluded from all analyses.

Eye movements were recorded at 2000 Hz using an Eyelink 1000 eye tracker (SR Research, Kanata, Ontario, Canada). Saccades were defined by a combined velocity (>30°/s) and acceleration (>9500°/s^2) threshold.

2.3.2 Results and Discussion

Manual response accuracy was uniformly high (M = 99% correct) across all conditions.

Selectivity of search. Observers used the cue to limit their gaze to the most likely target color. As Figure 2.2A shows, manual correct reaction time (RT) was fastest in the 100-0 condition and slowest when the target appeared in the 20% color of the 80-20 condition. All pairwise differences were significant ($p < .05$), except the difference in RT between the 50-50 condition and the trials from the 80-20 condition in which the target appeared in the 20% color. The same pattern was observed for the time required for gaze to reach the target item (all *p*s < .05; Figure 2.2A) and for the number of items fixated prior to fixating the target (all *p*s < .05; Figure 2.2B). The strong correspondence between eye movement measures and manual RTs validates the use of eye tracking to probe search efficiency in the paradigm. All subsequent eye movement analyses reported here are limited to fixations prior to the target fixation.

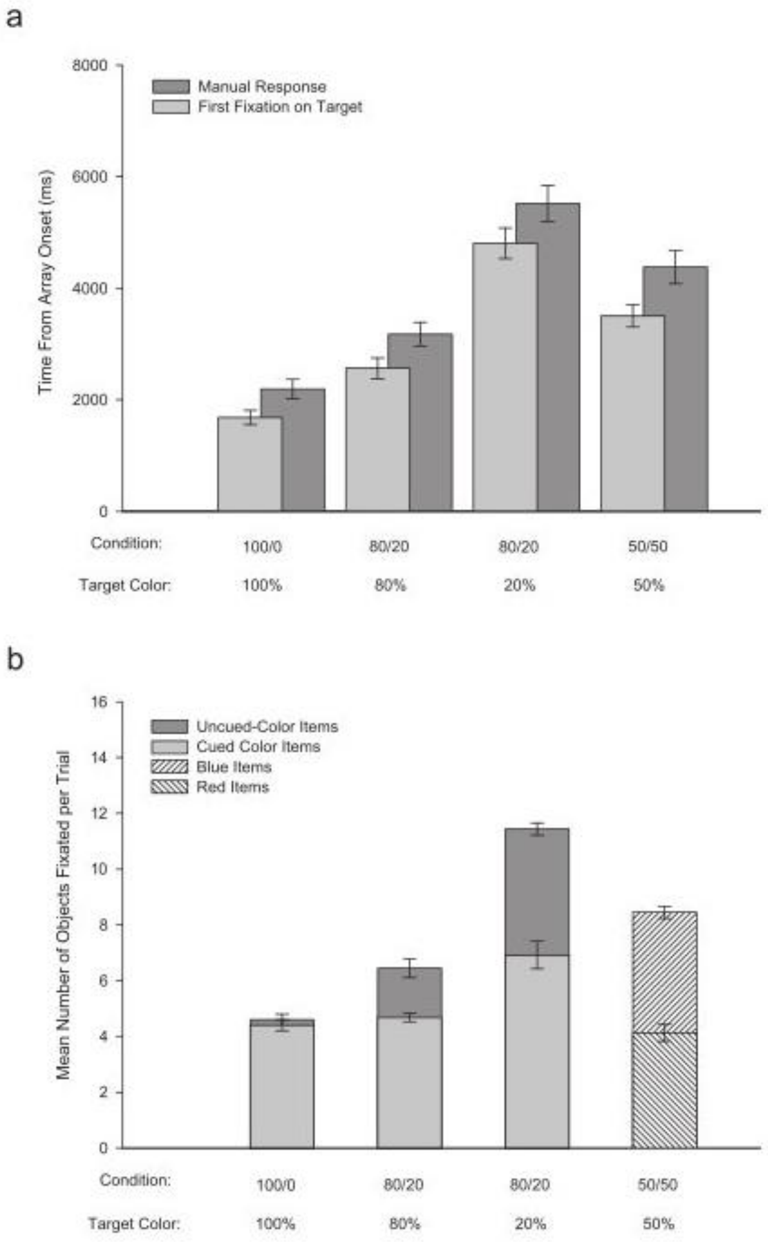


Figure 2.2. Response times (A) and number of objects fixated per trial (B) in Experiment 1. Mean manual response times and mean times to target fixation are shown as a function of condition. The mean number of objects fixated per trial is shown as a function of condition and whether items were cued or uncued; the height of each bar indicates the total number of objects fixated, and the shading indicates how that total was divided between cued- and uncued-color objects (in the 100-0 and 80-20 conditions) or between red and blue objects (in the 50-50 condition). Error bars in both panels show within-subjects 95% confidence intervals (Morey, 2008).

Selectivity was nearly perfect in the 100-0 condition, with almost all fixations directed to the cued color instead of the uncued color, $t(11) = 22.12$, $p < .001$. In the 80-

20 condition, gaze was directed to the 80% color much more often than to the 20% color when the target was in the 80% color, $t(11) = 7.00$, $p < .001$, and somewhat more often when the target was in the 20% color, $t(11) = 4.57$, $p < .001$. In the 50-50 condition, gaze was directed nearly equally to the red and blue items, $t(11) = 0.90$, $p = .39$. Thus, observers used the color probability information to control the search process.

Run length. Next, we examined whether observers maintained a consistent color template in the 80-20 condition, producing several consecutive fixations on items in the same color. In this condition, observers might use a *sequential-exhaustive* strategy, in which they search the 80% color exhaustively and then switch to the 20% color if the target had not been found. Alternatively, observers might use an *independent-search* strategy, in which they select each successive saccade target independently, with an 80% probability of selecting the 80% color and a 20% probability of selecting the 20% color. To distinguish these possibilities, we examined the number of items of a particular color fixated consecutively (*run length*). The sequential-exhaustive strategy should result in a greater mean run length than the independent-search strategy. Monte Carlo simulations were used to assess whether the observers conformed to these strategies (see the supplemental material at the end of this chapter). We examined the initial run at the beginning of each trial. In addition, we focused on trials in which the target appeared in the 20% color and observers started by searching items in the 80% color, as this circumstance required observers to switch colors to detect the target (similar results were obtained when the target appeared in the 80% color).

The mean initial run length was 6.61 items, which was significantly greater than the run length of a simulated observer (4.63 items) that independently selected each saccade destination according to the 80-20 probabilities, $t(11) = 2.203$, $p = .05$. Observed run length was also significantly greater than the initial run length of 2.07 in the 50-50 condition, $t(11) = 5.12$, $p < .001$. Run length for the 50-50 condition was nearly identical to the value expected if red and blue items were fixated randomly (2.00 items). Thus, run length can be a signature of search template use.

Monte Carlo analyses demonstrated that the optimal strategy in the 80-20 condition would be to first search all 12 items in the 80% color, but the mean initial run length (6.61 items) was significantly less than 12, $t(11) = 5.98$, $p <.001$. Although observers maintained a template of the 80% color, they tended to switch to the 20% color sooner than was optimal. This may reflect limits on the ability to keep track of which items have already been searched (Horowitz & Wolfe, 1998; Peterson, Kramer, Wang, Irwin, & McCarley, 2001) or it may reflect a tendency to engage in suboptimal probability-matching strategies (Vulkan, 2000).

Switch cost. We next examined the process of switching from one template to another. As Figure 2.3 shows, the duration of the fixation immediately before switching (preswitch fixation) was significantly greater than both the duration of the fixation immediately prior to the preswitch fixation (preswitch fixation minus one), $t(11) = 3.12$, $p = .01$, and the duration of the first fixation on the new color (postswitch fixation), $t(11) = 2.16$, $p = .05$. A key finding is that this switch cost was not present in the 50-50 condition, in which observers often switched randomly from one color to the other. The difference in the switch costs between the 80-20 and 50-50 conditions was confirmed by an analysis of variance (ANOVA) with condition (80-20 vs. 50-50) and fixation position (preswitch fixation minus one vs. preswitch fixation) as factors. There was a significant interaction between condition and fixation position, *t*(11) = 2.61, *p* = .02, but there were no significant main effects. Thus, observers produced a switch cost only when they were actively selecting on the basis of color; this finding provides a second signature of a search template use.

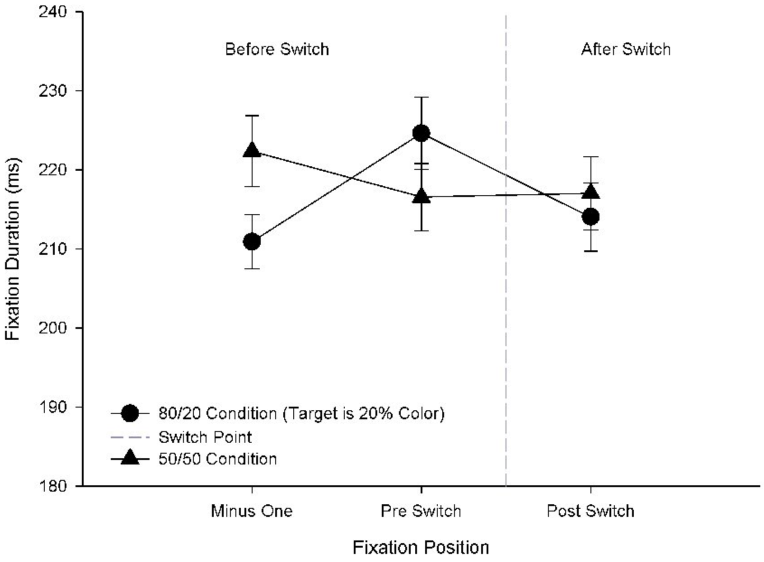


Figure 2.3. Mean duration for fixations immediately prior to and following switches from fixating objects of a given color to fixating objects of the other color in Experiment 1. Durations are shown for the two fixations prior to the switch and the fixation after the switch in the 80-20 and the 50-50 conditions. In the 80-20 condition, this analysis was restricted to trials on which observers switched from a run of cued-color items to a run of uncued-color items. In the 50-50 condition, we analyzed trials on which observers switched from a run of one color to a run of the other color. A run occurred when two or more objects of the same type were fixated consecutively. Error bars show within-subjects 95% confidence intervals (Morey, 2008).

Summary. Together, these results provide strong evidence that observers can form a strong search template when the task encourages it, limiting gaze almost perfectly to cued-color items when the cue is 100% valid and limiting gaze primarily to cued-color items when the cue is 80% valid. Moreover, observers consecutively searched many items of the cued color, and they exhibited a cost when they switched from searching items of one color to items of the other. When color was nonpredictive, however, observers ignored color and switched randomly between red and blue with no switch cost. These patterns serve as signatures of search template use that can be applied to the main question of the study: Can observers maintain two templates concurrently in VWM?

2.4 Experiment 2: Searching for Multiple Features Simultaneously

In Experiment 2, a cue was presented before the onset of the search array, and the cued colors changed randomly from trial to trial (Figure 2.4). Consequently, it was necessary to store the cued colors in VWM and use the VWM representation to guide attention (Chelazzi, Miller, Duncan, & Desimone, 1993; Vickery et al., 2005; Wolfe et al., 2004; Woodman et al., 2007). Each search array contained eight items in each of four colors, and either one or two of these four colors was indicated by the cue. The target was always a cued color. We tested whether observers would concurrently search items in two of the four colors when two colors were cued or, alternatively, search multiple items of one color and then switch to the other color (as they typically did in the 80-20 condition of Experiment 1).

Because observers may be able to strategically control whether they maintain two simultaneous templates or switch between one template and another, we gave observers explicit instructions about which strategy to use. In half of the trial blocks, they were instructed to search items of one color and then switch to the other. In the other half, they were instructed to search items of both of the two cued colors concurrently. The goal was to determine whether they could actually search both cued colors concurrently when instructed to do so.

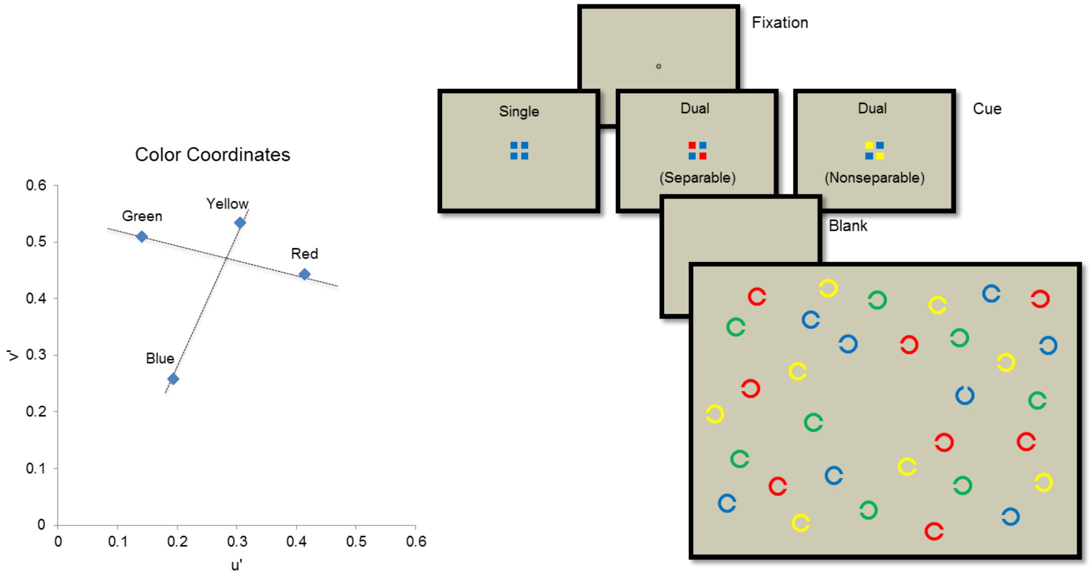


Figure 2.4. Color coordinates for the search objects and trial sequence in Experiment 2. The graph shows the values of the four colors used in the experiment; these colors were quantified using the Commission Internationale de l'Éclairage 1976 color-space diagram (Wyszecki & Stiles, 1982) to form a quadrangle in color space. Observers began each trial by gazing at a central fixation region for 300 to 500 ms, after which a cue appeared in the center of the screen for 500 ms. On single-cue trials, all four squares in the cue were the same color; on dual-cue trials, the two cued colors were presented in diagonally opposed squares. There were two types of dual-cue trial: On separable trials, the two cued colors were drawn from one side of the quadrangle. On nonseparable trials, the two cued colors were drawn from opposite sides of the quadrangle. A 500-ms blank interval followed presentation of the cue, after which the search array appeared. Each array contained 32 Landolt Cs – 8 red, 8 blue, 8 yellow, and 8 green – presented at randomly selected locations on a grey background.

2.4.1 Method

Eleven new observers (8 female, 3 male; age range = 18-30 years) participated in Experiment 2. Stimuli were presented on a CRT monitor at a viewing distance of 70 cm. Each trial began with the presentation of a cue square, which subtended 0.79° and was composed of four smaller squares, each subtending 0.36°. On single-cue trials, all four squares in the cue were the same color; on dual-cue trials, two diagonally opposed squares were presented for each of the two cued colors.

On all trials, the cue square was followed by a search array containing 32 Landolt Cs – 8 red (CIE 1976 colors: u' = 0.414, v' = 0.443; 18.75 cd/m^2), 8 blue (CIE 1976 colors: *u'* = 0.193, *v'* = 0.259; 18.60 cd/m^2), 8 yellow (CIE 1976 colors: *u'* = 0.305, *v'* = 0.535; 18.67 cd/m^2), and 8 green (CIE 1976 colors: *u'* = 0.141, *v'* = 0.510; 18.60 cd/m^2) – presented against a grey background (39.65 cd/m^2). As in Experiment 1, each circle was 0.67° in diameter, had a line width of 0.10°, and a gap measuring 0.07°. Landolt Cs were assigned randomly to locations with a 20.85° x 15.82° region, with a minimum inter-item distance of 2.10° and a minimum distance from the region's center of 1.96°.

To ensure that observers focused on the cue colors and did not simply search for an item with a top or bottom gap, one item of an uncued color contained a top or bottom gap. The target was therefore defined as having both the cued color and a top or bottom gap.

When two colors are cued, observers might form a single template that covers a broad area of color space including both colors, but this is possible only when the cued colors are linearly separable from the uncued colors (D'Zmura, 1991; Duncan & Humphreys, 1989). Color values were selected to form a quadrangle in CIE 1976 color space (see Figure 2.4). On separable dual-cue trials, the two cued colors were on one side of the quadrangle (e.g., red and yellow), and the two uncued colors were on the other (e.g., green and blue); presenting them in this fashion made it possible for observers to form a single template that was closer to the two cued colors than to the two uncued colors. On nonseparable dual-cue trials, the two cued colors were diagonally opposed in color space (e.g., red and green), and the two uncued colors were diagonally opposed along the orthogonal direction (e.g., blue and yellow). Presenting the colors in this manner ensured that no single color value was closer to the cued colors than to the uncued colors. It has been well established that this method precludes the use of a single template for both cued values (D’Zmura, 1991; Duncan & Humphreys, 1989). Single-cue, separable dual-cue, and nonseparable dual-cue trials were randomly intermixed.

Observers began each trial by directing their gaze to a central fixation region (1.55°) for 300 to 500 ms, after which the cue appeared in the center of the screen for 500 ms. After a 500-ms blank interval, the search array appeared. Observers were instructed to search items in one color at a time in half of the trial blocks (sequential-search condition) and to search items in the two colors simultaneously in the other half (simultaneous-search condition). They reported whether the gap on the target circle was on the top or the bottom by pressing a button. Observers performed 16 blocks of 32 trials each, which yielded a total of 120 single-cue, 240 separable dual-cue, and 120 nonseparable dual-cue trials (after excluding two warm-up trials in each block). Block order was counterbalanced, and there was a 1,200-ms delay before each trial. Eye movements were recorded and saccades were defined as in Experiment 1.

2.4.2 Results and Discussion

Overall search performance. Manual response accuracy was uniformly high across all conditions (M = 97% correct). Search RT was lower on single-cue trials than on dual-cue trials (Figure 2.5A), $t(10) = 18.27$, $p < .001$, which reflected the fact that attention was limited to 8 items on single-cue trials versus 16 items on dual-cue trials. The single-cue trials replicated the results from the 100-0 condition of Experiment 1.

For dual-cue trials, there was no significant effect of instructions (sequential vs. simultaneous search) on manual RT, elapsed time to target fixation, or the number of items fixated prior to target fixation (Figure 2.5; all $ps > .22$). For all three of these measures, there was no difference between separable and nonseparable trials (all $ps >$

.25). A Bayes factor analysis (Rouder, Speckman, Sun, Morey, & Iverson, 2009) indicated that the null hypothesis was substantially more probable than the hypothesis that performance in the separable and nonseparable dual-cue trials differed (odds ratio of 4.0 for RT, 3.4 for time to target fixation, and 2.3 for number of fixations). Consequently, we collapsed the data for separable and nonseparable dual-cue trials in all subsequent analyses.

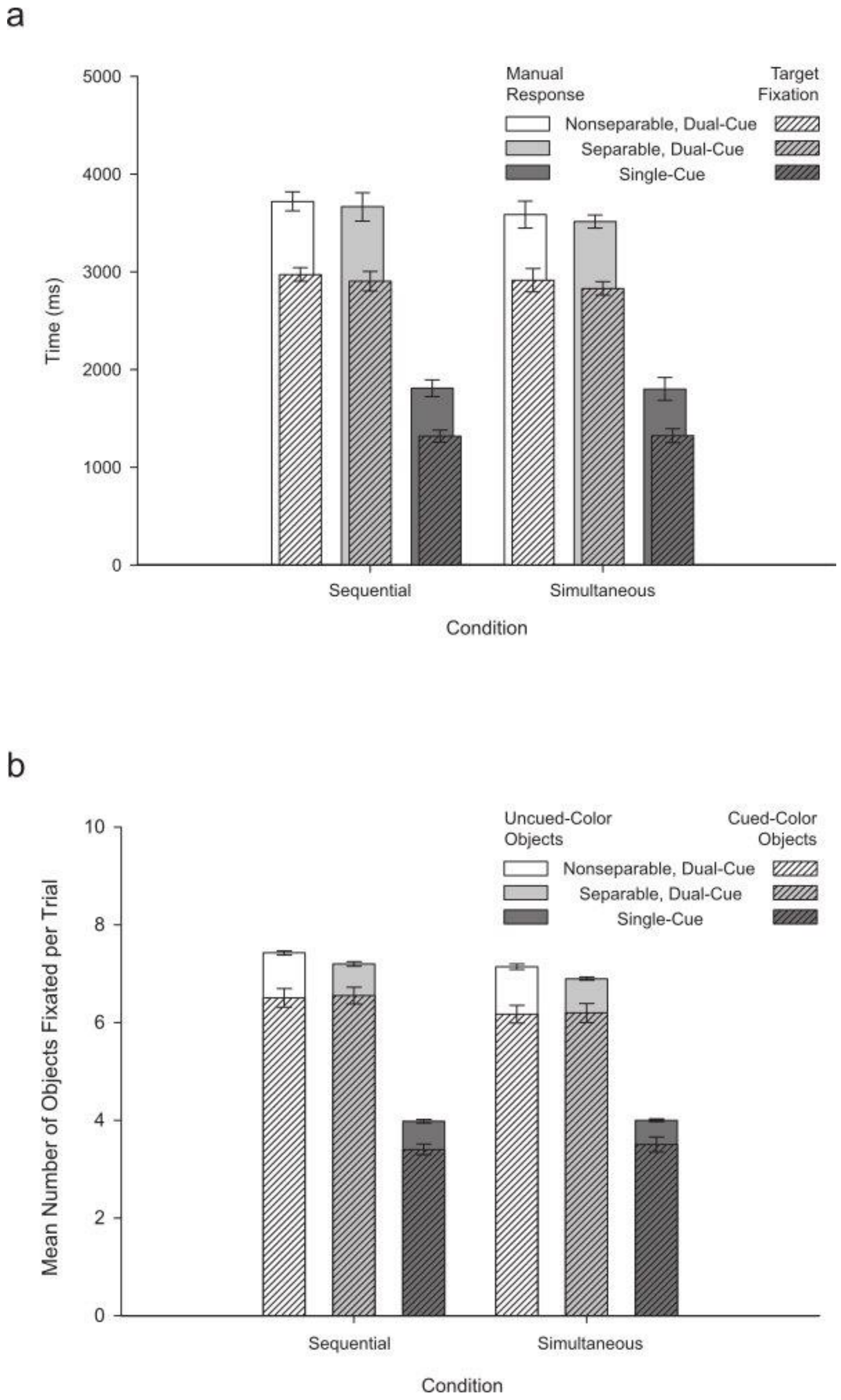


Figure 2.5. Response times (A) and number of objects fixated per trial (B) in Experiment 2. Mean manual response times and mean times to target fixation are shown as a function of condition and cue type. The mean number of objects fixated per trial is shown as a function of condition and cue type, separately for objects of the cued and uncued colors. The height of each bar indicates the total number of objects fixated, and the shading shows how that total was divided between cued- and uncued-color objects. Error bars in both panels show within-subjects 95% confidence intervals (Morey, 2008).

*Selectivity and speed of search***.** Observers fixated fewer items on single-cue trials than on dual-cue trials (Figure 2.5B), which reflects the smaller number of potential targets on single-cue trials. Fixation durations were 18 ms faster on single-cue trials than on dual-cue trials, $t(10) = 9.00$, $p < .001$. Thus, there was an advantage to having a single target color. This does not imply that observers were unable to maintain multiple templates; it may simply indicate that maintaining multiple templates requires additional resources.

Observers were just as selective and just as fast when instructed to search both colors simultaneously as when instructed to search the two colors sequentially (Figure 2.6). To quantify selectivity, we computed the proportion of fixations that were directed to the cued color (fixations to cued color/(fixations to cued color + fixations to uncued color)). These values did not differ significantly between the sequential- and simultaneous-search conditions, $t(10) = 0.52$, $p = .62$, and Bayes factor analysis indicated that the null hypothesis was 3.9 times more probable than the alternative hypothesis. Fixation durations were nearly identical in the sequential- and simultaneous-search conditions, $t(10) = 1.34$, $p = .21$, with the null hypothesis 2.0 times more likely than the alternative hypothesis. Thus, attempting to search both cued colors simultaneously produced no disruption in the ability to search rapidly or selectively.

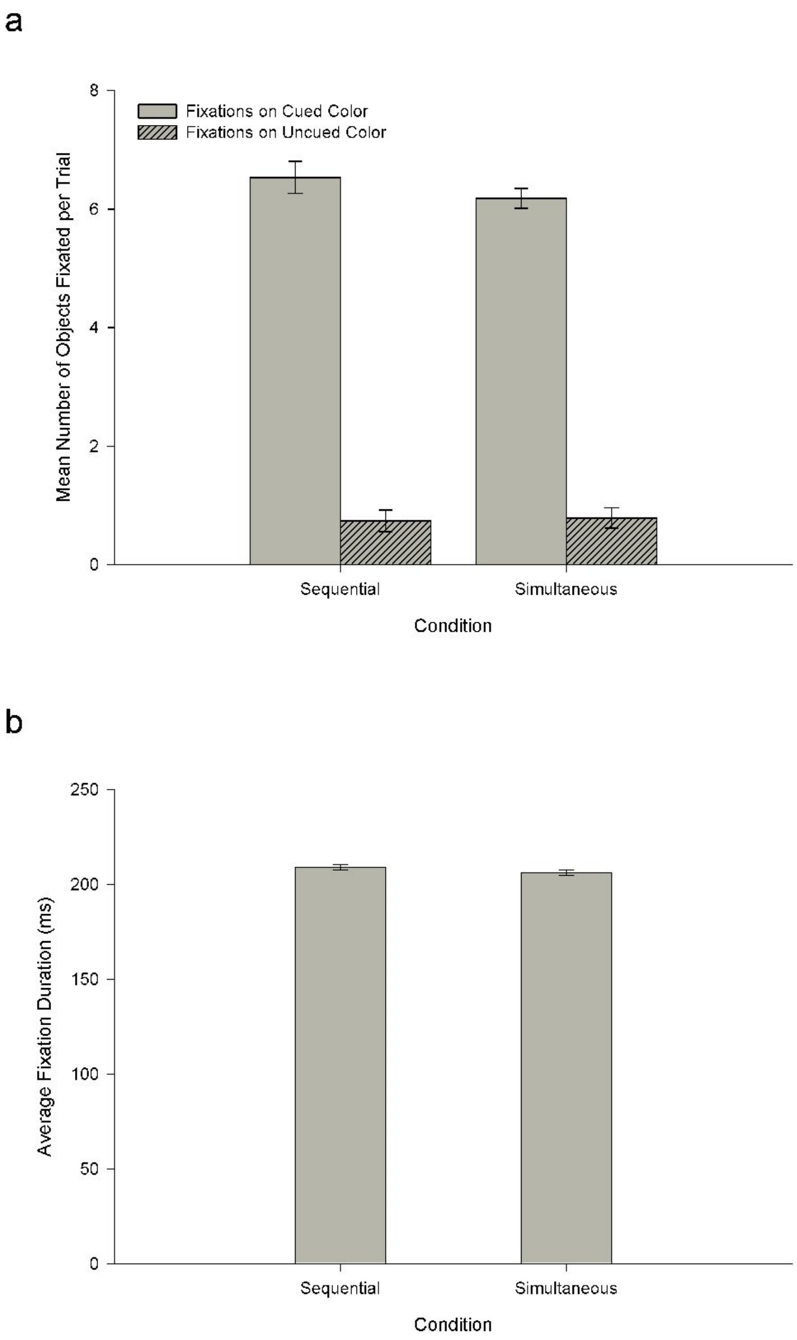


Figure 2.6. Mean number of cued-color and uncued-color objects fixated per trial (A) and mean fixation duration for cued-color objects (B) as a function of condition in Experiment 2. Results are shown for dual-cue trials only; data are collapsed across separable and nonseparable trials. Error bars show within-subjects 95% confidence intervals (Morey, 2008).

Run length. Figure 2.7 shows representative scan paths from individual trials on which red and green were cued in the sequential-search and simultaneous-search conditions. The observer was highly selective in both conditions, limiting gaze to the two cued colors. The observer searched seven consecutive red items and then five consecutive green items in the sequential-search example, but went back and forth between red and green items multiple times with short runs in the simultaneous-search example. To quantify this difference, we computed mean initial run length, as in Experiment 1. Mean run length was significantly smaller in the simultaneous-search condition (2.4 items) than in the sequential-search condition (3.4 items), *t*(10) = 2.72, *p* = .02. Mean initial run length for the simultaneous-search condition was quite close to the value expected if observers randomly selected items in the two cued colors (1.8 items), whereas the mean run length for the sequential-search condition (3.4 items) was significantly greater than would be expected by random selection, *t*(10) = 4.27, *p* = .002.

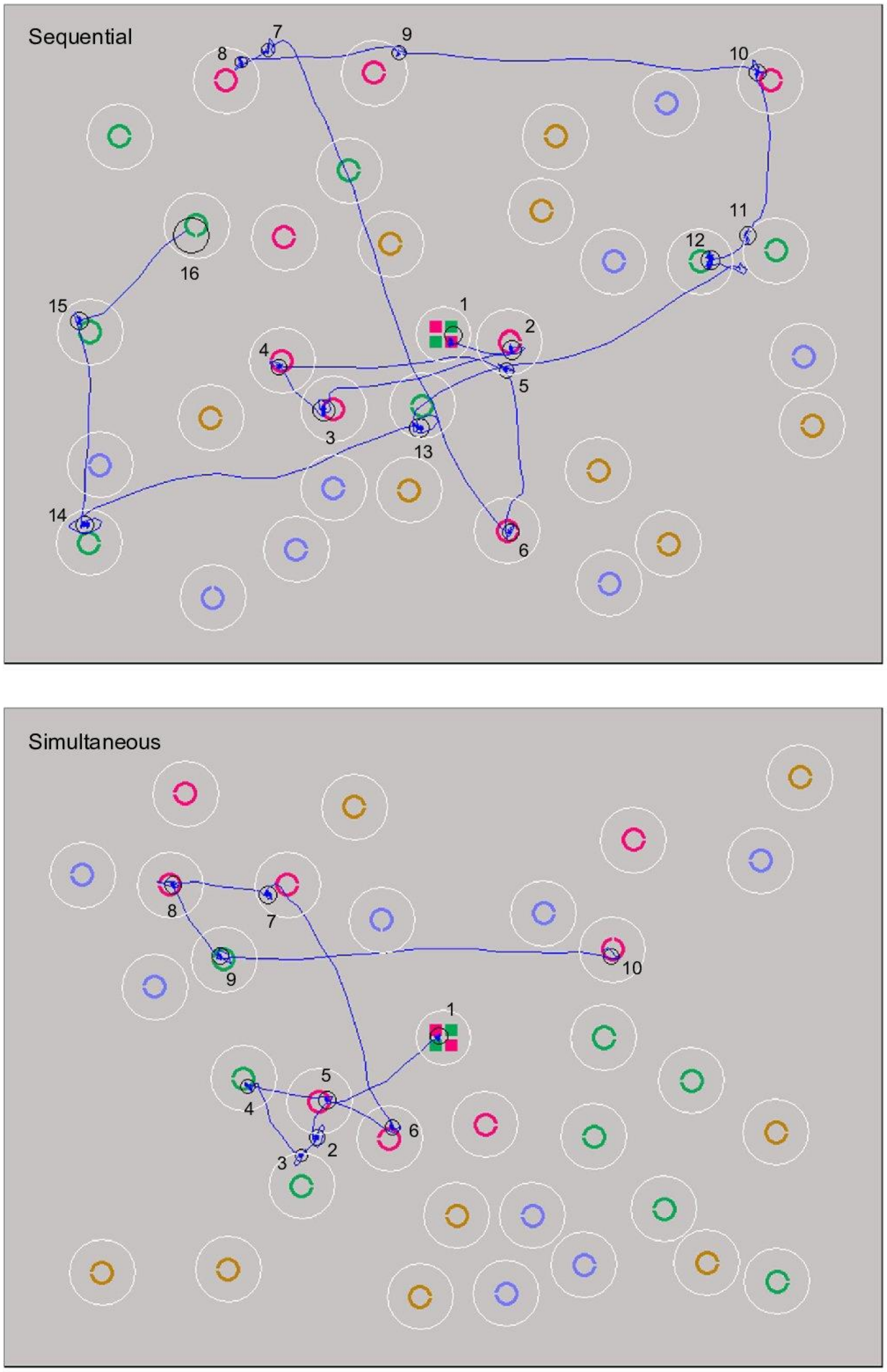


Figure 2.7. Sample scan paths for a sequential-search trial (upper panel) and a simultaneous-search trial (lower panel) in Experiment 2. In both trials, the observer was cued to search for a target among both red and green objects. The order of fixations (indicated by the small black circles) is numbered.

*Switch cost***.** There was a significant switch cost (increase in the duration of preswitch fixations relative to the preceding fixations) in the sequential-search condition (23-ms difference), *t*(10) = 2.57, *p* = .03; this finding indicates that observers actively switched from one template to the other in this condition (Figure 2.8). However, there was no significant switch cost in the simultaneous-search condition (1.5-ms difference), *t*(10) = 0.23, *p* = .82. Bayes factor analysis indicated that the null hypothesis was 4.4 times more likely than the alternative hypothesis, which indicates that observers were not switching between templates in this condition. An ANOVA with instruction condition and fixation position as factors yielded a significant interaction, *t*(10) = 2.35, *p* = .04; this interaction indicates that there was a smaller switch cost in the simultaneous-search condition than in the sequential-search condition.

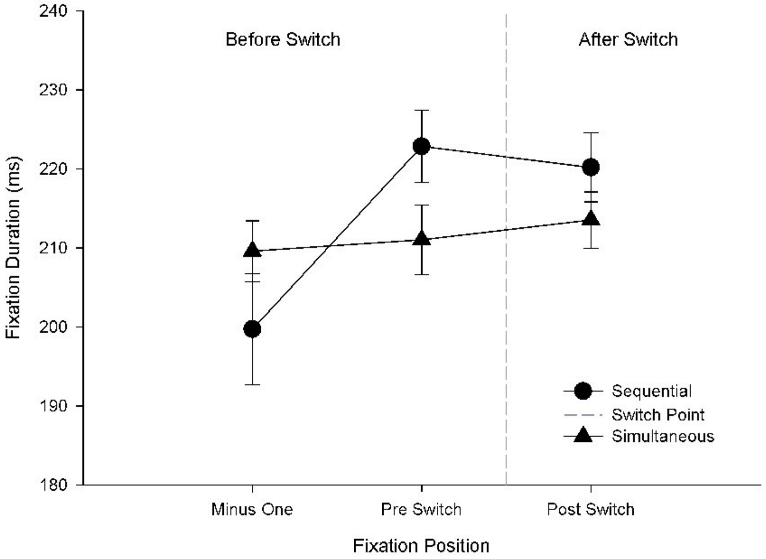


Figure 2.8. Mean duration for fixations immediately prior to and following switches from searching objects of one cued color to searching objects of the other cued color in Experiment 2. Durations are shown for the two fixations prior to the switch and the fixation after the switch in the sequential-search and simultaneous-search conditions. This analysis was restricted to trials on which the target color was not initially searched, and it was limited to trials on which observers switched from a run of nontarget cued-color items to a run of target-color cued-color items. A run occurred when two or more objects of the same type were fixated consecutively. Error bars show within-subjects 95% confidence intervals (Morey, 2008).

One possible alternative explanation for a lack of switch cost is that, in the simultaneous-search condition, the preparation for switching was spread out over several fixations instead of being limited to the preswitch fixation. If this were the case, and the switch cost in the simultaneous-search condition was incorporated into many fixations, the overall mean fixation duration should be greater in that condition than in the sequential-search condition. As Figure 2.6B shows, however, there was no difference in mean fixation durations across the simultaneous- and sequential-search conditions.

*Summary***.** These results indicate that observers can either activate two templates sequentially or activate them both simultaneously, depending on the task instructions. When asked to search items in two colors sequentially, observers exhibited relatively long runs of items in a given color and a switch cost when they shifted from items in one color to items in the other. When asked to search items in the two colors simultaneously, they shifted back and forth between items in both colors more frequently, and there was no switch cost when they shifted from items in one color to items in the other. In addition, the overall speed and selectivity of search was virtually equivalent for these two search tasks. These results demonstrate that people are able to maintain two active representations in VWM that guide attention concurrently.[1]

2.5 General Discussion

The results of the experiments reported here directly demonstrate that people can use multiple attentional templates to simultaneously guide search toward relevant objects. In Experiment 1, we identified two signatures of the use of a single attentional template

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[1] We frame this ability as the simultaneous maintenance of two templates in VWM. An equivalent formulation would be to say that a single template composed of multiple, individual color values is maintained in VWM. The only difference between these descriptions is whether one applies the term "template" to the entire system of VWM or to the individual representations maintained within VWM.

to guide search: long runs of fixations on items that matched the template and a switch cost when observers shifted from one template to another. In Experiment 2, we used these signatures along with other measures to demonstrate that observers can maintain two concurrent templates when asked to do so. Searching objects in either of two colors concurrently led to no impairment in the time required to find and report the target compared with searching objects in either of the two colors sequentially. Moreover, in the simultaneous-search condition, observers shifted their gaze back and forth between the two cued colors over short run lengths, and no switch cost was present when they shifted from one color to the other. Thus, searching for two distinct features concurrently led to no cost relative to searching for these features sequentially, and gaze patterns indicated that both templates were concurrently active.

These results provide an important constraint on the architecture of cognition. Specifically, they demonstrate that the multiple representations that are concurrently stored in VWM (Cowan, 2001; Luck, 2008) can simultaneously be linked to the control of attention. In other words, there is no single-channel bottleneck in top-down attentional control. Instead, multiple VWM representations may interact directly with the flow of sensory information through the visual system, a finding consistent with the fact that visual perception and VWM operate within the same regions of visual cortex (Harrison & Tong, 2009; Serences et al., 2009).

It is difficult to know with certainty why previous studies failed to find evidence of multiple simultaneous templates (see reviews by Huang & Pashler, 2007; Olivers et al., 2011). The present study found that observers could voluntarily decide whether to search for items in two cued colors sequentially or simultaneously, so it is possible that previous studies simply failed to induce the observers to activate the templates simultaneously. Indeed, one previous study found a switch cost that was comparable with the cost observed in the sequential condition of our study (Dombrowe, Donk, & Olivers, 2011). Moreover, the present results indicate that there is a cost to maintaining multiple templates, and this cost may have motivated observers in previous studies to use other strategies (e.g., using singleton-detection mode in the study of Eimer & Kiss, 2010). In other cases, the task required observers to link particular features with particular locations (Adamo et al., 2008; Parrott, Levinthal, & Franconeri, 2010; Wolfe et al., 1990), and this may be more difficult than merely activating two features. In any case, the present results demonstrate that people can, under some circumstances, activate multiple search templates simultaneously, even if there are limits on the situations in which they can do so.

2.6 Supplementary Materials

The goal of the first set of Monte Carlo simulations was to determine the number of consecutive fixations that would be expected if an ideal observer selected each saccade target according to the probability that the target would be a given color, with each fixation determined independently of the prior fixations. In the 80/20 condition (Experiment 1), it was used to determine the initial run length that would be expected if the observer simply selected each item with an 80% probability of one color and a 20% probability of the other color. In the 50/50 condition (Experiment 1), it was used to determine the initial run length that would be expected if the observer selected each item with a 50% probability of red and a 50% probability of blue. Ten thousand trials were simulated for each condition. For the sake of simplicity, the ideal observer was given perfect memory (i.e., gaze never returned to a previously fixated item on a given trial).

The hypothetical observer data for the 50/50 condition was also used to simulate the initial run length when the observer searched two colors simultaneously in Experiment 2. That is, it was used to estimate the expected initial run length if the observer randomly shifted back and forth between the two cued colors. However, to account for the fact that real observers directed approximately 10% of their fixations to one or two uncued colors in this experiment, the Monte Carlo simulation also incorporated a 10% probability that a fixation was directed to an uncued color.

The goal of the second set of Monte Carlo simulations was to determine the run length that would result in the fewest number of objects selected before locating the target item. These simulations were used to calculate the initial run length that would be expected if the observer was searching most efficiently (least number of eye movements).

We ran a series of simulations (one thousand trials each) in which run length varied from one to twelve. Again, the hypothetical observer was given perfect memory, and run length was the same for each of the two colors (e.g., a run length of five would mean that the first five items selected were from one color, the second five from the other color, and so on).

CHAPTER 3: ATTENTIONAL GUIDANCE BY MULTIPLE VWM REPRESENTATIONS

3.1 Overview

The content of visual working memory (VWM) guides attention, but whether this interaction is limited to a single VWM representation or functional for multiple VWM representations is under debate. To test this issue, we developed a gaze-contingent search paradigm to directly manipulate selection history and examine the competition between multiple cue-matching saccade target objects. Participants first saw a dual-color cue followed by two pairs of colored objects presented sequentially. For each pair, participants selectively fixated an object that matched one of the cued colors. Critically, for the second pair, the cued color from the first pair was presented either with a new distractor color or with the second cued color. In the latter case, if two cued colors in VWM interact with selection simultaneously, we expected substantial competition from the second cued color, even though the first cued color was used to guide attention in the immediately previous pair. Indeed, in the second pair, selection probability of the first cued color was substantially reduced in the presence of the second cued color. This competition between cue-matching objects provides strong evidence that both VWM representations interacted simultaneously with selection.

The experiments described in this chapter are under review: Beck, V. M. and Hollingworth, A. Competition in Saccade Target Selection Reveals Attentional Guidance by Simultaneously Active Working Memory Representations. *Journal of Experimental Psychology: Human Perception and Performance*.

3.2 Introduction

Visual attention strongly influences what we see (Cohen, Cavanagh, Chun, & Nakayama, 2012), recognize (Lachter, Forster, & Ruthruff, 2004), and remember (Averbach & Coriell, 1961; Sperling, 1960). To understand human vision, we must therefore understand the control mechanisms that determine where attention is deployed. Most theories implement strategic guidance of attention as a template representation in visual working memory (VWM). Indeed, attention is directed toward objects that match VWM content (e.g., Wolfe et al., 2004), even when doing so is counterproductive (e.g., Soto et al., 2005). Although this basic relationship is well established, the architecture of interaction between VWM and attentional selection is currently under debate (Beck, Hollingworth, & Luck, 2012; Olivers et al., 2011). To illustrate, imagine you are searching for an apple in a basket of mixed fruit. You would prefer either a Granny Smith or a Red Delicious. Can you search for green and red apples simultaneously while avoiding the bananas and oranges? Or, are you only able to search for a green apple first and then a red apple? That is, do structural constraints limit the number of representations in VWM that guide attention simultaneously?

Olivers et al. (2011) proposed that only one item in VWM can guide attention, a *single-item template hypothesis* (SIT). Although VWM can maintain multiple items in prefrontal regions, only one of these items can be in an “active” state that biases selection. The remaining items are maintained in an “accessory” state, unable to influence selection. In contrast, we have proposed that multiple items in VWM can be maintained in an “active” state and guide attention simultaneously (Beck et al., 2012), a *multiple-item template hypothesis* (MIT). VWM and perceptual systems are tightly integrated, with visual-sensory regions recruited in the course of memory maintenance. In particular, perceptual features of items maintained in VWM can be reliably decoded from activity in visual-sensory cortex during the retention of a single item (Harrison & Tong, 2009; Serences et al., 2009) and multiple items (Emrich et al., 2013). We proposed that multiple active VWM representations in visual cortex interact with sensory processing to bias selection simultaneously, allowing attention to be guided, say, to both the red and green apples.

Early evidence supporting the SIT came from attention capture paradigms (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006). A remembered item failed to capture attention when included as a distractor during search for a different target, suggesting that only the single, target template representation was able to influence selection. In a related method using a static search target, attention was captured by a memory-matching distractor when a single color was held in VWM but not when multiple colors were held in VWM (van Moorselaar et al., 2014), again indicating a limit on the number of items interacting with selection. More recently, however, Hollingworth and Beck (2016) found reliable memory-based capture when more than one item was maintained in VWM, and capture magnitude scaled with the number of matching distractors in the display, consistent with the MIT. Nevertheless, capture paradigms are suboptimal for testing the architecture of strategic guidance, as they are limited to guidance that is contrary to task demands and might not provide a comprehensive measure of guidance capabilities.[2] The most diagnostic evidence, to date, comes from a

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[2] Additional evidence cited in favor of the SIT comes from a study in which a one-template model better predicted observed performance in an RSVP detection task with multiple possible targets (Houtkamp & Roelfsema, 2009). However, this result could reflect limitations in the comparison of VWM representations to perceptual objects rather than limitation in the guidance of attention.

study examining the efficiency of switching selection between two different template features (Beck et al., 2012). Participants searched items of two different target colors either sequentially or simultaneously. The sequential instruction led to long sequences of selection of a particular color and a saccade latency switch cost when switching between colors, consistent with template reconfiguration. However, the simultaneous instruction led to frequent switches between the two target colors, with no switch cost, suggesting that both colors were maintained in an "active" state that guided selection simultaneously.

In sum, the extant data provide substantial support for the MIT but fall short of being conclusive. In the present study, we sought a definitive test, contrasting novel predictions of the two theories for resolving competition in selection. Consider choosing between two objects that each match one of two target colors. If both target colors are maintained in an active state in VWM, as held by the MIT, the two objects should generate substantial competition, as they should both receive top-down prioritization. In contrast, the SIT predicts minimal competition in this situation. If the template is limited to one active VWM representation, then top-down prioritization will be applied to only one of the two cue-matching items. Thus, selection should be efficient: specifically, no less efficient than selection when only one of the two items matches a cued color.

In the present experiments, we tested these predictions in a new sequential search task that allowed us to control the history of selection within a trial. Each trial began with a dual-color cue (e.g., red and blue) followed by two pairs of colored objects presented sequentially (Figure 3.1). Participants fixated one item in each pair, with the instruction to always saccade to a cue-matching object. The first pair contained one cue-matching object (e.g., red) and one distractor object (e.g., yellow). The key data came from selection in the second pair. In the *same* condition, the cue-matching color in the first pair was repeated, along with a novel distractor color. In the *switch* condition, the other cue-matching color was presented (e.g., blue), along with a novel distractor color. Finally, in the critical *both* condition, the objects in the second pair were both cue-matching but different colors (e.g., red and blue), and participants could select either object.

Under the SIT, after successful fixation of the cue-matching object in the first pair, the color of that object should be in the “active” state; it had just been used for selection. Thus, in the second pair, this *first-cued-color* should be selected again efficiently, and the selection process should be similar in the *same* and *both* conditions. In particular, the *second-cued-color* in the *both* condition should be in an “accessory” state that does not interact with selection and should produce competition no greater than a novel color distractor in the *same* condition. Under the MIT, however, the two objects in the *both* condition should generate substantial competition for selection as the saccade target, increasing the probability that gaze is directed to the *second-cued-color*. Additionally, we sought to replicate the switch cost results obtained by Beck et al. (2012). Because both colors should be maintained in a state that guides selection, the MIT predicts minimal switch costs when comparing the *same* condition with the *switch* condition. However, the SIT predicts a significant cost on switch trials, as the template must be reconfigured.

3.3 Experiment 1: Competition in Saccade Target Selection

3.3.1 Method

Participants. Thirty-two University of Iowa students participated for course credit: 16 in each experiment.

Stimuli, Apparatus, and Procedure. Stimuli were presented on an LCD monitor (100Hz) at a distance of 77cm. Eye position was recorded at 1000Hz using an Eyelink 1000 eyetracker. Saccades were defined using a combined velocity (>30°/s) and acceleration ($>9500°/s^2$) threshold. Fixation on an object was defined as twelve consecutive samples within the surrounding interest area (2.01 degrees visual angle, hereafter *dva*).

The procedure is illustrated in Figure 3.1. The cued colors varied from trial to trial, ensuring that cue representation depended on VWM. Each of the four colors (red, yellow, green, blue) appeared equally often in the cue. Each pair of objects appeared 4-6 dva from the previous fixation positon and were 40° apart. The second pair was presented within the range of 90°-270°, if 0° represents the trajectory of the previous saccade, so that saccades to the second pair were always progressive. If a distractor was fixated in either pair, the trial terminated with an error message. The secondary, line orientation task was included to replicate the demands of a visual search task, requiring discrimination of the properties of each object.

In Experiment 1A, the color of the cue-matching object in the first pair changed to dark grey during the saccade so that there was no direct perceptual match with an object in the second pair. Experiment 1B was the same except that the cue-matching object in the first pair retained its color until the end of the trial.

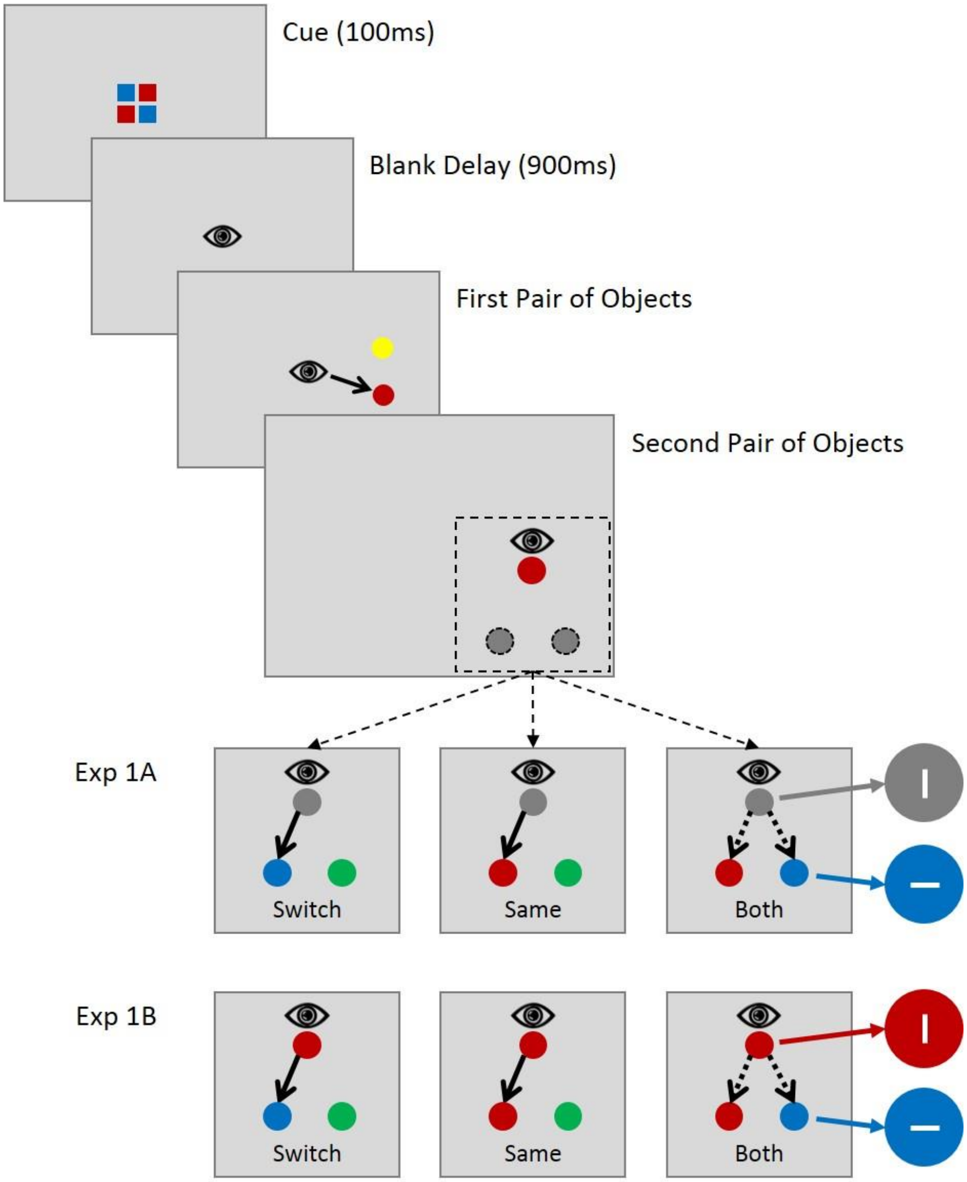

Figure 3.1. Example sequence of trial events for Experiment 1A and 1B. Each trial began with a cue stimulus (100 ms) presented as a mini checkerboard (1.34 x 1.34 dva), with two squares (0.63 x 0.63 dva) for each of the two colors. After a 900-ms delay, two disks (0.67 dva) appeared simultaneously (first pair): one cue-matching and one distractor. Once participants fixated the cue-matching object, the distractor disappeared, and after a 200-ms delay, two new objects appeared simultaneously (second pair). The second pair could contain a same-color cue-matching object with a new distractor (“same”), a new cue-matching object with a new distractor (“switch”), or two objects that each matched a different cue color (“both”). These three conditions were equally probable. Each object had a central vertical or horizontal line (0.04 x 0.17 dva; light grey, like the background), and participants indicated whether the lines in the cue-matching objects had the same or different orientations. In Experiment 1A, the color of the cue-matching object in the first pair changed to grey during the saccade to it, so that there was no direct perceptual match with an object in the second pair. Experiment 1B was the same except that the objects retained their colors until they offset.

The session began with 20 practice trials on which participants simply fixated cue-matching objects. Then they completed a second practice block (24 trials) implementing the full design. Participants completed 10 blocks of 46 experimental trials, with a short break every 3-4 blocks.

3.3.2 Results

Participants were excluded for manual response accuracy less than 75% in one or more conditions (Exp1A: *N* = 4; Exp1B: *N* = 3) yielding 12 participants in Experiment 1A and 13 participants in 1B. Accuracy for remaining participants was high (Exp1A: *M* = 93%; Exp1B: *M* = 90%) with no meaningful differences between trial types.[3] The primary measure was selection probability, defined as the first object fixated after the onset of a pair.[4] For the first pair, selection probability for the cue-matching object was high (Exp1A: *M* = 82.6%; Exp1B: *M* = 82.0%). This is similar to a comparable task in which there was only one template color (76.9%, unpublished data), indicating that participants in the present study efficiently used the dual-color cue to guide selection.

Same versus Both Trials: Evaluation of Competition Between Template Colors

The key results concerned selection probability in the second pair (see Figure 3.2). For *same* trials, participants frequently selected the first-cued-color again (Exp1A: *M* = 76.5%; Exp1B: *M* = 75.1%). The key question was whether, on *both* trials, selection probability of the first-cued-color would be similarly high (consistent with the SIT), or

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[3] See Table 3.1 in the supplemental materials at the end of this chapter for accuracy by trial type.

[4] The angular separation between objects in a pair (40°) was designed to produce a discrete saccade to one of the objects and avoid a “global effect” on landing position (Findlay, 1982). Indeed, the distributions of landing position for the first saccade following the onset of an object pair were bimodal (see supplemental materials at the end of this chapter for analysis details and Figure 3.3 for saccade angle distributions).

whether competition from a simultaneously active, second-cued-color would reduce that probability (consistent with the MIT). Not only was the probability of first-cued-color selection reduced from *same* to *both* trials [Exp1A: $t(11) = 7.54$, $p < .001$, $\eta_p^2 = .84$; Exp1B: $t(12) = 4.94$, $p < .001$, $\eta_p^2 = .67$], selection in the *both* condition was roughly equivalent between the two cue-matching colors. Specifically, selection probability for the first-cued-color did not significantly differ from 50% in either experiment (both $ps > .46$). This indicates that both colors were maintained in a similar state vis-à-vis attentional guidance.[5]

We also examined saccade latency for *same* and *both* trials. Saccades to either cue-matching object on *both* trials (Exp1A: $M = 175$ ms; Exp1B: $M = 155$ ms) were slightly faster than saccades to the cue-matching object on *same* trials (Exp1A: $M = 182$ ms; Exp1B: $M = 157$ ms). These differences were statistically reliable [Exp1A: $t(11) = 2.92$, $p = .01$, $\eta_p^2 = .44$; Exp1B: $t(12) = 2.26$, $p = .04$, $\eta_p^2 = .30$], but numerically very small. The competition for selection was therefore observed primarily on selection probability rather than on selection latency.

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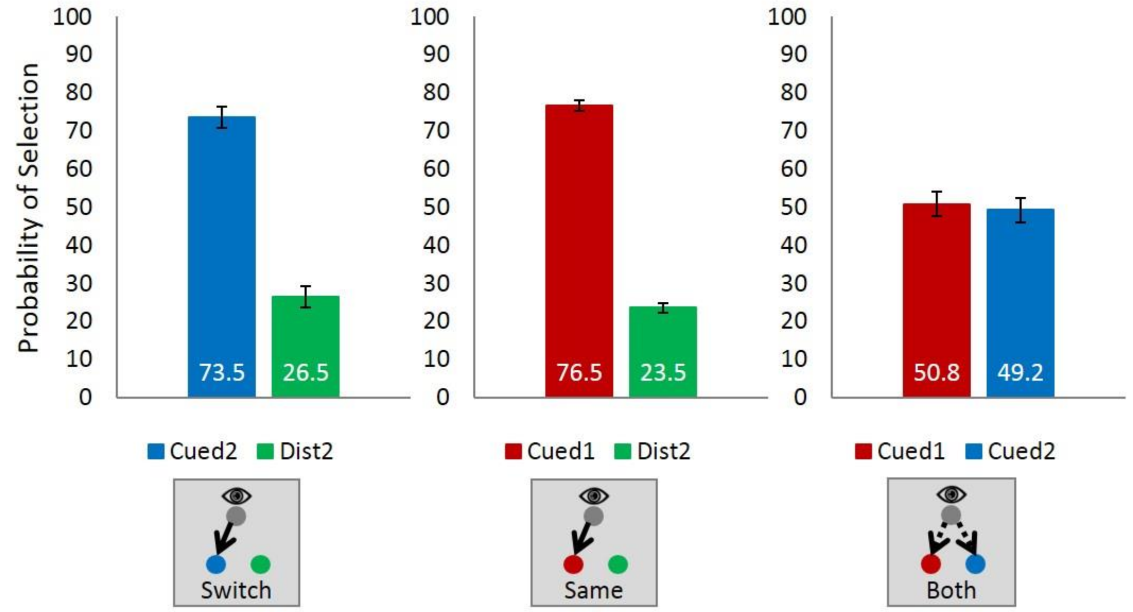
[5] For some color pairs that are linearly separable in color space (e.g., red and yellow) from the remaining distractor colors, participants might have formed a single representation in VWM that included a range of color values or a single intermediate value (e.g., orange). However, when the two cued colors are not linearly separable from the distractor colors (e.g., red and green cued, yellow and blue distractors), it is not possible to form a single template that includes both cued colors and excludes the others (D'Zmura, 1991; Duncan & Humphreys, 1989). Limiting our analysis to these latter trials did not change the pattern of results. The probability of first-cued-color selection in the second pair was reduced from the *same* to the *both* condition [Exp1A: $t(11) = 5.44$, $p < .001$, $\eta_p^2 = .73$; Exp1B: $t(12) = 3.80$, $p = .003$, $\eta_p^2 = .55$], and selection in the *both* condition was roughly equivalent between the two cue-matching colors (first-cued-color selection probability: Exp1A, $M = 50.5\%$; Exp1B, $M = 53.3\%$).

A) Exp 1A



B) Exp 1B

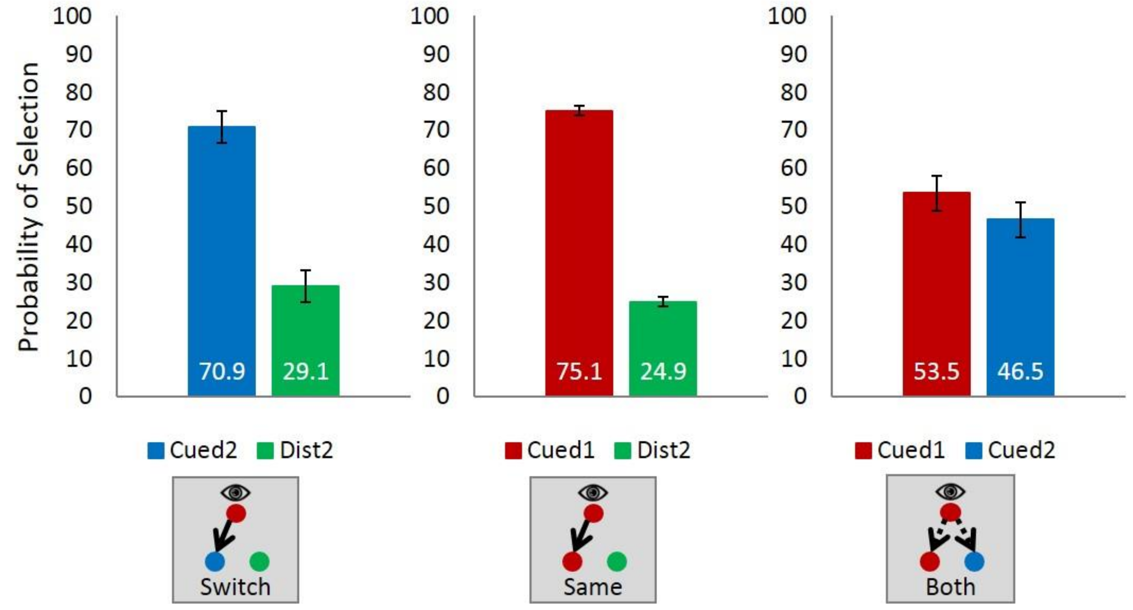


Figure 3.2. Probability of selecting the different types of objects (Cued1: same cue-matching color used in the first pair; Cued2: cue-matching color not used in the first pair; Dist2: novel distractor color) presented in the second pair split by trial type (Switch, Same, or Both). A) Selection probability results from Experiment 1A. B) Selection probability results from Experiment 1B. Error bars indicate within-subjects 95% confidence intervals (Morey, 2008).

Same versus Switch Trials: Evaluation of Switch Costs

Selection probability for the cue-matching color did not differ between *same* and *switch* trials for either experiment (both *p*s>.24; see Figure 3.2). To examine possible switch costs on saccade latency, we excluded saccades with latencies < 90 ms and > 600 ms (Exp1A: 1.0%; Exp1B: 0.3%) and restricted the analysis to the initial eye movement after the second pair appeared, using only saccades that landed within the interest area of the cue-matching object (Exp1A: 61.1% retained; Exp1B: 61.3% retained). Saccade latency was not increased for *switch* trials compared with *same* trials for either Experiment 1A (*switch*: *M* = 183 ms, *same*: *M* = 182 ms) or Experiment 1B (*switch*: *M* = 159 ms, *same*: *M* = 157 ms; both *ps* > .41), replicating our previous finding (Beck et al., 2012).

3.4 Discussion

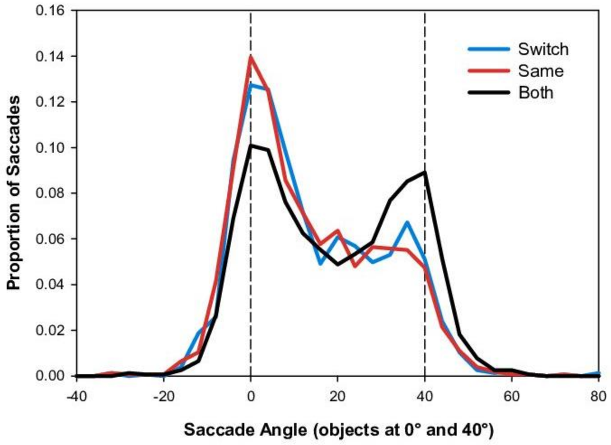
In a novel, sequential search task we observed substantial competition for selection between two objects that both matched a target color, suggesting that both colors were maintained in an “active” state in VWM and influenced selection. Additionally, as in Beck et al. (2012), we observed no cost when switching from one cued color to another. The present approach provides a particularly strong test of the SIT and MIT, as it examined selection directly, rather than indirectly via capture. In addition, the reliable difference in selection probability between the *same* and *both* conditions provides novel evidence for simultaneous guidance. The results converge with several other studies indicating that multiple representations in VWM interact with perceptual selection (Beck et al., 2012; Hollingworth & Beck, 2016; Roper & Vecera, 2012). A similar resolution has emerged in the traditional literature on visual search. Wolfe (2007) proposed that search could be guided by only one feature value on a dimension. However, several recent studies have demonstrated simultaneous guidance by multiple values (Grubert & Eimer, 2015, 2016; Irons, Folk, & Remington, 2011; Moore & Weissman, 2010; Stroud, Menneer, Cave, & Donnelly, 2011). In this literature, the target values are fixed across the experiment, and guidance is likely to depend on long-term memory (LTM) rather than VWM (Carlisle et al., 2011). The two literatures therefore converge on a common principle of multiple-item guidance that appears to span guidance by active VWM representations and guidance by LTM.

The present results also have implications for general theories of working memory. Competing theories diverge on whether the “active” component of working memory, or “focus of attention”, is limited to a single representation/chunk (McElree, 2006; Oberauer, 2002) or spans multiple representations (Cowan, 2001). The need for a single-item “focus of attention” has been argued to arise from the need for item-level selectivity in cognitive operations (Oberauer & Hein, 2012). In vision, this type of discrete selection is ultimately instantiated by the oculomotor system via fixation. However, the VWM system that guides oculomotor selection has the capability to maintain multiple active representations, allowing for flexibility in strategic attentional control.

3.5 Supplementary Materials

The 40° separation between the two objects in each pair was chosen to ensure that saccades were directed discretely to one of the two objects, minimizing the proportion of saccades directed to the center of the group. Typically, such a “global effect” is observed only for angular separations less than 30° (Ottes, Van Gisbergen, & Eggermont, 1984). To ensure that this design feature was successful, we analyzed the angle of the saccade vector from the cue-matching object in the first pair to the objects in the second pair (see Figure 3.3). This analysis was limited to the first eye movement to leave the cue-matching object in the first pair. The data were normalized, such that on *switch* and *same* trials, the cue-matching object in the second pair was plotted at 0°, and the distractor object was plotted at 40°. For *both* trials, the first-cued-color object is plotted at 0°, and the second-cued-color object is plotted at 40°. Consistent with our assumptions, the distributions of saccade angle were clearly bimodal, indicating that saccades were typically directed to one of the two objects, rather than landing between them. This is illustrated most clearly in the *both* condition, with approximately half of the saccade directed to each of the two objects.

Experiment 1A



Experiment 1B

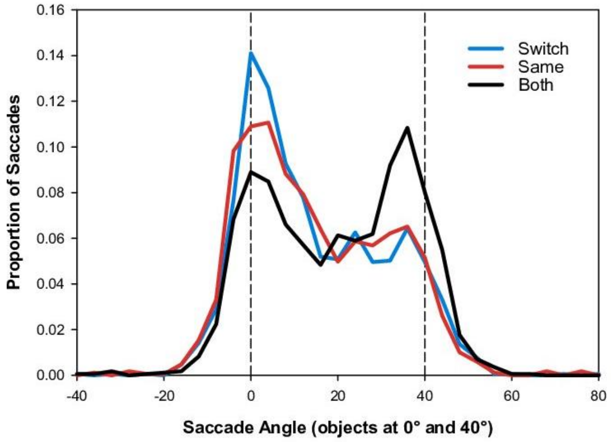


Figure 3.3. Angle of the saccade vector from the cue-matching object in the first pair to the objects in the second pair. For the *same* and *switch* conditions, the data were normalized to plot the cue-matching object at 0° and the distractor at 40°. For the *both* condition, the first-cued-color object is plotted at 0° and the second-cued-color object at 40°.

Trial Type	Experiment 1A	Experiment 1B
Switch	93.28%	89.15%
Same	94.03%	92.77%
Both	92.65%	88.75%

Table 3.1. Mean manual response accuracy for line-match task for the three different trial types in both Experiments 1A and 1B.

CHAPTER 4: NEGATIVE TEMPLATE VIA SPATIAL RECODING

4.1 Overview

Theories of attention and visual search explain how attention is guided toward objects with known target features. But can attention be directed away from objects with a feature known to be associated only with distractors? Most studies have found that the demand to maintain the to-be-avoided feature in visual working memory biases attention toward matching objects rather than away from them. In contrast, Arita, Carlisle, and Woodman (2012) claimed that attention can be configured to selectively avoid objects that match a cued distractor color, and they reported evidence that this type of negative cue generates search benefits. However, the colors of the search array items in Arita et al. (2012) were segregated by hemifield (e.g., blue items on the left, red on the right), which allowed for a strategy of translating the feature-cue information into a simple spatial template (e.g., avoid right, or attend left). In the present study, we replicated the negative cue benefit using the Arita et al. (2012) method (albeit within a subset of participants who reliably used the color cues to guide attention). Then, we eliminated the benefit by using search arrays that could not be grouped by hemifield. Our results suggest that feature-guided avoidance is implemented only indirectly, in this case by translating feature-cue information into a spatial template.

The experiments described in this chapter are published under the following citation: Beck, V. M., and Hollingworth, A. (2015). Evidence for Negative Feature Guidance in Visual Search Is Explained by Spatial Recoding. *Journal of Experimental Psychology: Human Perception and Performance*, 41(5), 1190-1196. DOI: 10.1037/xhp0000109.

4.2 Introduction

Most theories of attention proposed that goal-directed orienting is implemented by means of an attentional template specifying the feature of task-relevant items (Bundesen, 1990; Duncan & Humphreys, 1989; Wolfe, 1994). Consistent with this assumption, numerous studies have demonstrated that participants are able to use feature information (e.g., color) to limit attention to task-relevant objects in a search array (Beck et al., 2012; Vickery et al., 2005; Wolfe et al., 2004). In addition, most theories propose that an attentional template is implemented by an active visual working memory representation (VWM) of the relevant features (Bundesen, 1990; Desimone & Duncan, 1995). The VWM representation biases perceptual competition among objects in favor of matching items (Desimone & Duncan, 1995).

Although VWM-based attentional biases are well documented, there is debate over whether they are automatic. Memory-matching objects often capture attention even when the matching feature is always associated with distractors (e.g., Olivers et al., 2006; Soto et al., 2005). Because VWM maintenance involves sustained activation of feature-specific neural populations in sensory cortex (Harrison & Tong, 2009; Serences et al., 2009; for a review, see Postle, 2006), it may not be possible to maintain an active VWM representation that does *not* facilitate perceptual processing of matching items. However, Woodman and Luck (2007) argued that VWM can be configured flexibly either to prioritize or *deprioritize* memory-matching objects. They found faster response times (RTs) when a majority of the distractors matched a color in memory, suggesting use of an exclusionary feature template. More recently, Arita, Carlisle, and Woodman (2012) consistently found evidence in favor of an exclusionary template. They presented a circular search array with items in the two hemifields drawn in different colors (see Figure 4.1). A color cue at the beginning of the trial was either negative (distractor color), positive (target color), or neutral (color not present in the array), and cue condition was blocked. Search RT was faster in both the positive and negative cue conditions compared with the neutral condition. Participants were able to use the negative cue information to restrict search to relevant items, though not as efficiently as in the positive cue condition.

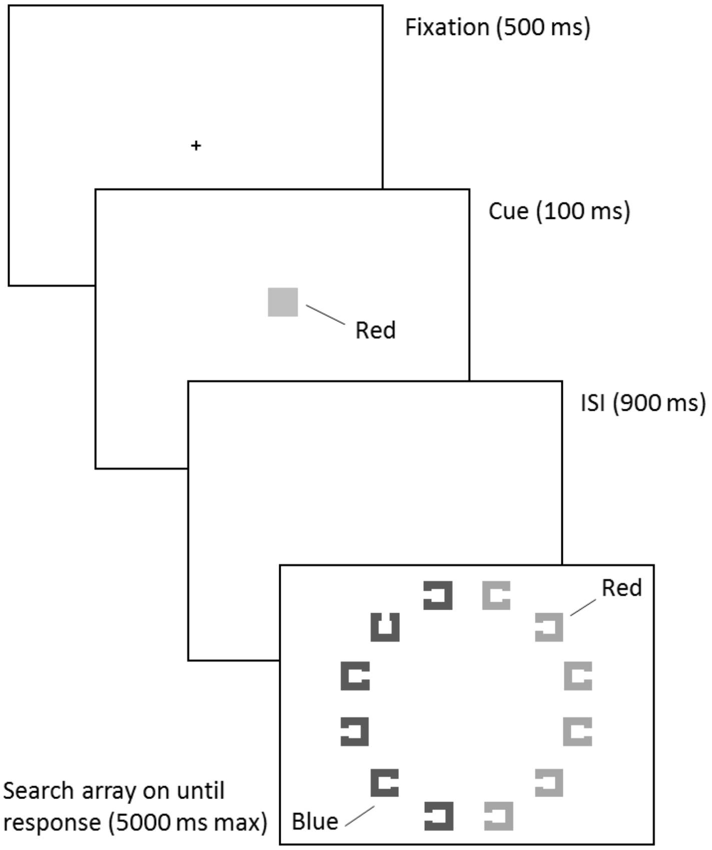


Figure 4.1. Example of trial events and search array for a negative-cue trial in Experiment 1 (replication of Experiment 1A from Arita et al., 2012). ISI = interstimulus interval; max = maximum.

The results from Arita et al. (2012) suggest that attention is not oriented automatically to memory-matching items and that, moreover, participants can avoid memory-matching items when they have sufficient incentive. However, there is a clear alternative explanation of the Arita et al. (2012) results that would not require configuring a feature-based, exclusionary template. In their study, search array colors were always segregated by hemifield. Participants may have used this relationship to convert the negative feature cue into a simple spatial template specifying the relevant hemifield. This process could be similar to the "search and destroy" mechanism of inhibition described by Moher and Egeth (2012), in which attention is first directed to an object with the to-be-ignored feature before other objects with that feature can be avoided. However, Moher and Egeth did not specify whether avoidance is implemented by a spatial or feature-based template. We propose that, in the present context, avoidance is implemented by spatial recoding of feature information, and we are agnostic as to whether this depends on directing attention first to a single cue-matching object. Resolving whether avoidance is implemented directly or indirectly is central to understanding how VWM modulates attentional selection. Direct, feature-based avoidance would suggest that an active VWM representation could inhibit the processing of, or bias perceptual competition against, matching items. Indirect, spatially mediated avoidance would be consistent with a fundamentally facilitatory relationship between VWM and perceptual selection. Without an efficient means to spatially recode the search array, it may not be possible to implement an exclusionary search template.

To test this, we first replicated the results obtained by Arita et al. (2012) using their method. Then, we modified the paradigm to manipulate the ease with which participants could spatially recode the cue information. We were able to replicate the basic avoidance effect of Arita et al. (2012), but this effect was eliminated when spatial recoding was rendered inefficient.

4.3 Experiment 1: Replication of Arita et al. (2012)

4.3.1 Method

Participants. Twenty-nine participants (18-30 years old; 12 female) from the University of Iowa community participated and received either course credit or pay.

Stimuli and procedure. Stimuli were presented on an LCD monitor (100 Hz) at a distance of 88 cm. Each circular search array (5.3° radius) contained 12 Landolt-square objects (0.8° × 0.8°; line thickness 0.1°), with six objects in each hemifield. The two colors (one for each hemifield) were drawn randomly from a set of three (red, green, blue). The target had a top or bottom gap (0.2°). Distractors had a left or right gap.

Each trial began with a central fixation cross (500 ms). A cue square (0.8° × 0.8°; presented 1.0° above fixation) appeared for 100 ms, followed by a 900-ms blank screen and the search array. The cue-square either indicated the distractor color (negative), the target color (positive), or a color absent from the array (neutral). Participants were instructed to locate and respond to the target item as quickly as possible by pressing one of two buttons to indicate gap location. The search array remained visible until response or until 5 s had elapsed. Cue condition was blocked, and the order of conditions was counterbalanced across participants. For each condition block, there were 15 practice trials, then three subblocks of 75 trials. At the end of practice and at the end of each subblock, participants were given average accuracy and RT feedback.

4.3.2 Results and Discussion

Three participants were excluded for accuracy less than 75% in one or more conditions. Mean accuracy for the remaining participants (*N* = 26) was 97%, 98%, and 98%, for negative, neutral, and positive, respectively. RTs 2.5 *SD* beyond a participant's condition mean were excluded as outliers (2.7% of trials). These exclusions did not alter the pattern of results. A table that includes all of the condition mean values for RT in both experiments can be found in the supplemental materials at the end of this chapter.

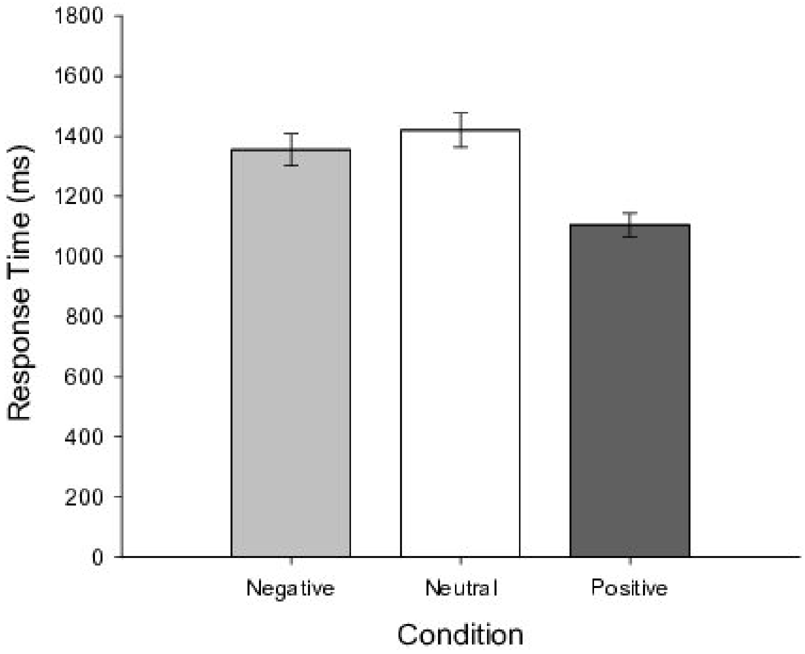


Figure 4.2. Manual response time results from Experiment 1 plotted as a function of cue condition (negative, neutral, or positive). Mean correct RT was faster in the positive-cue condition than in the neutral-cue condition, but there was no RT advantage for the negative-cue condition compared with the neutral-cue condition. Error bars represent within-subject 95% confidence intervals (Morey, 2008).

Replicating Arita et al. (2012), mean correct RT was lower in the positive-cue condition than in the neutral-cue condition, *t*(25) = 4.65, *p* < .001 (see Figure 4.2). Unlike in Arita et al. (2012), there was no RT advantage for the negative-cue condition compared with the neutral-cue condition, *t*(25) = 0.77, *p* = .448. However, there were substantial individual differences in the pattern of cuing effects: participants who demonstrated a strong positive cue benefit also exhibited a negative cue benefit. To analyze this pattern, we calculated the positive and negative cuing effect for each participant relative to their neutral baseline (with half of the neutral trials used to calculate the positive cue effect and half used to calculate the negative cue effect, so that the two measures were independent). The two effects were strongly correlated (see Figure 4.3; $r = .67$, $p < .001$). We split the participants into two groups based on the magnitude of the positive cue benefit. Little or no positive cue benefit indicates poor use of cue information, making the negative cue effect difficult to interpret. It is possible that some participants perceived little advantage to using the color cue, because the target item could be identified solely by gap location throughout the experiment, and the color cue information had to be applied differently in each block. Participants in the low group ($N = 13$) did not show either a positive or a negative cuing benefit ($p > .1$ for both comparisons; Figure 4.4). However, the high group ($N = 13$) demonstrated a significant negative cue benefit, $t(12) = 2.73$, $p = .018$, in addition to a significant positive cue benefit, $t(12) = 9.97$, $p < .001$. Thus, within the group of participants that consistently used cue information to guide search, Experiment 1 replicated the Arita et al. (2012) results.

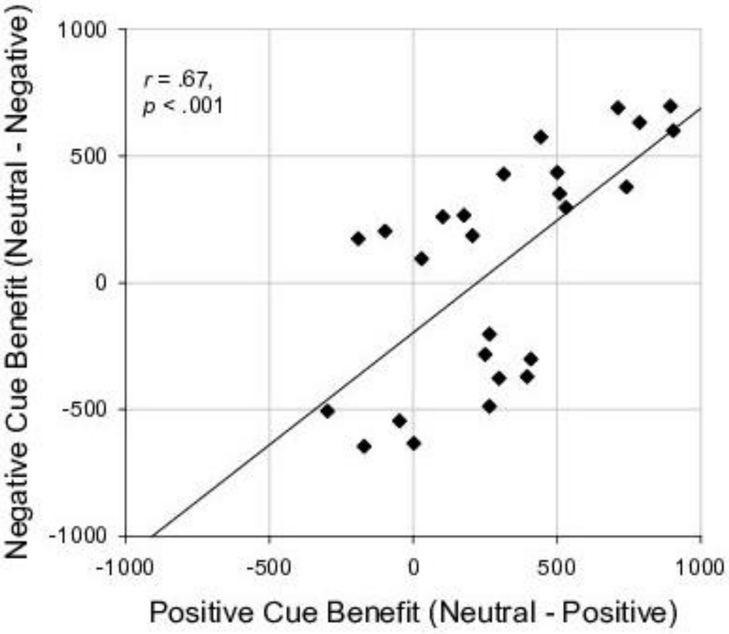


Figure 4.3. In Experiment 1, the positive cue benefit (neutral RT – positive RT) was strongly correlated with negative cue benefit (neutral RT – negative RT).

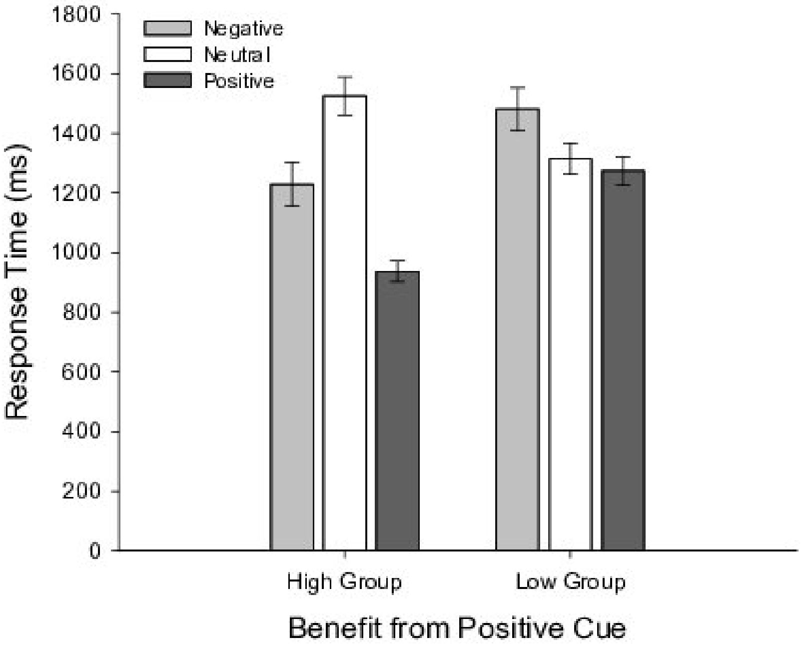


Figure 4.4. Participants were split into two groups based on magnitude of positive cue benefit: high group (greatest positive cue benefit, *N* = 13), low group (least positive cue benefit, *N* = 13). Participants in the high group demonstrated a reliable benefit from the negative cue, relative to the neutral cue, which replicated the pattern of results found by Arita et al. (2012). Participants in the low group demonstrated no benefit from the negative cue. Error bars represent within-subject 95% confidence intervals (Morey, 2008).

4.4 Experiment 2: Intermixing Prevents Spatial Recoding

To examine whether the negative cue benefit here and in Arita et al. (2012) was caused by translating a feature cue into a spatial template, we manipulated whether the colored items in the search array were spatially segregated (as in Experiment 1) or intermixed (see Figure 4.5). If participants can implement direct, *feature*-guided avoidance, then a negative cuing benefit should be observed in both types of spatial configuration. If, however, guidance by a negative cue can be implemented only by translation to a spatial template, this process should be hindered when the items are spatially intermixed, reducing or eliminating the negative cue benefit.

4.4.1 Method

Participants. Eighteen participants (18-30 years old; 11 female) from the University of Iowa community participated and received either course credit or pay.

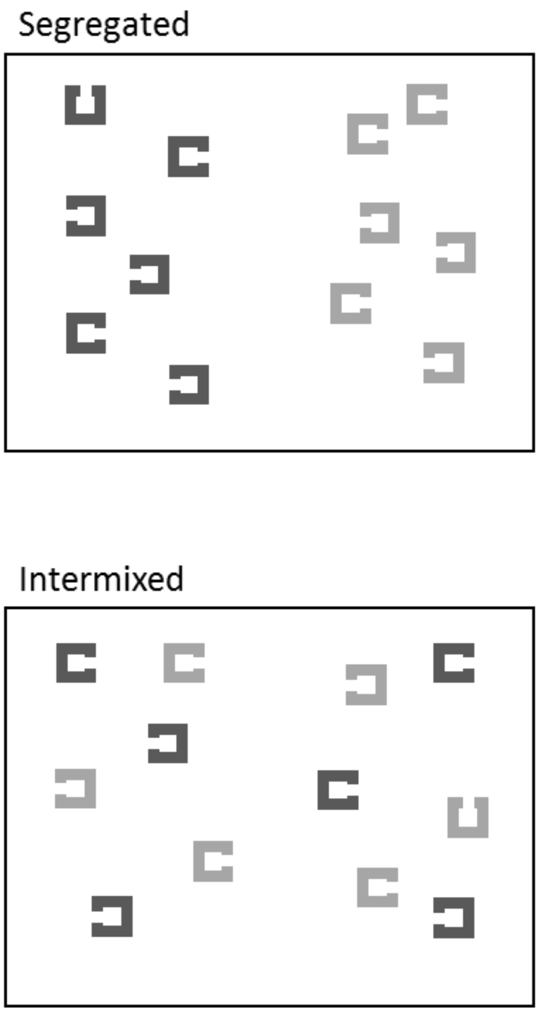


Figure 4.5. Example search arrays illustrating the segregated (top panel) and intermixed (bottom panel) conditions used in Experiment 2. All other trial events (fixation, cue, interstimulus interval) were the same as used in Experiment 1.

Stimuli and procedure. Stimuli and procedure were the same as Experiment 1, except that there were seven total colors (red, green, blue, cyan, magenta, yellow, and grey), although only two colors appeared in any one search display, and the search displays were arranged differently. Items were no longer arranged on an invisible circle but were assigned random locations in two rectangular regions (4.4° × 13.9°, nearest edge 1.8° to the left/right of center), one in each hemifield (see Figure 4.5). Placing items in rectangular regions, rather than on an invisible circle, allowed greater variation in generating intermixed displays while also keeping the two hemifields distinct.[6] The two colors were segregated by hemifield or intermixed (three items of each color in each hemifield). To compare feature-based and location-based guidance, half of the trials used a spatial cue instead of a feature cue. The spatial cue was negative (arrow pointed to the hemifield that did not contain the target), neutral (double-headed arrow), or positive (arrow pointed to hemifield containing the target). Cue condition (negative, neutral, positive), cue type (color, location), and array type (segregated, intermixed) were blocked. Cue condition order was counterbalanced across participants, but the order of cue type and array type blocks was fixed within each cue condition. Participants began the session with 12 practice trials (one trial of each possible trial type), then completed 12 blocks of 55 trials each.

4.4.2 Results and Discussion

Manual response accuracy was uniformly high across all 12 conditions (*M* = 98.7%) and did not differ between any comparisons of interest (see Table 4.1 in the supplemental materials at the end of this chapter for accuracy by condition). RT trimming (2.5 *SD*) eliminated 2.8% of trials but did not alter the pattern of results.

Location cue. Positive and negative spatial cues both generated search RT benefits relative to the neutral condition, *t*(17) = 3.65, *p* = .002; *t*(17) = 2.27, *p* = .037, respectively (see Figure 4.6A). In neither case was the benefit modulated by the spatial

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[6] Because of the design changes, we first replicated Experiment 1 using the Experiment 2 design parameters (7 possible colors, items placed in rectangular regions instead of on a circle), but with the same trial types as in Experiment 1. We replicated the Experiment 1 results. When all subjects were included, there was a reliable positive cue benefit, *t*(15) = 2.72, *p* = .008, but no negative cue benefit, *t*(15) = 0.04, *p* = .484. After performing a median split on the basis of the positive cue benefit, the high group demonstrated significantly faster RTs on both positive cue trials, *t*(7) = 4.22, *p* = .002, and negative cue trials, *t*(7) = 2.35, *p* = .025, compared with neutral trials. However, the low group showed neither a positive cue benefit, *t*(7) = 0.36, *p* = .365, nor a negative cue benefit, with a nonreliable trend toward a negative cue cost, *t*(7) = 1.76, *p* = .061.

distribution of colors in the display (*p*s > .24; see Figure 4.6B). These results demonstrate that participants were able to efficiently implement a negative spatial template (consistent with Munneke et al., 2008) based on the type of location information that could have been inferred from the distribution of colored items in the segregated arrays of Experiment 1 and Arita et al. (2012).

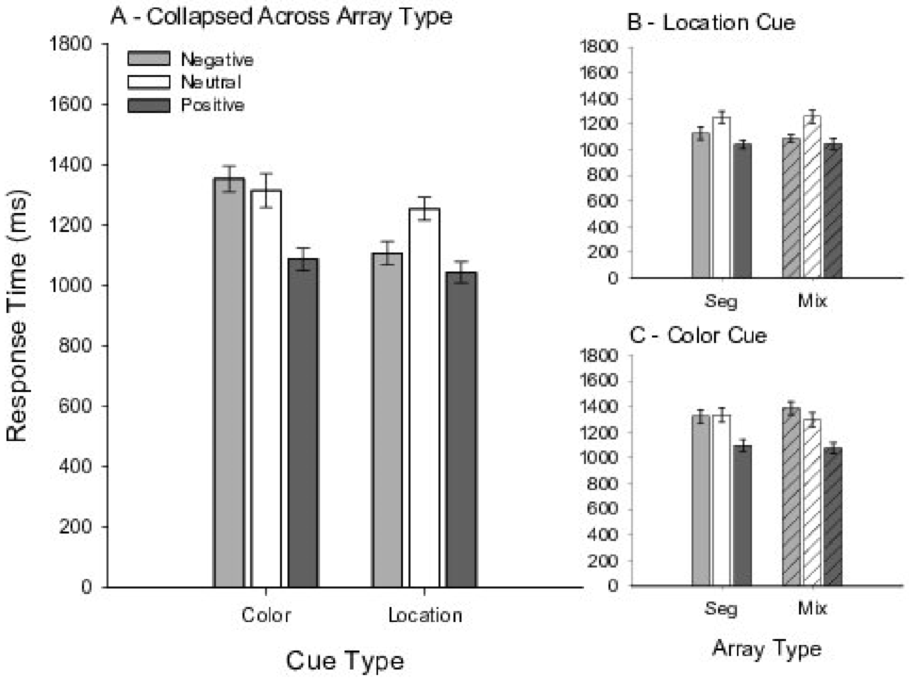

Figure 4.6. Manual response time results from Experiment 2 plotted as a function of cue type (color, location) and collapsed across array type (segregated [Seg], intermixed [Mix]; Panel A). When given a location cue, participants were faster to respond to the target item in both the negative-cue and positive-cue conditions compared with neutral. When given a color cue (as in Experiment 1), participants demonstrated a positive-cue benefit compared with the neutral-cue condition, but not a negative-cue benefit. There was no effect of array type within the location cue (Panel B) or color cue (Panel C) condition. Error bars represent within-subject 95% confidence intervals (Morey, 2008).

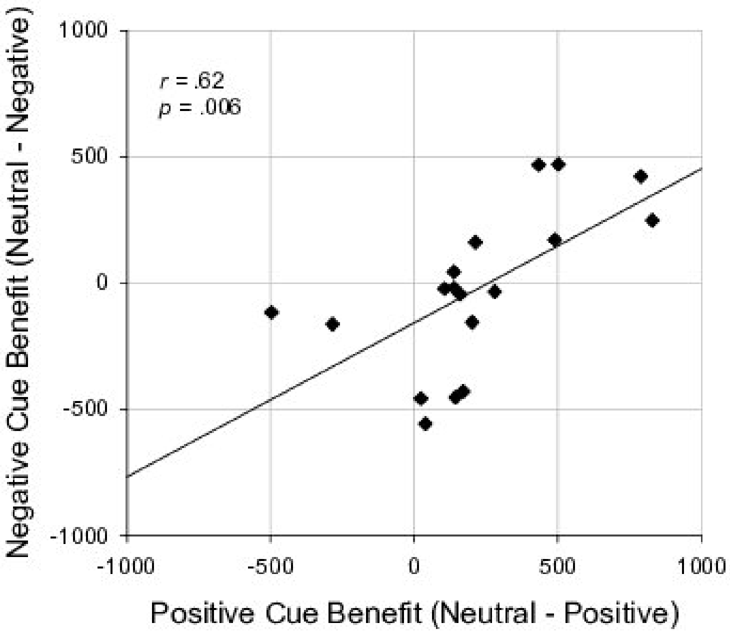

Figure 4.7. Similar to the results from Experiment 1, the magnitude of the positive cue benefit (neutral RT – positive RT) was strongly correlated with the magnitude of the negative cue benefit (neutral RT – negative RT).

Color cue. There was a reliable positive cue benefit, $t(17) = 3.07$, $p = .006$, but no negative cue benefit, $t(17) = 0.51$, $p = .617$, replicating the pattern of results in Experiment 1 (see Figure 4.6A). Moreover, the cuing effects were not modulated by the spatial distribution of colored items, (*p*s > .27; see Figure 4.6C). However, there was again a strong correlation between participants' positive and negative cue effects ($r = .62$, $p = .006$), indicating individual differences in the utilization of feature-cue information (see Figure 4.7). When the RT data were split by the magnitude of the positive cue effect (using only trials from the positive color cue condition), the high group ($N = 9$) reliably demonstrated a negative cue benefit in the color cue condition when the array was segregated, $t(8) = 2.64$, $p = .030$ (see Figure 4.8A), replicating the results from Experiment 1, but not when the array was intermixed, $t(8) = 0.15$, $p = .886$ (see Figure 4.8B). The low group ($N = 9$) did not demonstrate a negative or positive cue benefit for either array type (*p* > .86; Figure 4.8). In fact, mean RTs in the low group were higher in the negative cue condition than in the neutral condition, *t*(8) = 2.39, *p* = .044. In sum, participants were able to benefit from the negative cue information, but only if they demonstrated a benefit from a positive cue and only if color cue information could be easily recoded into a spatial template (segregated array type).

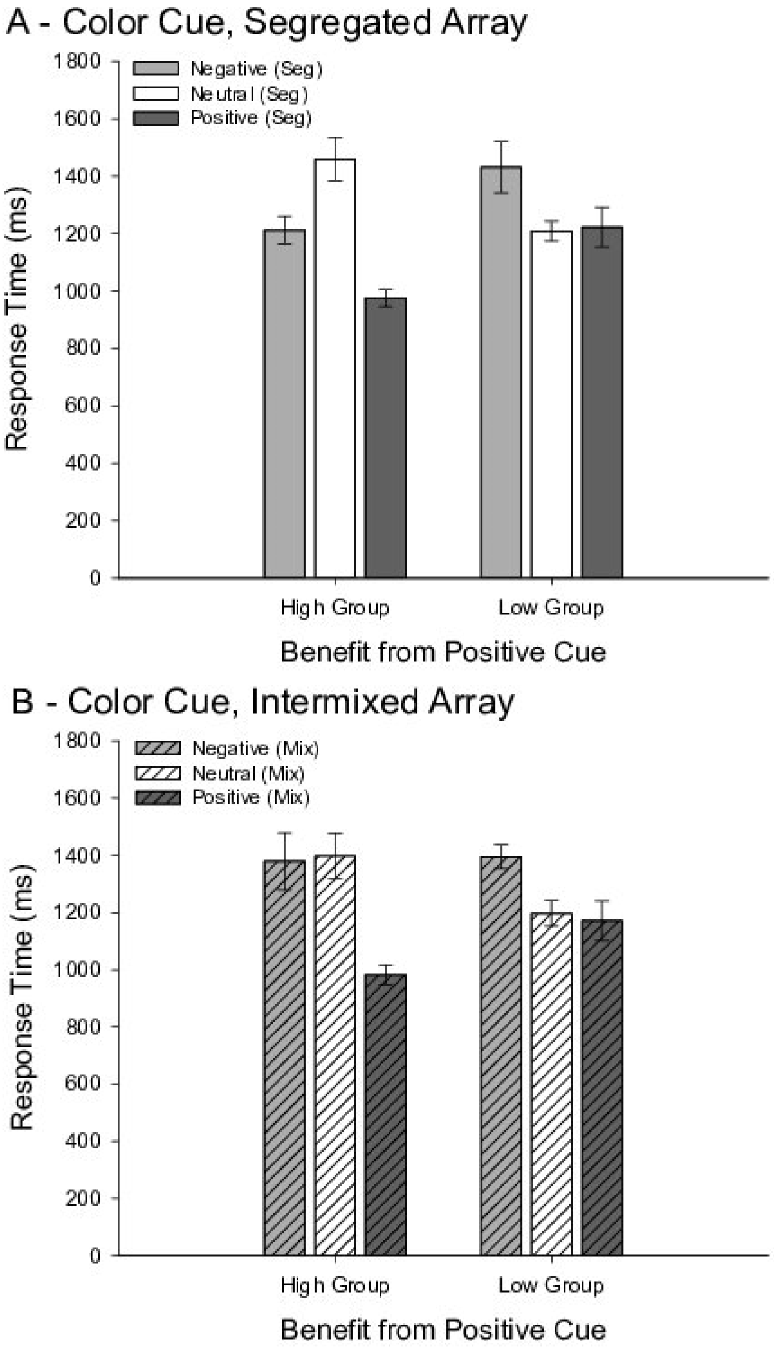

Figure 4.8. As in Experiment 1, participants were split into two groups based on magnitude of positive cue benefit: high group (greatest positive cue benefit, *N* = 9), low group (least positive cue benefit, *N* = 9). Participants in the high group demonstrated a reliable negative cue benefit relative to the neutral condition but only when the different colored items were segregated (Seg) by hemifield (Panel A). When the different colored items were intermixed (Mix) within each hemifields (Panel B), participants in the high group no longer demonstrated a benefit from the negative cue relative to the neutral condition. Participants in the low group did not demonstrate a negative cue benefit for either array type. Error bars represent within-subject 95% confidence intervals (Morey, 2008).

4.5 General Discussion

In several theories of attention, it is possible to configure a VWM template to either prioritize or deprioritize objects that match a particular feature value. For example, in Bundesen's (1990) theory of visual attention, the pertinence value of one color could be set to a level either above or below that of other colors, implementing a bias to select for or against that color. In practice, however, implementing a negative feature template may be difficult, if not impossible. To avoid attending to a particular feature, a participant must remember the feature value, typically done by maintaining that value in VWM. Maintenance of a feature in VWM involves sustained activation of feature-specific neural populations in sensory cortex (Harrison & Tong, 2009; Postle, 2006; Serences et al., 2009), which is likely to interact with subsequent sensory processing, biasing competition for selection in favor of the remembered feature (Bundesen, 1990; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Wolfe, 1994). Thus, attention will be drawn to objects containing the to-be-avoided feature, a consequence of the demand to remember which feature to avoid. This type of capture effect has been observed in numerous studies: Visual attention is oriented to memory-matching objects, even when these objects should be avoided (Downing & Dodds, 2004; Folk et al., 1992; Han & Kim, 2009; Hollingworth & Luck, 2009; Hollingworth et al., 2013; Olivers et al., 2006; Olivers, 2009; Soto et al., 2005, 2006b).

In contrast, a few studies have indicated that this capture effect can be overridden, or even reversed, suggesting the content of VWM can be used flexibly to select against memory-matching items (Arita et al., 2012; Han & Kim, 2009; Moher & Egeth, 2012; Woodman & Luck, 2007). We have argued that the most compelling evidence in support of a negative feature template can be explained instead by spatial recoding. Arita et al. (2012) observed a substantial benefit for negative color cue trials in a visual search task. However, the displays had colored items segregated by hemifield, allowing simple spatial recoding of the side of the display to be avoided (or, equivalently, the side to be attended). If the negative cue benefit resulted from direct feature-guided avoidance, it should not depend strongly on the spatial arrangement of items. However, when we spatially intermixed colored objects within the search array (Experiment 2), making location grouping more difficult, participants no longer demonstrated a negative cue benefit. Without a means to efficiently recode the negative cue information into a simple spatial template, they were unable to use the negative feature cue to direct attention away from irrelevant objects.

Furthermore, spatial recoding provides a plausible explanation for the findings of two other experiments in which negative feature cues generated benefits in visual search. In Han and Kim (2009) and Moher and Egeth (2012), participants saw a negative color cue, followed by a set of placeholders corresponding to the upcoming search locations. It is important to note that the placeholders had the same colors as the subsequent search items. During the placeholder display, participants had ample time to identify the location of the color-matching item and to create a simple spatial template marking that location as to-be-avoided (or marking other locations as to-be-attended). When participants were cued to avoid a particular location in a similar paradigm, Munneke et al. (2008) found a cuing benefit, indicating participants were able to successfully avoid searching the cued location. Although we cannot be certain that spatial recoding was the source of the negative-cue benefit in Han and Kim (2009) and in Moher and Egeth (2012), this clear alternative would need to be eliminated before those data could provide strong evidence in favor of feature-based avoidance.

In sum, our data are consistent with a fundamentally facilitatory relationship between VWM and perceptual selection. We usually know the features of the object we are looking for. Maintaining those features in VWM facilitates selection of matching items to guide attention toward plausible objects. It is rarely the case that an object is best described by a feature that it lacks. It may be possible to implement the latter type of guidance under some circumstances, but the present data suggest that this guidance is at best indirect, implemented by translating feature information into a spatial template.

4.6 Supplementary Materials

	Cue Condition	Array Type	Participants	Negative	Neutral	Positive
Exp 1	Color Cue		All	1355 [53]	1420 [57]	1106 [39]
			High Group	1229 [73]	1525 [64]	937 [35]
			Low Group	1481 [72]	1315 [51]	1274 [49]
Exp 2	Location Cue		All	1108 [39]	1256 [38]	1045 [35]
		Segregated	All	1129 [48]	1253 [45]	1043 [32]
		Intermixed	All	1087 [29]	1258 [49]	1046 [45]
	Color Cue		All	1354 [43]	1316 [56]	1088 [38]
		Segregated	All	1322 [55]	1344 [55]	1099 [46]
			High Group	1212 [47]	1460 [75]	976 [30]
			Low Group	1432 [89]	1209 [34]	1223 [69]
		Intermixed	All	1387 [53]	1297 [54]	1076 [43]
			High Group	1379 [100]	1398 [79]	982 [35]
			Low Group	1395 [41]	1197 [45]	1171 [69]

Table 4.1. Mean response times (ms) for each condition of Experiments 1 and 2. Standard errors used to calculate within-subject 95% confidence intervals (Morey, 2008) are in brackets.

CHAPTER 5: EVALUATING GUIDANCE BY AN EXCLUSIONARY TEMPLATE

5.1 Overview

Participants are able to use an attentional template consisting of one, or even two, features to guide the eyes to matching objects in a search array. But can we also use feature information to guide attention *away* from known irrelevant items? Some studies have found a response time benefit from foreknowledge of a distractor feature, while others have found a response time cost. Importantly, most of the previous work has relied on manual responses made at the end of the trial; it is unclear how feature-guided avoidance might unfold as candidate objects are inspected. In the current experiments, participants' eye movements were recorded as they performed a visual search task, after being cued with a distractor feature to avoid. Participants initially fixated an object they should have avoided more frequently than predicted by chance, but also demonstrated avoidance of cue-matching objects later in the trial. When provided more time in between the cue stimulus and the search array, participants continued to be initially captured by a cued-color item. These results suggest that the conflicting findings in previous negative-cue experiments may be explained by a mixture two separate processes: initial attentional capture by memory-matching items and later avoidance of known irrelevant items.

The experiments described in this chapter are awaiting comments from S.J. Luck in preparation for submission: Beck, V. M., Luck, S.J., and Hollingworth, A. Whatever you do, don't look at the… Evaluating guidance by an exclusionary attentional template.

5.2 Introduction

Almost all theories of attention propose that a template specifying the features of task-relevant items allows for goal-directed control of selection (e.g., Bundesen, 1990; Duncan & Humphreys, 1989; Wolfe, 1994). Indeed, when participants receive knowledge about a relevant feature prior to search (e.g., a cue specifying that the target will be red), they can largely limit attention to matching items in the search array (Beck et al., 2012; Vickery et al., 2005; Wolfe et al., 2004). Maintaining a representation of the relevant template features requires memory, and because search targets frequently change during real-world behavior, most researchers have proposed that the substrate of the template representation is typically visual working memory (VWM).

Theories of attention have typically accounted for template-based guidance by assigning a higher weight to features maintained in VWM in processes that resolve the competition among objects for selection (Bundesen, 1990; Desimone & Duncan, 1995; Navalpakkam & Itti, 2005; Wolfe, 1994). This raises a key architectural question. Although it is well established that the content of VWM can be used to facilitate the selection of matching items, can the interface between VWM and attentional control be configured so that attention is biased *away* from objects matching VWM content? Do the attentional weights necessarily have to be positive? Or, is it possible to assign a negative attentional weight for a feature value, relative to other features values, so as to implement feature-guided avoidance?

The evidence thus far has been mixed, representing one of the central outstanding questions in the field of goal-directed vision. Most studies have demonstrated that when the content of VWM is known to be associated only with distractors, attention is nevertheless captured by matching items (Folk et al., 1992; Hollingworth & Luck, 2009; Hollingworth et al., 2013; Olivers et al., 2006; Olivers, 2009; Experiment 4 in Soto et al., 2005, 2008; Soto & Humphreys, 2007), suggesting that participants cannot configure a feature-based, negative template. However, other studies have found some evidence of successful avoidance (Arita et al., 2012; Woodman & Luck, 2007), as indicated by lower overall search times when memory-matching distractors were present in the search array.

Woodman and Luck (2007) were the first to propose that a VWM representation could be used to not only guide attention toward matching items ("template for selection") but also away from matching items ("template for rejection"). Participants were asked to hold a colored square in memory, perform a shaped-defined search task, and then respond to a memory probe. In the critical experiment, the search array contained two items drawn in one color, four items drawn in a second color, and six items drawn in a third color. One of the colors used in the search array always matched the color held in memory, but the number of memory-matching distractors could vary (2, 4, or 6). The search target was a Landolt-C with a gap in the top or bottom and never matched the color in memory. Participants were faster to respond to the target item when there were a greater number of memory-matching distractors (6) than when there were fewer (2 or 4), suggesting they were able to configure a VWM-based "template for rejection" and exclude these memory-matching items from search.

The Woodman and Luck (2007) results are the strongest evidence to date in favor of the capability to configure a negative VWM template. Several other studies have reported converging evidence, but these have been limited in important ways. First, Arita et al. (2012) used a circular search array, with items on the left side presented in one color (e.g., red) and items on the right side presented in another color (e.g., blue). A color cue that preceded the search array could indicate the target item color (positive cue), a distractor color (negative cue), or a color not present in the search array (neutral cue). Arita et al. (2012) found faster response times in the negative cue condition than in the neutral cue condition, suggesting that participants were able to avoid attending to cue-matching items. However, Beck & Hollingworth (2015) argued that what appeared to be feature-based avoidance could be explained instead by the rapid conversion of the negative feature cue into a simple spatial template (attend left or attend right). When the different colored items were intermixed, making this conversion strategy more difficult to implement, the response time benefit in the negative cue condition was eliminated (see also Becker, Hemsteger, & Peltier, 2016).

Moher and Egeth (2012) also reported evidence of avoidance on the basis of a negative feature cue, but with a caveat. They claimed that avoidance was dependent on directing attention initially to an item or items matching the to-be-avoided color, terming this a “search and destroy” process. Participants were provided a negative cue indicating a distractor color prior to the appearance of a search array. In an initial experiment, response times were slower in the negative cue condition than in a neutral condition, suggesting that participants were attending to the cue-matching distractor even though they knew it was irrelevant. To examine the time-course of selection during search, Moher and Egeth (2012) used a dot-probe technique and an SOA manipulation to probe the spatial locus of attention early versus late during the search process. They found significantly faster dot-probe RTs at the cue-matching distractor location early during search (117 ms SOA), suggesting that attention was captured initially. They found a nonsignificant trend toward slower dot-probe RTs at the cue-matching distractor location later during search (167 ms SOA), concluding that initial capture was followed by later avoidance. However, even if the latter avoidance effect were robust, the composition of the arrays precluded strong inferences about avoidance. The arrays contained only one cue-matching item. Thus, if attention was initially captured by that item, later "avoidance" may have been the simple consequence of having already attended to it; there need not have been any explicit mechanism of avoidance, just the deployment of attention to the remaining items in the array after initial capture by the cue-matching item.

As an additional test of later avoidance, Moher and Egeth (2012) preceded the search array with a set of placeholders that were the same colors as the search array items. The placeholders were visible for 100, 800, or 1500 ms before the search array appeared. There was a negative cue cost (relative to a neutral condition) at 100 ms duration and a negative cue benefit at 800 and 1500 ms duration, suggesting that during the placeholder array, participants initially attended to the cue-matching placeholder, but with longer placeholder presentation, they were able to deprioritize those locations in preparation for the upcoming search. What is not clear from this method is whether the ultimate advantage in search RT at the longer placeholder durations was due to feature-based avoidance or due to the ability to mark particular array locations as to-be-avoided (or the complementary set at to-be-attended). That is, participants may have converted the feature information into a spatial template before search commenced, similar to the strategy apparently used in the method of Arita et al (2012; see also Han & Kim, 2009).

Note that Moher and Egeth (2012) did not specify a mechanism by which later avoidance was implemented, so this possibility is not necessarily inconsistent with their claims.

In sum, the current literature leaves open key questions. On the empirical side, it has yet to be determined if participants can use a negative feature cue to generate any type of avoidance of cue-matching objects, except in the limited circumstances in which spatial locations can be marked beforehand (Moher & Egeth, 2012) or the cue can be efficiently converted into a simple spatial template after the appearance of the array (Arita et al., 2012; Beck & Hollingworth, 2015). The results of Woodman and Luck (2007) suggest that such avoidance might be possible, but similar paradigms have produced conflicting results (Olivers et al., 2006; Olivers, 2009; Experiment 4 in Soto et al., 2005; Soto & Humphreys, 2007). Additionally, little is understood about how selection evolves over the course of a trial, either for a positive template or for a negative template. The Moher and Egeth (2012) results suggest that negative templates produce a pattern of initial capture and later avoidance. However, as discussed above, their method yielded ambiguous results with respect to later avoidance. Finally, if such a capture/avoidance pattern were observed, it would need to be determined whether there is a functional relationship between early capture and later avoidance.

In the following three experiments, we examined these issues by recording eye movements while participants performed a visual search task. Prior to appearance of the search array, they saw either a positive cue (target item color), a negative cue (distractor color), or a neutral cue (cue uninformative). Similar to previous studies, search performance was evaluated in terms of accuracy and manual response time. However, the key innovation of the present method was the use of eye movement recording to capture the object-by-object pattern of selection during search, providing a real-time window on the evolution of selection throughout the trial. This allowed us to examine the time-course of positive- and exclusionary-template guidance during the trial in terms of the probability, for each object fixated, that the fixated object matched the cued attribute. Moreover, we included multiple cue-matching objects, so that, in the negative cue condition, we could examine the possible effect of early capture on the probability of selecting other cue-matching objects later in the trial.

5.3 Experiment 1: Implementing an Exclusionary Template

Experiment 1 was designed to determine whether participants are able to use information about a non-target color to exclude matching items from visual search and how selectivity develops across the trial. In the basic search task used in all three experiments, participants viewed an array of circles drawn in different colors. Distractors had a gap on the left or right. The target had a gap on the top or bottom, and participants reported gap location. Before the onset of the search array, a colored cue was displayed. There were three cuing conditions, illustrated in Figure 5.1. In the *cue-target* condition, the cue indicated the color of the target item, as in the classic visual search paradigm. Participants could use cue information to select cue-matching items during search. In the *cue-avoid* condition, the cue indicated one of the colors in which the target would *not* be drawn. Participants could potentially use the cue information to avoid selecting cue-matching items. Finally, in the *cue-all* condition, the cue was a composite of all possible colors and thus conveyed no information.

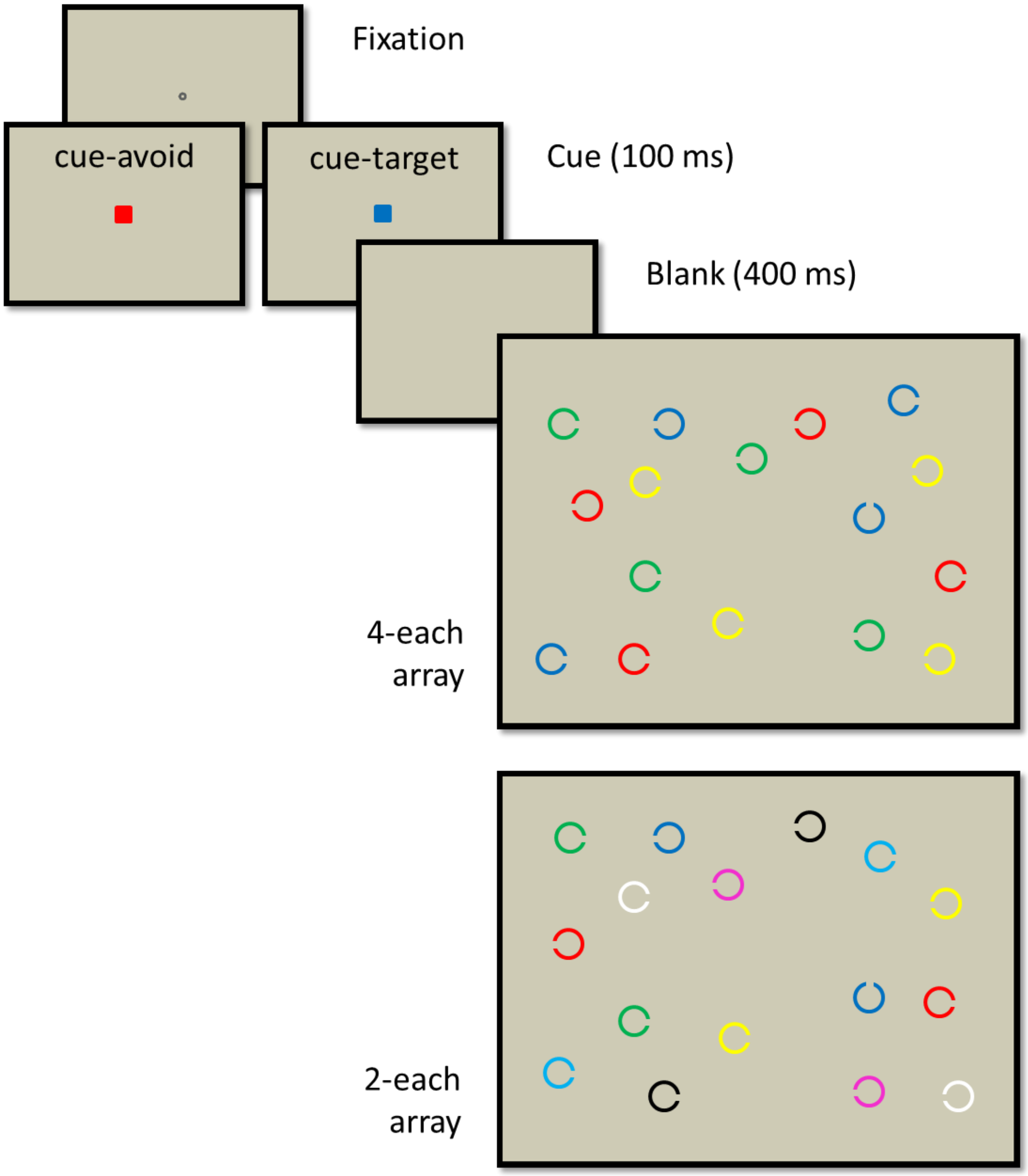

Figure 5.1. Example trial sequence and search arrays for Experiments 1-3. Participants were instructed to locate the Landolt-C with a top or bottom gap and report the gap location. The cue stimulus could indicate either the color of the target item (*cue-target*), the color to avoid (*cue-avoid*), or that the target item could be any color (*cue-all*; not shown). The search array could contain either four each of four different colors (*4-each*) or two each of eight different colors (*2-each*). Cue condition was blocked and the type of search array was intermixed.

5.3.1 Method

Participants. Twelve participants (8 female) from the University of California, Davis completed the experiment and were compensated for their time. All participants reported normal color vision and normal or corrected-to-normal acuity.

Stimuli and Procedure. Stimuli were presented on a CRT monitor at a distance of 70 cm. Each search array contained 16 Landolt-C objects against a grey background (see Figure 5.1). Landolt-C objects were 0.67° in diameter, had a line width of 0.10°, and had a gap measuring 0.07°. Objects were placed in random locations on the screen with the following constraints: a minimum distance of 2° from the center of the screen, a minimum distance of 2.07° between objects, and a minimum distance of 2.51° from the edge of the screen. The total visible area of the screen subtended 26.74° x 20.05°, but objects could only appear within an area that subtended 21.72° x 15.03°. New locations were generated for each trial, and the target object was randomly assigned to one of the locations.

The Landolt-C objects were drawn in either four each of four different colors (*4-each*) or two each of eight different colors (*2-each*) and appeared on a light grey background. Presenting arrays in this manner allowed us to examine search efficiency by varying the number of objects that could be the target (*cue-target*: 4 or 2 items; *cue-avoid*: 12 or 14 items; *cue-all*: always 16 items) without changing the total number of objects on the screen. The eight possible colors were chosen to be highly discriminable: red, yellow, green, blue, white, black, magenta, and cyan. For the *4-each* condition, the four colors on each trial were selected randomly from the set of eight. In a given array, the assignment of each color to each object was determined randomly. Thus, the target color was selected randomly on each trial. There was one target object (top or bottom gap, randomly selected) and 15 distractor objects (left or right gap, randomly selected). Participants reported the target item gap location via button press. Importantly, the gaps were so small that gap position discrimination required object fixation, and the task therefore required participants to translate covert attentional control into overt shifts of gaze.

At the beginning of each trial, a cue square (0.67° x 0.67°) appeared briefly (100 ms) at fixation, 500 ms prior to the onset of the search array. Once the search array appeared (after a 400 ms blank delay), it remained visible until the manual response, which terminated the trial. The cue was either the color in which the target would be drawn (*cue-target*), a color that would be present in the array but would not be the target color (*cue-avoid*), or a checkerboard composed of all possible colors (4x4 grid containing 2 squares of each of the 8 possible colors) indicating that the target item could be any color (*cue-all*; not shown). For the *cue-avoid* condition, the cue square color was selected randomly from the set of distractor colors to appear in the subsequent array. Cue condition was blocked, and block order was randomized across participants. The task began with eight trials of each condition (*cue-target, cue-all, cue-avoid*), followed by three blocks of 32 trials for each of the three conditions. At the beginning of each condition section, participants received instructions about what the cue signified (Cue = Target Item Color, Cue = NOT Target Item Color, Cue = Target Item is Any Color). The first two trials in each block were considered buffer trials and were excluded from analysis.

Eye movements were recorded using an Eyelink 1000 eye tracker with a sampling rate of 2000 Hz. Saccades were defined by a combined velocity (>30°/s) and acceleration (>9500°/s^2) threshold. Gaze position was calibrated using a typical 9-point calibration/validation routine at the beginning of each block and any time the participant failed to meet gaze-contingent fixation criteria at the beginning of a trial. Each trial began with a gaze-contingent fixation routine that required participants to fixate a central region (1.67° x 1.67°) for 300 ms, which served to provide a check on tracking accuracy as well as ensure the participant would see the cue square that appeared at the same location as soon as the gaze-contingent fixation criteria were met.

Data Analysis. For the eye movement analyses, interest areas were defined around each object and the central fixation region. The central fixation interest area was a circle 1.67° in diameter at the center of the screen. Object interest areas were circles centered on each object subtending 2°, which allowed for natural variation of gaze accuracy while also defining non-overlapping regions. An object was considered to be fixated when a fixation occurred within the defined interest area for that object.

5.3.2 Results and Discussion

To examine whether participants were able to benefit from the cue information both in the *cue-target* and *cue-avoid* conditions relative to the *cue-all* condition, we first report the standard end-of-trial measures of response accuracy and search efficiency. The key analyses come from the eye movement data. By recording eye movements, we were able to examine how selection proceeds object by object and determine whether participants were able to avoid cue-matching objects in the *cue-avoid* condition.

As anticipated, manual response accuracy was uniformly high (*M* = 99% correct) across all conditions (see Table 5.1 for accuracy by condition and array type) and trials with incorrect responses were excluded from all further analyses. Although an object's gap location could not be determined parafoveally, the task itself was straightforward and participants tended to make very few, if any, errors. All trials with response times that were less than 150 ms or greater than 10,000 ms were excluded from analysis (6.78% of trials). Furthermore, trials with response times that were greater or less than 2.5 standard deviations from the mean of each condition for each subject were also excluded from all analyses (additional 1.94% of trials).

Experiment	Array Type	Cue Condition		
		Positive	Neutral	Negative
Experiment 1	4-each	99.0%	98.5%	99.6%
	2-each	97.5%	99.6%	99.1%
Experiment 2	4-each	98.9%	99.0%	98.6%
	2-each	98.7%	99.6%	99.0%

Table 5.1. Mean manual response accuracy for each condition in Experiments 1 and 2.

Global Measure of Target Detection Time. We first report a measure of search efficiency reflecting the total time required to find the target: elapsed time until the first fixation in the target region, or time to target fixation (TTF). This measure is comparable to manual response time (RT), but has the advantage of removing variability due to selecting and executing and the manual response. Furthermore, using TTF rather than manual RTs also ensures we are only including trials during which participants fixated the target item. TTF and manual RT produced the same pattern of condition means. If participants were able to make use of cue information in the *cue-target* and *cue-avoid* conditions and limit their search to the relevant objects, then TTF should be reduced compared to the *cue-all* condition, when all objects are potentially relevant.

To examine search efficiency, we compared the *cue-target* (positive template) and *cue-avoid* (negative template) conditions against *cue-all* (neutral) separately. For the positive template, a condition X array type ANOVA run on mean TTF revealed a main effect of condition [$F(1, 11) = 354.93$, $p < .001$, $\eta_p^2 = .97$], a main effect of array type [$F(1, 11) = 22.86$, $p = .001$, $\eta_p^2 = .68$], but no significant interaction (Figure 5.2). Collapsing across array type, we found faster TTF in the *cue-target* condition ($M = 623$ ms) than in the *cue-all* condition ($M = 2048$ ms), indicating efficient attentional guidance by a positive template. Similarly, collapsing across cue condition, we found faster TTF for *2-each* ($M = 1241$ ms) than *4-each* arrays ($M = 1430$ ms), driven by the fewer number of relevant items in *2-each* (2) compared to *4-each* (4) arrays in the *cue-target* condition.

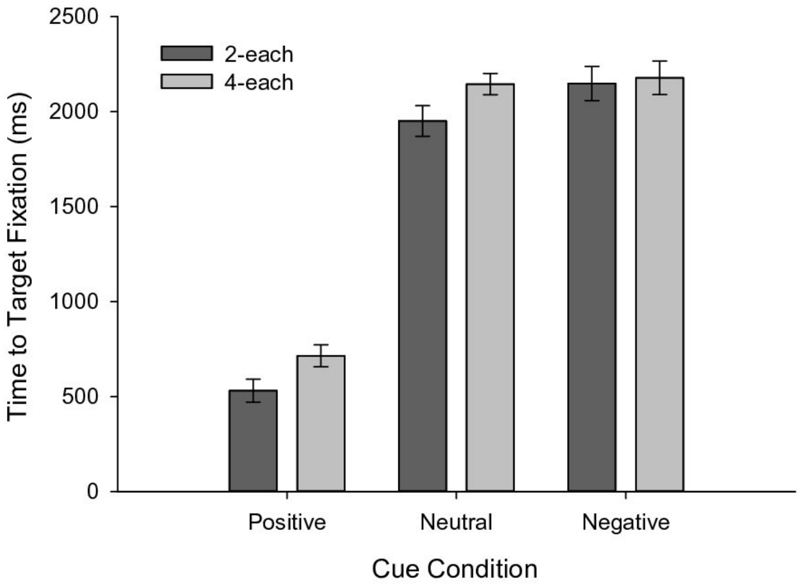

Figure 5.2. Elapsed time to first fixation on the target item plotted as a function of cue condition (*cue-target*: Positive, *cue-all*: Neutral, *cue-avoid*: Negative) and array type (*4-each*, *2-each*) for Experiment 1 (color cue stimulus). Error bars indicate within-subjects 95% confidence intervals (Morey, 2008).

For the negative template, a condition X array type ANOVA run on mean TTF revealed no significant main effects or interaction (all *p*s >.17), suggesting participants were not able to make use of the cue information in the *cue-avoid* condition. The same analyses were run on manual RTs and produced the same pattern of results. Thus, the measures that reflected the total time required for visual search suggested that participants were not able to implement an exclusionary template based on the cue information in the *cue-avoid* condition.

Measures of mean fixation duration and saccade amplitude were consistent with the patterns observed in end-of-trial measures of search efficiency. In the *cue-target* condition, fixation durations were reliably shorter (M = 148 ms) and saccades reliably longer (M = 4.7 degrees amplitude) than in the *cue-all* condition (M = 183 ms latency; M = 4.1 degrees amplitude) [$t(11) = 15.38$, $p < .001$, $\eta_p^2 = .96$ for fixation duration; $t(11) = 5.92$, $p < .001$, $\eta_p^2 = .76$ for saccade amplitude]. These results are consistent with efficient template use and replicate previous reports (Beck et al., 2012). However, in the *cue-avoid* condition, neither fixation duration (M = 187 ms) nor saccade amplitude (M = 4.1) differed significantly from the *cue-all* condition [$t(11) = 1.62$, $p = .13$ for fixation duration; $t(11) = 0.49$, $p = .64$ for saccade amplitude], consistent with the finding that participants did not use an exclusionary template to guide search.

Object-by-object Analysis of Selectivity. To examine the evolution of selection across the course of a trial, the eye movement data were binned by ordinal object fixated during search (i.e., first object fixated, second object fixated, etc.). Note that for this analysis, the functional unit was the object, not the individual fixation. For each subject in each bin, we compared the observed probability of fixating a cue-matching object against chance by calculating an odds ratio: observed probability of fixating a cue-matching object over the probability of fixating a cue-matching object by chance. Chance probability was calculated for each trial, considering the preceding events on that trial, and then averaged across trials in a bin. To illustrate the calculation of chance probability, consider a trial in the *4-each* array condition in which the first object fixated was cue-matching and the second object fixated was not. The probability of fixating a cue-matching object by chance as the third object fixated in a trial would be 3/14 (approximately 21%), as there were 3 cue-matching objects and 14 total objects remaining.[7] By calculating the ratio of observed probability to chance probability, we were able to control for the history of the types of objects fixated within any particular trial and obtain a direct measure of guidance toward cue-matching objects in the *cue-target* condition and possible avoidance of cue-matching objects in the *cue-avoid* condition.

The odds ratio data were then log-transformed so that this measure would be on a linear scale and chance performance would be represented by a value of zero. To avoid undefined values when the probability of fixating a cue-matching object was zero in a bin, prior to log transformation, 1/32 (one half of the smallest unit of performance increment) was added to each observed probability and to each chance probability, similar to methods used in the signal detection theory literature (Hautus, 1995). In the final log odds ratio measure, values greater than zero indicate a cue-matching object was fixated *more* frequently than predicted by chance, and values less than zero indicate a cue-matching object was fixated *less* frequently than chance.

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[7] Note that this method of calculating chance assumes that the probability of object refixation is very low, and this was indeed the case, with return to a previously fixated object occurring on only 4.82% of all fixations.

Because trials terminated at different points depending on how quickly participants located the target item, data for each ordinal object fixated was analyzed as long as at least 11 of the 12 subjects were contributing 5 or more trials to the cell mean. Cell means for each condition were entered into one-way ANOVAs with ordinal object fixated as a factor with a minimum of 2 and a maximum of 8 levels, depending on the condition. Because these binned data were not independent and sphericity was likely to be violated, all statistical tests on this analysis used Huynh-Feldt corrected values.

In the *cue-target* condition, there was a significant main effect of ordinal object fixated for both the *4-each* [$F(1.914, 21.058) = 655.95$, $p < .001$, $\eta_p^2 = .98$; Figure 5.3A] and *2-each* [$F(1, 11) = 263.01$, $p < .001$, $\eta_p^2 = .96$; Figure 5.3B] arrays. The probability of fixating a cue-matching object increased over the course of a trial, although participants successfully implemented the template even from the first object fixated. Note that the small number of objects fixated in a trial (on average the target was the 2.34th object fixated in the *4-each* and 1.74th object fixated in the 2-each condition) is directly related to the high probability of participants fixating a cue-matching object. Participants limited their search to relevant, cued-color items and thus found the target after having fixated only a few objects. Consistent with this clear pattern, follow-up one-sample *t*-tests indicated that participants fixated cued-colored objects significantly more often than predicted by chance at each of the first three objects in the *4-each* array (Figure 5.3A) and at each of the first two objects in the *2-each* array (Figure 5.3B).

In the *cue-avoid* condition, there were significant main effects of ordinal object fixated for both *4-each* [$F(5.742, 63.165) = 9.65$, $p < .001$, $\eta_p^2 = .47$; Figure 5.3C] and *2-each* [$F(7, 70) = 7.28$, $p < .001$, $\eta_p^2 = .42$; Figure 5.3D] arrays. These effects were driven by a decreasing probability of fixating a cue-matching item across the course of a trial. Follow-up one-sample *t*-tests revealed that participants fixated cued-color objects significantly more often than predicted by chance for the first object, no different from chance at the second and third objects, and significantly less often than chance for all remaining objects (up to the eighth object) for both the *4-each* (Figure 5.3C) and *2-each* (Figure 5.3D) arrays. Thus, there were two notable effects that emerged on *cue-avoid* trials: 1) initial capture of attention by cue-matching objects, and 2) subsequent avoidance of cue-matching objects.

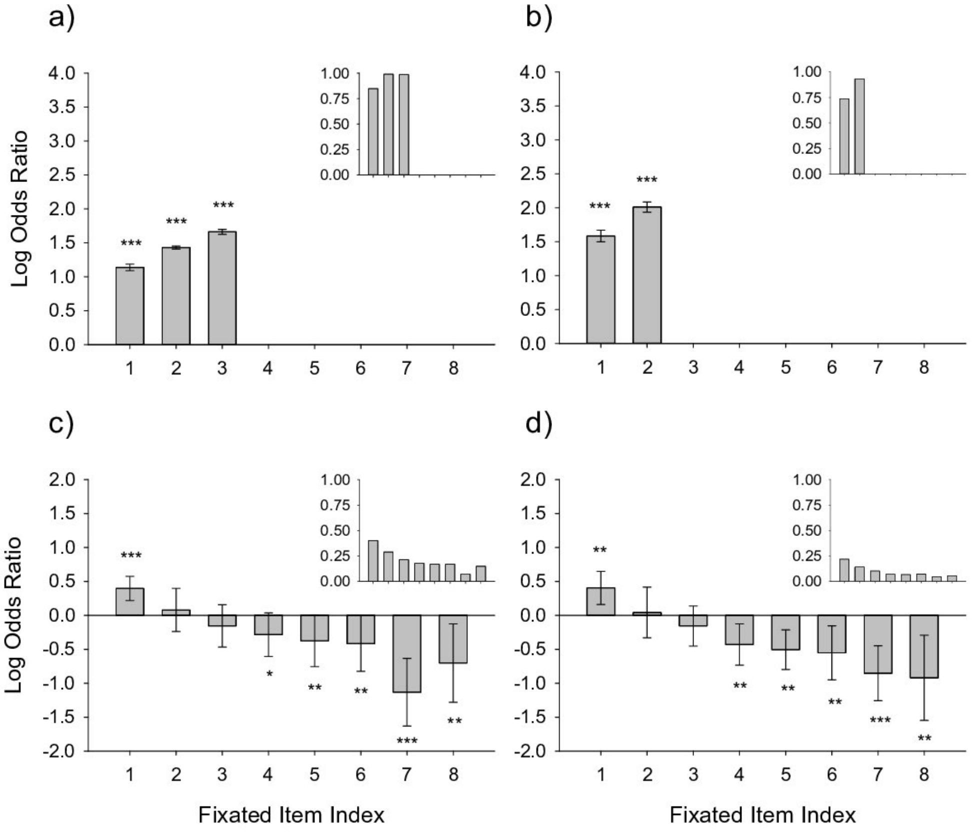

Figure 5.3. Log-transformed odds ratios indicating the probability of fixating a cue-matching object given the types of objects fixated thus far, plotted as a function of ordinal object fixated in a trial. Positive values indicate greater than chance probability whereas negative values indicate less than chance probability. Inset plots show the raw observed probability of fixating a cue-matching object as a function of ordinal object fixated. Data plotted are from the *4-each* (A) and *2-each* (B) arrays for the *cue-target* condition and from the *4-each* (C) and *2-each* (D) arrays for the *cue-avoid* condition in Experiment 1 (color cue stimulus). Error bars indicate standard 95% confidence intervals. Values in each bin were compared against zero with significance levels as follows: * indicates marginal significance ($p < .08$), ** indicates $p \leq .05$, and *** indicates $p \leq .001$.

Was early capture functionally related to later avoidance? In their “search and destroy” characterization of feature-guided avoidance, Moher and Egeth (2012) suggested that initial capture by a known irrelevant feature enables later avoidance of similar items. To test this, we sought to examine whether the reduced probability of fixating a cue-matching object late in a trial was contingent on early capture, dividing the trials by whether capture did or did not occur at the beginning of the trial. Although the ability to conduct this analysis was limited in Experiment 1 by small numbers of trials in each of the cells after division, we discuss the method here and provide preliminary results. More comprehensive tests are reported in Experiments 2 and 3. Early capture trials were defined as trials on which the to-be-avoided avoid color was fixated as either the first or second object. Because this split was determined by events that occurred on the first or second object fixated, this analysis was limited to trials for which three or more objects were fixated (*4-each*: 91% trials retained), and to ensure that there were at least several cue-matching objects left to fixate, the analysis was limited to the *4-each* condition. As illustrated in Figure 5.4, participants demonstrated avoidance of cue-matching objects both on trials for which they showed initial oculomotor capture (Figure 5.4A) and on trials for which they did not show initial oculomotor capture (Figure 5.4B). One-sample *t*-tests revealed reliable avoidance of cue-matching objects by the fifth and subsequent objects on capture trials and reliable avoidance of cue-matching objects by the third and fourth objects fixated on trials without initial capture. These results suggest that fixation of a cue-matching object early in the trial is not necessary to demonstrate avoidance of cue-matching objects later in the trial, although thorough analysis is precluded by the many bins in the “no capture” trials (Figure 5.4B) that could not be analyzed due to limitations in the number of trials available.

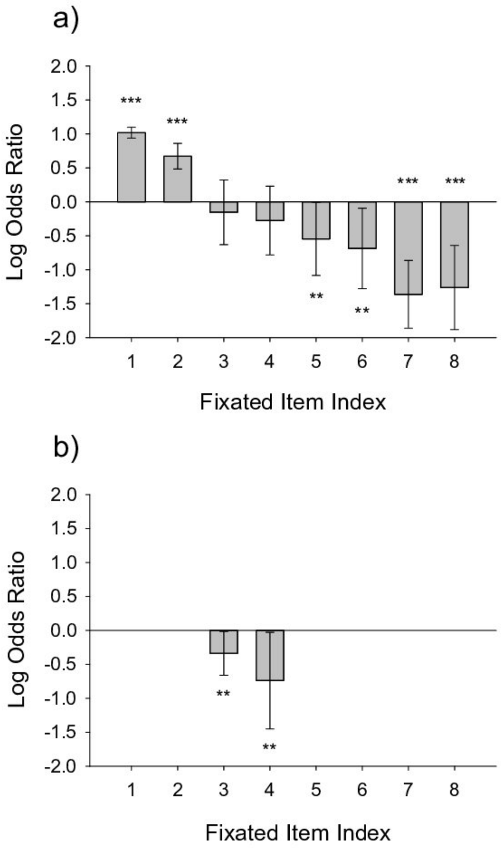

Figure 5.4. Log-transformed odds ratios indicating the probability of fixating a cue-matching object given the types of objects fixated thus far plotted as a function of ordinal object fixated in a trial. Positive values indicate greater than chance probability whereas negative values indicate less than chance probability. Data plotted are from the *4-each* array in the *cue-avoid* condition split into trials with initial capture (A) and without initial capture (B) from Experiment 1 (color cue stimulus). Error bars indicate standard 95% confidence intervals. Values in each bin were compared against zero with significance levels as follows: ** indicates $p \leq .05$, and *** indicates $p \leq .001$.

Summary. When the cue indicated the target color, participants used this information to efficiently restrict search to relevant items. This effect was observed on overall search times and on the probability that each fixated object matched the cued color. When the cue indicated a color to be avoided, measures of overall search time indicated no advantage relative to a neutral cue, suggesting that participants may not have been able to successfully implement a negative template or did not attempt to implement a negative template. However, inspection of the evolution of selection across the trial showed a systematic effect of negative cue use that was obscured in the overall measures of search time: early in the trial, attention was captured by the to-be-avoided color; later in the trial, participants successfully avoided that color. Finally, preliminary evidence suggested that later avoidance was not necessarily contingent on early oculomotor capture.

5.4 Experiment 2: Eliminating Feature Priming

One possible explanation for the early capture effect in the *cue-avoid* condition of Experiment 1 is that it resulted from low-level priming (Maljkovic & Nakayama, 1994) generated by sensory processing of the cue color patch. To test this possibility, we replicated Experiment 1, replacing the colored cue stimulus with the color name printed in dark grey. If the initial capture effect in the *cue-avoid* condition was driven primarily by perceptual priming, it should be eliminated with this modification. If, however, capture was caused by activation of the cued color value as a template in VWM, the capture effect should be preserved, although its magnitude might be reduced (e.g., Soto & Humphreys, 2007).

5.4.1 Method

Participants. Twelve participants (9 female) from the University of Iowa completed the experiment and were compensated for their time. All participants reported normal color vision and normal or corrected-to-normal visual acuity.

Stimuli and Procedure. Stimuli and procedure were the same as for Experiment 1 except that the colored cue square was replaced with the cue color name (“red”, “yellow”, “green”, “blue”, “white”, “black”, “purple”, and “aqua”) printed in dark grey at fixation.

In the *cue-all* condition, the checkerboard cue square was replaced with the word “any” printed in dark grey.

5.4.2 Results and Discussion

As in Experiment 1, manual response accuracy was uniformly high (M = 99%) across all conditions (see Table 5.1 for accuracy by condition and array type) and trials with incorrect responses were excluded from all further analyses. All trials with response times that were less than 150 ms or greater than 10,000 ms were excluded from analysis (8.24% of trials). Furthermore, trials with response times that were greater or less than 2.5 standard deviations from the mean of each condition for each subject were also excluded from all analyses (additional 1.57% of trials).

Global Measure of Target Detection Time. As in Experiment 1, we first examined the elapsed time to target fixation (TTF). To do this, we compared *cue-target* and *cue-avoid* conditions against *cue-all* separately. For the positive template, a condition X array type ANOVA run on mean TTF revealed a main effect of condition [$F(1, 11) = 735.03$, $p < .001$, $\eta_p^2 = .99$], a main effect of array type [$F(1, 11) = 7.15$, $p = .022$, $\eta_p^2 = .39$], and a significant interaction [$F(1, 11) = 6.39$, $p = .028$, $\eta_p^2 = .37$; see Figure 5.5]. Collapsing across array type, we found faster TTF in the *cue-target* condition (M = 612 ms) than in the *cue-all* condition (M = 1996 ms), indicative of attentional guidance by a positive template. Similarly, collapsing across cue condition, we found faster TTF for *2-each* (M = 1241 ms) than *4-each* arrays (M = 1367 ms), primarily driven by the fewer number of relevant items in the *2-each* (2) compared to *4-each* (4) arrays in the *cue-target* condition, which also explains the significant interaction.

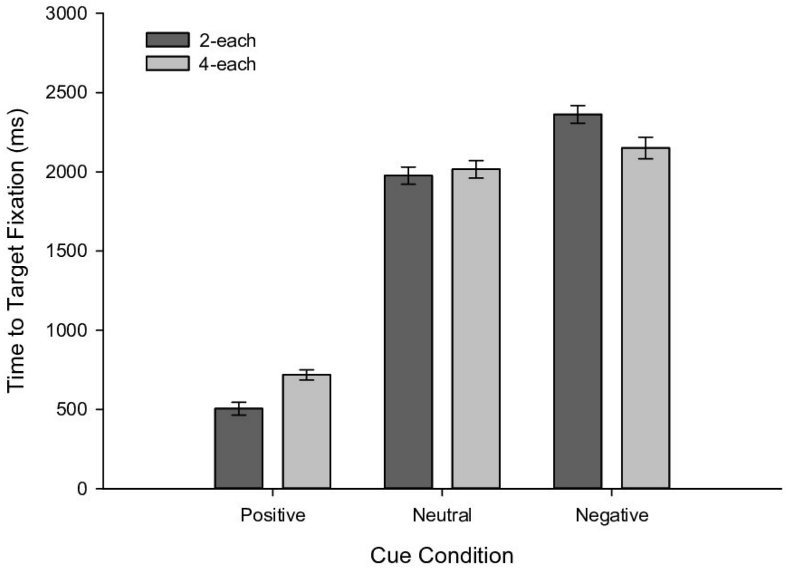

Figure 5.5. Elapsed time to first fixation on the target item plotted as a function of cue condition (*cue-target*: Positive, *cue-all*: Neutral, *cue-avoid*: Negative) and array type (*4-each*, *2-each*) for Experiment 2 (word cue stimulus). Error bars indicate within-subjects 95% confidence intervals (Morey, 2008).

For the negative template, a condition X array type ANOVA run on mean TTF revealed a significant main effect of condition [$F(1, 11) = 19.39$, $p = .001$, $\eta_p^2 = .64$], but no main effect of array type or significant interaction (all *p*s > .1). Collapsing across array type, we found slower TTF in the *cue-avoid* condition ($M = 2257$ ms) than in the *cue-all* condition ($M = 1996$ ms), which is the opposite pattern from what we would expect if participants were able to benefit from the negative cue information. Again, the same analyses were run on manual RTs and produced the same pattern of results.

As in Experiment 1, measures of mean fixation duration and saccade amplitude were consistent with the patterns observed in end-of-trial measures of search efficiency. In the *cue-target* condition, fixation durations were reliably shorter ($M = 136$ ms) and saccades were reliably longer ($M = 4.6$ degrees amplitude) than in the *cue-all* condition ($M = 175$ ms; $M = 3.9$ degrees amplitude) [$t(11) = 14.58$, $p < .001$, $\eta_p^2 = .95$ for fixation duration; $t(11) = 8.14$, $p < .001$, $\eta_p^2 = .86$ for saccade amplitude]. However, in the *cue-avoid* condition, neither fixation duration ($M = 176$ ms) nor saccade amplitude ($M = 3.8$ degrees amplitude) differed significantly from the *cue-all* condition, [$t(11) = 0.65$, $p = .53$ for fixation duration; $t(11) = 0.76$, $p = .46$ for saccade amplitude], consistent with the finding that participants did not use an exclusionary template to make search more efficient.

Object-object Analysis of Selectivity. As in Experiment 1, the eye movement data were binned by ordinal object fixated during search and log-transformed odds ratios were calculated to measure the probability of fixating a cue-matching object for each bin. In the *cue-target* condition, there was a significant main effect of ordinal object fixated for both the *4-each* [$F(2, 22) = 451.61$, $p < .001$, $\eta_p^2 = .98$; Figure 5.6A] and *2-each* [$F(1, 11) = 154.86$, $p < .001$, $\eta_p^2 = .93$; Figure 5.6B] arrays. The small number of objects fixated in a trial (on average the target was the 2.45th object fixated in the *4-each* and the 1.78th object fixated in the *2-each* condition) was caused by the fact that participants limited selection to relevant, cued-color items. Follow-up one-sample *t*-tests revealed that participants fixated cue-matching objects significantly more often than predicted by chance at each of the first three objects in the *4-each* array (Figure 5.6A) and at each of the first two objects in the *2-each* array (Figure 5.6B).

In the *cue-avoid* condition, there was a significant main effect of ordinal object fixated for both *4-each* [$F(4.113, 41.132) = 4.59$, $p = .003$, $\eta_p^2 = .32$; Figure 5.6C] and *2-each* [$F(7, 77) = 6.67$, $p < .001$, $\eta_p^2 = .38$; Figure 5.6D] arrays. These effects were again driven by a decreasing probability of fixating a cue-matching item across the course of a trial. Follow-up one-sample *t*-tests revealed that participants fixated a cue-matching object significantly more often than predicted by chance for the first object, no different from chance at the second object, and significantly less often than chance (except where indicated in Figure 5.6) for all remaining objects (up to the eighth object) for both the *4-each* (Figure 5.6C) and *2-each* (Figure 5.6D) arrays.

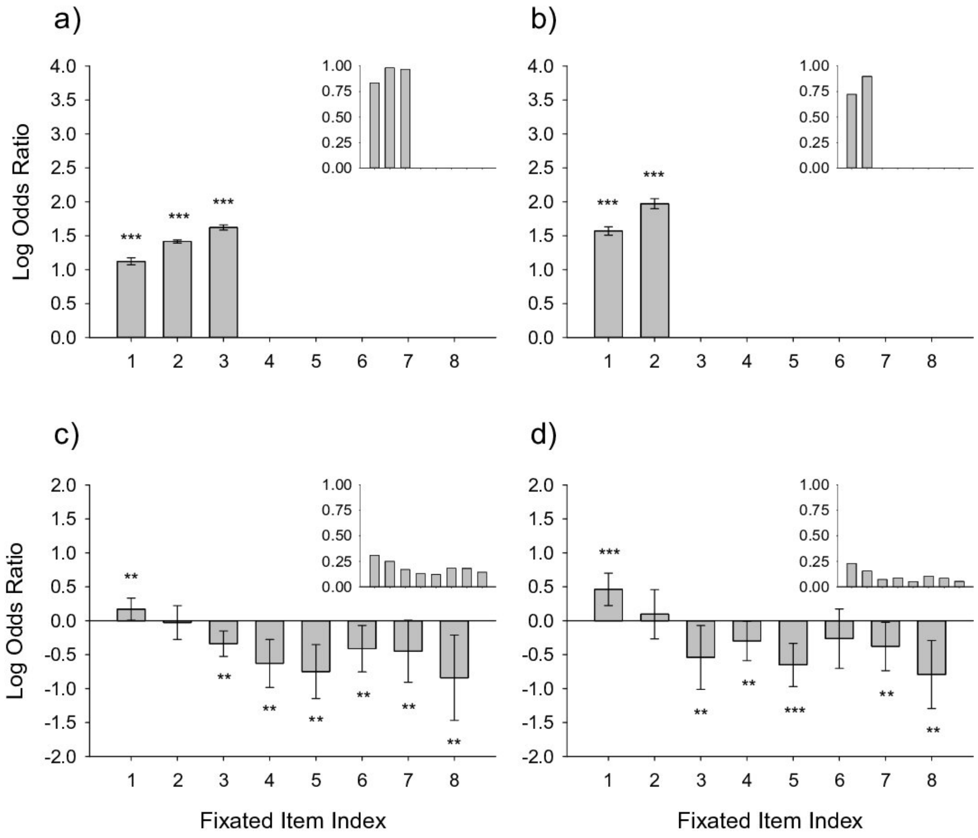

Figure 5.6. Log-transformed odds ratios indicating the probability of fixating a cue-matching object given the types of objects fixated thus far plotted as a function of ordinal object fixated in a trial. Positive values indicate greater than chance probability whereas negative values indicate less than chance probability. Inset plots show the raw observed probability of fixating a cue-matching object as a function of ordinal object fixated. Data plotted are from the *4-each* (A) and *2-each* (B) arrays for the *cue-target* condition and from the *4-each* (C) and *2-each* (D) arrays for the *cue-avoid* condition in Experiment 2 (word cue stimulus). Error bars indicate standard 95% confidence intervals. Values in each bin were compared against zero with significance levels as follows: ** indicates $p \leq .05$, and *** indicates $p \leq .001$.

To probe whether later avoidance was contingent on early capture, we again divided the trials by whether capture did or did not occur at the beginning of the trial and limited the analysis to trials for which three or more objects were fixated (*4-each*: 94% retained), as described in Experiment 1. Participants fixated cue-matching objects significantly less often than predicted by chance both when early capture occurred (Figure 5.7A) and when it did not (Figure 5.7B). One-sample *t*-tests revealed reliable avoidance of cue-matching objects by the fourth and fifth objects on capture trials and by the third and subsequent objects on trials without capture. As in Experiment 1, these results suggest that fixation of a cue-matching object early in the trial is not necessary to produce avoidance of cue-matching objects later in the trial, although the analysis must again be considered preliminary given the small number of observations available.

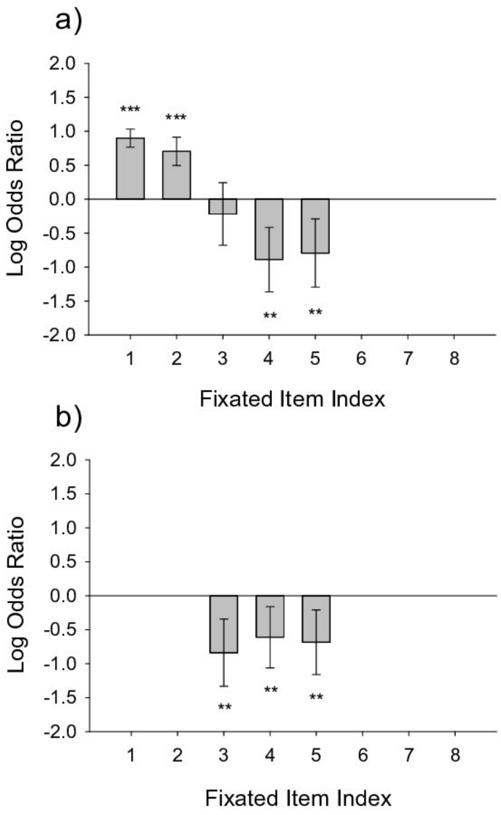

Figure 5.7. Log-transformed odds ratios indicating the probability of fixating a cue-matching object given the types of objects fixated thus far plotted as a function of ordinal object fixated in a trial. Positive values indicate greater than chance probability whereas negative values indicate less than chance probability. Data plotted are from the *4-each* array in the *cue-avoid* condition split into trials with initial capture (A) and without initial capture (B) from Experiment 2 (word cue stimulus). Error bars indicate standard 95% confidence intervals. Values in each bin were compared against zero with significance levels as follows: ** indicates $p \leq .05$, and *** indicates $p \leq .001$.

Summary. Experiment 2 replicated most of the principal results observed in Experiment 1. End-of-trial measures of search efficiency again obscured a more complicated pattern of selection across the trial. Unlike Experiment 1, there was an overall *cost* associated with the negative cue condition relative to the neutral condition. Yet, object-by-object selection indicated the same pattern as in Experiment 1, early capture and later avoidance, highlighting the need to assess selection across the course of the trial. Finally, the early capture effect in the *cue-avoid* condition was observed using a text label rather than a color square, demonstrating that the effect was unlikely to be caused by low-level priming.

5.5 Experiment 3: Allowing More Time to Establish an Exclusionary Template

A possible explanation for the delayed implementation of avoidance in Experiments 1 and 2 is that the delay between the avoid cue and search array was simply too short for participants to configure a functional exclusionary template. Previous work has demonstrated that, after as little as 200 ms, participants are able to efficiently use cue information to guide search toward matching items (Vickery et al., 2005; Wolfe et al., 2004). Perhaps, though, configuring an exclusionary template has a different time course altogether. In Experiments 1 and 2, the cue-stimulus delay was 500 ms, and participants consistently demonstrated avoidance of cue-matching objects by the third (Experiment 2) or fourth (Experiment 1) object fixated. Experiment 3 systematically extended the cue-stimulus delay past the point at which we previously observed avoidance (Experiment 1: 1929 ms; Experiment 2: 1528 ms) in order to test whether avoidance could be observed at the beginning of search given sufficient time to configure an exclusionary template. Specifically, the cue-stimulus delay was increased from the original 500 ms out to a maximum of 2000 ms. Additionally, since participants could have occasionally fixated both of the cued-color items in the *2-each* array and then not have any unvisited cued-color objects left to avoid, we only used arrays that contained four objects each of four different colors (*4-each* arrays). As in Experiments 1 and 2, the four colors present on any given trial were drawn randomly from a larger set of eight different colors: red, yellow, green, blue, white, black, magenta, cyan.

5.5.1 Method

Participants. Twelve new participants (5 female) were recruited from the University of Iowa and were compensated for their time. All participants reported normal color vision and normal or corrected-to-normal visual acuity.

Stimuli and Procedure. Participants in Experiments 1 and 2 demonstrated avoidance of cue-matching items by the third or fourth object fixated in a trial (Exp 1: approximately 1900 ms after cue onset; Exp 2: approximately 1500 ms after cue onset). Therefore, the delay between the cue and the search array was increased to a maximum of 2000 ms to allow for sufficient time to establish an exclusionary search template. The stimulus onset asynchrony (SOA) between the cue stimulus and the search array could be 500 (same SOA used in Experiments 1 and 2), 1000, 1500, or 2000 ms. The SOA interval was randomly intermixed within each cue condition. Lastly, the current task was further restricted to only include the two most relevant cue conditions: *cue-target, cue-avoid*. Again, cue condition was blocked and condition order was counterbalanced across participants. The session began with a 12-trial practice block (6 trials each for *cue-target* and *cue-avoid*). Then there were eight blocks of 24 trials for each of the two cue conditions. The first two trials in each block were considered buffer trials and were excluded from all analyses. This yielded 44 trials per SOA, per condition.

5.5.2 Results and Discussion

Manual response accuracy was uniformly high (*M* = 99% correct) across all conditions (see Table 5.2 for accuracy by condition and SOA) and trials with incorrect responses were excluded from all further analyses. All trials with response times that were less than 150 ms or greater than 10,000 ms were excluded from analysis (8.36% of trials). Furthermore, trials with response times that were greater or less than 2.5 standard deviations from the mean of each condition for each subject were also excluded from all analyses (additional 1.96% of trials).

SOA	Cue Condition	
	Positive	Negative
500	99.6%	98.7%
1000	98.4%	98.7%
1500	99.1%	98.4%
2000	99.0%	98.8%

Table 5.2. Mean manual response accuracy for each condition in Experiment 3.

Global Measure of Target Detection Time. As in Experiments 1 and 2, we first examined the elapsed time to target fixation (TTF). As the shortest SOA (500 ms) is already long enough to achieve maximal benefit from the cue information in the *cue-target* condition, we would not expect to find an effect of SOA when the cue indicated the target color. If, however, a longer SOA allows participants to set up an exclusionary template based on the cued color, TTF should decrease with increasing SOA. A condition (*cue-target*, *cue-avoid*) X SOA (500, 1000, 1500, 2000) ANOVA run on mean TTF revealed a main effect of condition [$F(1, 11) = 153.88$, $p < 0.001$, $\eta_p^2 = .93$], but no main effect of SOA and no significant interaction (all $ps > .30$; see Figure 5.8). Unsurprisingly, participants were able to locate the target item more quickly in the *cue-target* ($M = 777$ ms) than in the *cue-avoid* ($M = 2265$ ms) condition, reflecting attentional guidance by a positive template. However, there was no effect of SOA, even in the *cue-avoid* condition, suggesting participants did not benefit from the additional time to prepare an exclusionary template, at least as reflected in overall search time. The same analyses were run on the manual RTs and produced the same pattern of results.

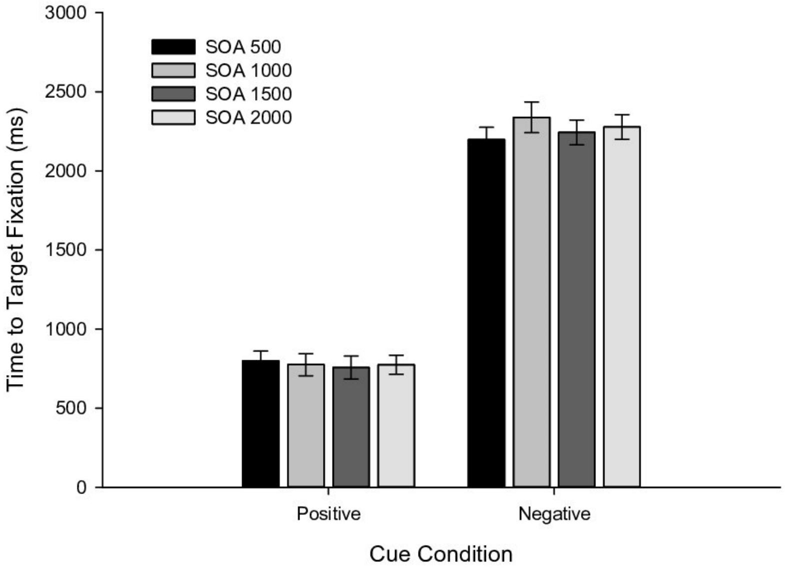

Figure 5.8. Elapsed time to first fixation on the target item plotted as a function of cue condition (*cue-target*: Positive, *cue-avoid*: Negative) and SOA (500, 1000, 1500, 2000) for Experiment 3. Error bars indicate within-subjects 95% confidence intervals (Morey, 2008).

Object-object Analysis of Selectivity. As in Experiments 1 and 2, the eye movement data were binned by ordinal object fixated during search and log-transformed odds ratios were calculated to measure the probability of fixating a cue-matching object for each bin. In the *cue-target* condition, there was a significant main effect of ordinal object fixated for SOA 500 [$F(1.842, 18.418) = 355.00$, $p < .001$, $\eta_p^2 = .97$; Figure 5.9A], SOA 1000 [$F(2, 22) = 161.31$, $p < .001$, $\eta_p^2 = .94$; Figure 5.9B], SOA 1500 [$F(1.662, 18.283) = 197.35$, $p < .001$, $\eta_p^2 = .95$; Figure 5.9C], and SOA 2000 [$F(1.820, 20.015) = 511.366$, $p < .001$, $\eta_p^2 = .98$; Figure 5.9D]. Follow-up one-sample *t*-tests examining whether each bin differed from zero revealed that participants fixated cue-matching objects significantly more often than predicted by chance at each of the first three (SOAs 1000, 1500, and 2000) or four objects (SOA 500) fixated (Figure 5.9A-D). Again, these data indicate participants were able to quickly restrict search to relevant, cued-color items.

In the *cue-avoid* condition, there was a significant main effect of ordinal object fixated for SOA 500 [$F(5.833, 58.330) = 6.152$, $p < .001$, $\eta_p^2 = .38$; Figure 5.10A], SOA 1000 [$F(5.106, 56.168) = 8.48$, $p < .001$, $\eta_p^2 = .44$; Figure 5.10B], SOA 1500 [$F(6.644, 73.085) = 6.58$, $p < .001$, $\eta_p^2 = .37$; Figure 5.10C], and SOA 2000 [$F(5.631, 61.943) = 6.70$, $p < .001$, $\eta_p^2 = .38$; Figure 5.10D]. Follow-up one-sample *t*-tests revealed that participants fixated cue-matching objects more frequently than predicted by chance for the first object (SOA 1000 was borderline, $p = .065$), and reliably less often than chance by the third object for all SOAs (by the second object for SOA 1500; see Figure 5.10A-D). Even at the longer SOAs, at a time point after the cue when participants were able to avoid cue-matching objects in Experiments 1 and 2, we again observed early capture during search. These results suggest that failure to find evidence of avoidance of cue-matching objects early in the trial in Experiments 1 and 2 was not because participants needed more time in between appearance of the cue stimulus and the search array to instantiate an exclusionary template.

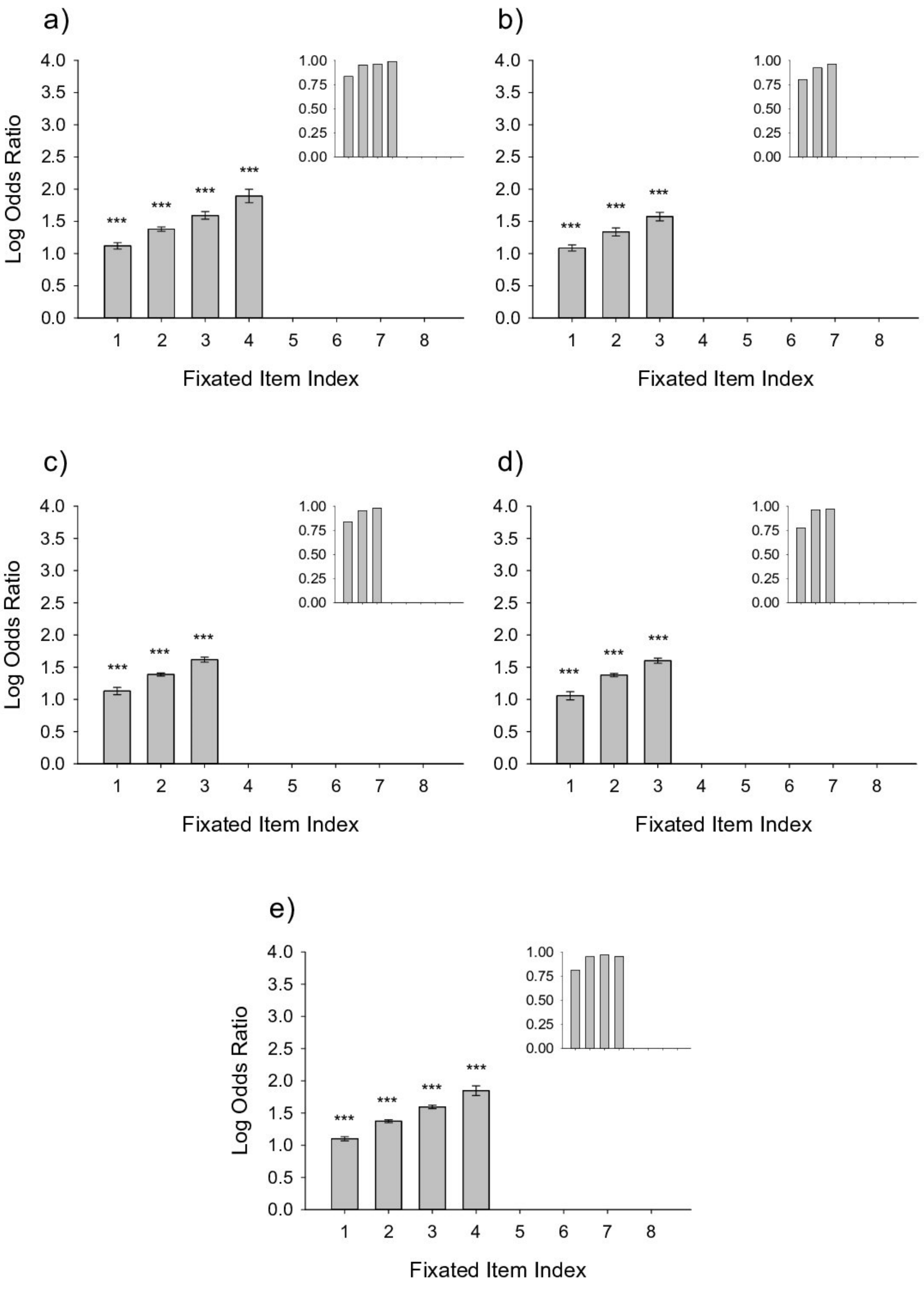

Figure 5.9. Log-transformed odds ratios indicating the probability of fixating a cue-matching object given the types of objects fixated thus far plotted as a function of ordinal object fixated in a trial. Positive values indicate greater than chance probability whereas negative values indicate less than chance probability. Inset plots show the raw observed probability of fixating a cue-matching object as a function of ordinal object fixated. Data plotted are from the SOA 500 (A), SOA 1000 (B), SOA 1500 (C), SOA 2000 (D), and all SOAs (E) for the *cue-target* condition in Experiment 3. Error bars indicate standard 95% confidence intervals. Values in each bin were compared against zero with significance levels as follows: ** indicates $p \leq .05$, and *** indicates $p \leq .001$.

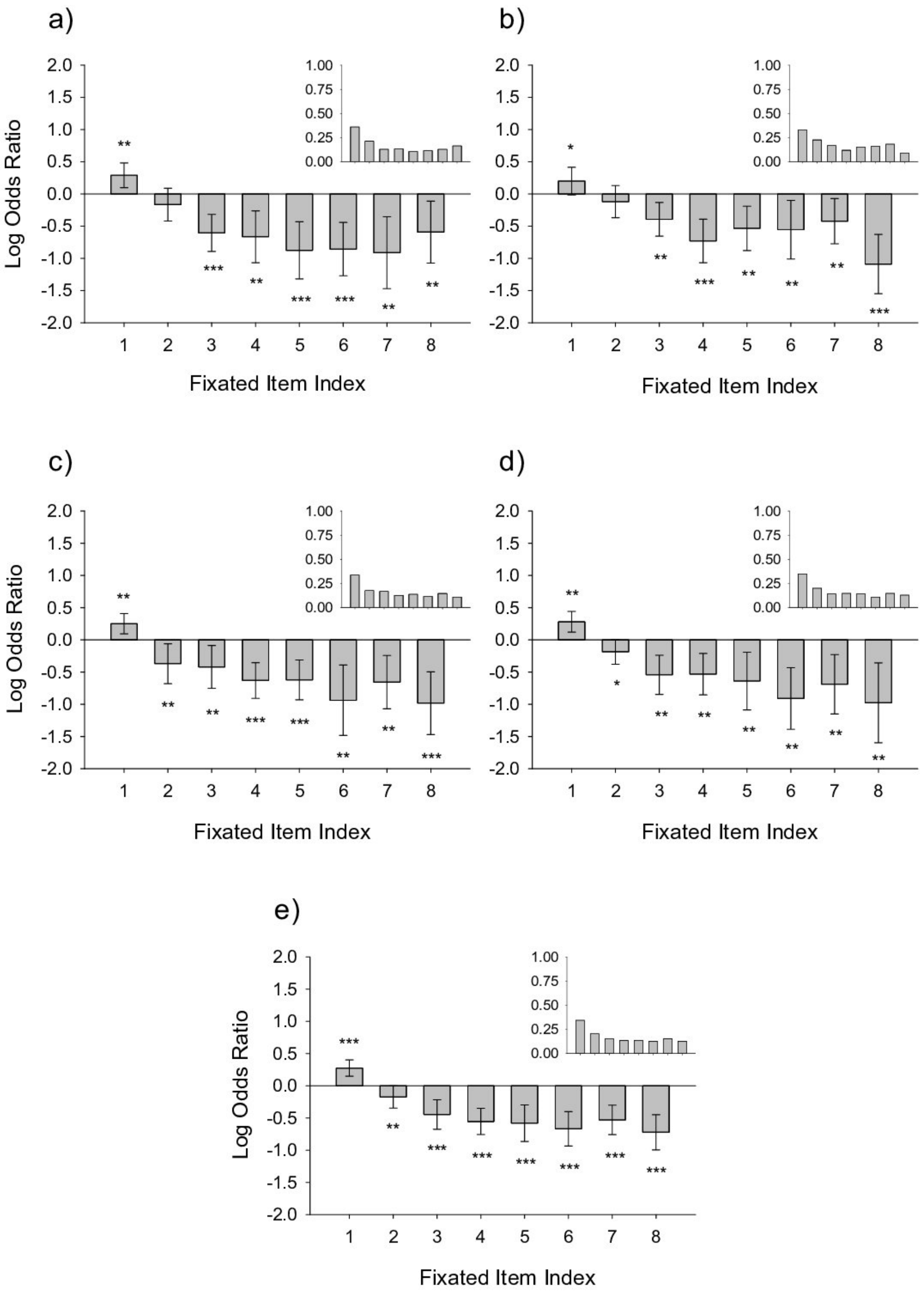

Figure 5.10. Log-transformed odds ratios indicating the probability of fixating a cue-matching object given the types of objects fixated thus far plotted as a function of ordinal object fixated in a trial. Positive values indicate greater than chance probability whereas negative values indicate less than chance probability. Inset plots show the raw observed probability of fixating a cue-matching object as a function of ordinal object fixated. Data plotted are from the SOA 500 (A), SOA 1000 (B), SOA 1500 (C), SOA 2000 (D), and all SOAs (E) for the *cue-avoid* condition in Experiment 3. Error bars indicate standard 95% confidence intervals. Values in each bin were compared against zero with significance levels as follows: * indicates marginal significance ($p \leq .065$, ** indicates $p \leq .05$, and *** indicates $p \leq .001$.

To examine whether later avoidance was contingent on early capture, we split the ordinal object fixated data by the same capture criteria used previously (collapsed across SOA). As in Experiments 1 and 2, this analysis was limited to trials for which three or more objects were fixated (92% retained across all SOAs). Participants fixated cue-matching objects significantly less often than predicted by chance both when early capture occurred (Figure 5.11A) and when it did not (Figure 5.11B). One-sample *t*-tests comparing each bin against zero revealed reliable avoidance of cue-matching objects by the third object fixated for trials with and without capture and this avoidance of cue-matching objects remained reliable through the eighth object fixated. As in Experiments 1 and 2, these results suggest that fixation of a cue-matching object early in the trial is not necessary to produce avoidance of cue-matching objects later in the trial. Furthermore, this avoidance was robust for all objects beyond the third object fixated in a trial.

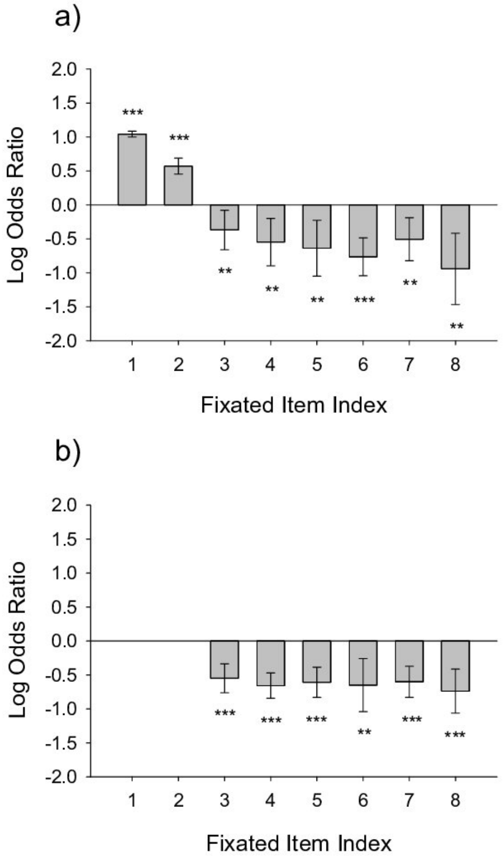

Figure 5.11. Log-transformed odds ratios indicating the probability of fixating a cue-matching object given the types of objects fixated thus far plotted as a function of ordinal object fixated in a trial. Positive values indicate greater than chance probability whereas negative values indicate less than chance probability. Data plotted are collapsed across SOA in the *cue-avoid* condition split into trials with initial capture (A) and without initial capture (B) from Experiment 3. Error bars indicate standard 95% confidence intervals. Values in each bin were compared against zero with significance levels as follows: ** indicates $p \leq .05$, and *** indicates $p \leq .001$.

Summary. If participants simply needed more time between the cue stimulus and the search array to configure an exclusionary template, the initial capture effect observed in Experiments 1 and 2 should have been eliminated or should have diminished as the SOA increased. However, the initial capture effect was observed across SOAs and remained robust at the longest SOAs.

5.6 General Discussion

Woodman and Luck (2007) originally proposed that a VWM representation could be used flexibly either to guide attention toward or away from matching objects. Many studies have demonstrated attentional capture by memory-matching distractors (Folk et al., 1992; Hollingworth & Luck, 2009; Hollingworth et al., 2013; Olivers et al., 2006; Olivers, 2009; Soto et al., 2005, 2008, 2006b; Soto & Humphreys, 2007), but others have suggested this capture can be overridden (Arita et al., 2012; Han & Kim, 2009; Moher & Egeth, 2012; Woodman & Luck, 2007) such that memory-matching distractors can be selectively avoided. These empirical inconsistencies may arise, in part, from the fact that selectivity in search was assessed only by global measures of search time. In the current experiments, we directly examined whether a VWM representation could be used to guide attention away from matching items by recording eye movements while participants performed a search task, allowing us to observe the fine-grained evolution of selection across a trial. The eye movement data revealed both initial capture by and later avoidance of cue-matching items when the cue indicated a distractor feature. Furthermore, initial capture by cue-matching distractors occurred even with a relatively long delay between presentation of the cue and appearance of the search array, suggesting that a negative attentional template could not be prepared prior to the appearance of the search array. These results incorporate and potentially reconcile previously discrepant findings.

To account for this pattern of early capture and later avoidance, Moher and Egeth (2012) proposed a “search and destroy” mechanism as a means of implementing a negative attentional template. “Search and destroy” is an extension of Tsal and

Makovski's (2006) "process all" mechanism that was proposed to account for allocation of attention to any location where an item was expected to appear, regardless of task relevance. Specifically, Moher and Egeth (2012) proposed that attention was initially deployed to a cue-matching distractor, even though it was known to be task irrelevant, in order to facilitate later avoidance of cue-matching items. However, because Moher and Egeth (2012) frequently only had a single cue-matching distractor in the search array and used placeholders that were the same color as the objects to be revealed, it is unclear whether the avoidance they observed at longer SOAs was truly feature-guided avoidance or a result of having already attended all cue-matching items and refocused search on the remaining relevant features or locations. That being said, we did find the same pattern of early capture followed by later avoidance of cue-matching objects. Critically, though, the avoidance we observed later in the trial was not dependent on initial capture. Without evidence to support a functional relationship between the two, early capture by and later avoidance of memory-matching items are likely effects of separate processes that tend to co-occur: rapid memory-based attentional capture, task-dependent attentional control.

Theories of visual attention account for guidance toward particular features by assigning a positive weight to a relevant feature, but do not allow for a feature to be assigned a negative weight (Bundesen, 1990; Wolfe, 1994). Assigning a negative weight to a known irrelevant feature would be the most direct way to implement a negative template, but is not supported by the data. If participants were able to assign a negative weight to a feature, they should have been able to do this prior to the appearance of the search array and prevented attentional capture by cue-matching objects. Nonetheless, we repeatedly observed initial capture by cue-matching items in the *cue-avoid* condition, even at the longest SOA. Thus, it is unlikely that participants were able to implement direct, feature-guided avoidance. On the other hand, participants were able to successfully avoid early capture by cue-matching objects on a subset of trials. Although we cannot rule out that they attended a cue-matching item covertly, shifting attention without also making an eye movement is effortful and, since fixating a cue-matching distractor was not penalized, it is unlikely that participants adopted this strategy.

In addition to early capture, we also consistently observed later avoidance of cue-matching distractors, suggesting that participants were able to implement some kind of exclusionary template perhaps by converting the cued distractor information into some kind of relevant information that attention could be biased toward. We previously demonstrated that the results from at least one study interpreted as supporting a “template for rejection” (Arita et al., 2012) can be explained by spatially recoding the negative cue information (Beck & Hollingworth, 2015). When the different colored items were segregated by hemifield, the hemifield containing cue-matching items could quickly be identified and attention shifted to the opposing hemifield. This type of translation would not yield search as efficient as when the target feature was cued, but it would be more efficient than searching randomly and is consistent with previous work demonstrating a benefit from directly cuing a distractor location (Munneke et al., 2008). When the different colored items were intermixed, however, this translation into a simple spatial template was not possible and a negative cue benefit was no longer observed (Beck & Hollingworth, 2015). Because the search arrays in the current study were always intermixed, it seems unlikely that the observed avoidance of cue-matching items could be due to a similar spatial recoding strategy. However, further work will need to be done in order to rule this out entirely.

Another possible mechanism for implementing a negative template would be to transform the “avoid” feature into potential “attend” features. One way to implement this that is largely consistent with current theories of attention would be to set the attentional weight for the “avoid” feature to zero and all other feature weights above zero. However, it is unclear whether it is possible to assign attentional weights to unknown features. It may be necessary to determine which features are present in the search array before increasing the attentional weights for all potentially relevant features (all colors present except the cued color). This delayed conversion of a known irrelevant feature to potentially relevant features may allow for rapid attentional capture by a cue-matching item before the other features present can be identified and prioritized.

Thus, implementing an exclusionary template indirectly by transforming the negative cue information into relevant locations or features could account for the discrepant findings of both memory-driven attentional capture and later avoidance memory-matching items. Transforming a known irrelevant feature into a spatial template for relevant locations or positively weighted templates for potentially relevant features takes time and likely cannot occur until the search array has appeared. On trials when this transformation has been completed quickly, attentional capture may be precluded. On other trials, however, attentional capture may occur before the transformation has been completed. Although proposing that early capture by and later avoidance of memory-matching items are the effects of two separate processes is less parsimonious than a single “search and destroy” mechanism, it preserves the facilitatory nature of the relationship between VWM and attentional guidance. In this manner, a VWM representation can facilitate guidance of attention toward matching objects, but when it indicates an irrelevant feature, matching objects can be excluded by transforming the irrelevant feature into relevant locations or features.

CHAPTER 6: GENERAL DISCUSSION

6.1 Multiple Templates

The *single-item template* (SIT) hypothesis proposes that only a single visual working memory (VWM) representation can influence attentional guidance at any particular time (Olivers et al., 2011). However, evidence in support of the SIT hypothesis comes primarily from attentional capture studies that are a better test of whether VWM representations automatically influence attentional guidance than whether it is possible for multiple VWM representations to guide attention simultaneously. When only a single item is held in VWM and the search target remains the same throughout the experimental session (and is likely no longer in VWM), attention is directed to memory-matching items (Olivers et al., 2006; Soto et al., 2008). However, when the search target varies from trial to trial (and thus is stored in VWM), attention is no longer directed to memory-matching items (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, 2009), suggesting that the search target can be prioritized over the memory item that is irrelevant for the search task. Thus, maintenance of an item in VWM is not necessarily sufficient for it to act as a template. In a converging approach, distractors matching an item that was encoded into memory but subsequently deprioritized for the later memory test did not result in interference during search (Hollingworth & Hwang, 2013; Experiment 6 in Olivers et al., 2006; van Moorselaar et al., 2014). These data are consistent with multiple states within VWM, such that an "active" representation can influence attentional guidance, whereas an "accessory" representation cannot (Olivers et al., 2011), but they do not conclusively demonstrate that attentional guidance by VWM is limited to a single "active" representation.

The most recent evidence supporting the SIT hypothesis comes from a study that again relied on measuring interference from memory-matching distractors during a shape-defined search task (van Moorselaar et al., 2014). In this study, the memory load varied from one to four items. Guidance of attention to a memory-matching distractor was found when the memory load was a single item, but not when the memory array contained two, three, or four items. The authors concluded that, when VWM contained more than one item, all items in VWM remained in an "accessory" state and were unable to influence attentional guidance. As mentioned above, though, this is a stronger test of whether multiple VWM representations automatically guide attention than whether such guidance is possible. Furthermore, a more recent study has demonstrated that this type of paradigm – a singleton-shape search task with a single memory-matching distractor – may not be sensitive enough to detect guidance of attention by multiple VWM representations.

Hollingworth and Beck (2016) found evidence of attentional capture when multiple items were held in VWM using a modified version of the van Moorselaar et al. (2014) paradigm. Participants viewed one (mem-1) or two (mem-2) colors to hold in memory, searched for a target item, and completed a memory test for one of the colors held in VWM. Two key modifications of the paradigm used by van Moorselaar et al. (2014) were implemented. First, one group (Experiment 1) performed a gap-location search task and were instructed to search for the Landolt-square that had a left or right gap (and report the gap orientation) among Landolt-squares with a top or bottom gap. This type of search task results in inefficient search and may be more sensitive to capture by memory-matching distractors. The other group (Experiment 2) performed a singleton-shape search task and were instructed to search for the diamond among circles and report the orientation of the line inside the shape, as in van Moorselaar et al. (2014). Critically, rather than including only a single memory-matching distractor in the search arrays, both search tasks included two memory-matching distractors and zero (match-0), one (match-1), or both (match-2) of the colored distractors could match the colors held in VWM.

Including multiple memory-matching distractors in the search array maximized the potential overlap with the content of VWM and set up competing predictions from the SIT and *multiple-item template* (MIT) hypotheses. Because the SIT hypothesis proposes that only a single VWM representation can influence attentional guidance, the attentional capture effect when two colors are held in memory (mem-2) and both colored distractors match (match-2) should be no greater than when a single color is held in memory (mem-1) and only one of the colored distractors match (match-1). On the other hand, the MIT hypothesis predicts that attentional capture will be greater on mem-2/match-2 trials than mem-1/match-1 trials because both of the colors held in VWM will be able to influence attentional guidance. With the gap-location task, the capture effect was greater on mem-2/match-2 trials than mem-1/match-1 trials, consistent with the MIT hypothesis. With the singleton-shape search task, though, the capture effect was not significantly greater on mem-2/match-2 trials than mem-1/match-1 trials. When one of the colored distractors matched (match-1), there was a significant capture effect in the mem-1 condition, but not the mem-2 condition, replicating the absence of a capture effect at higher memory loads in van Moorselaar et al. (2014). However, when both the colored distractors matched (match-2) and multiple colors were held in VWM (mem-2), a significant capture effect reappeared, similar to the gap-location task. Although this is still an indirect way to examine attentional guidance by multiple VWM representations, the results provide support for the MIT hypothesis and suggest that paradigms using only a single memory-matching distractor in the search array and a singleton-shape search task may not be sensitive enough to detect guidance by multiple VWM representations.

To directly measure attentional guidance by multiple VWM representations, I recorded eye movements as participants searched for two colors simultaneously (Chapters 2 and 3). After oculomotor markers of template switching (switch cost, run length) were identified (Experiment 1 in Chapter 2), attentional guidance by multiple VWM representations was tested by asking participants to search for a target item that could be either of two colors (Experiment 2 in Chapter 2). When they were instructed to search the two colors sequentially, participants again exhibited a switch cost and longer run length prior to searching the second color. When participants were instructed to search the two colors simultaneously, however, they demonstrated a shorter run length (indicative of more frequent switching between colors) and no switch cost. Furthermore, data from a gaze-contingent search task indicated that two differently-colored cue-matching objects actively competed for selection as the saccade target (Chapter 3). Even though participants had just selected a first-cued-color object in the first pair, ensuring that the first-cued-color would be in an “active” state, selecting a first-cued-color object again in the second pair was less efficient when it was presented with a second-cued-color object than when it was presented with a distractor object. These data suggest both cued colors remained active during the trial and, when differently-colored cue-matching objects appeared together, they actively competed for selection. When either cue-matching object appeared with a distractor, however, selection of the cue-matching object was quite efficient. In sum, with paradigms that incentivize using multiple VWM representations to guide attention, and with a more direct measure of how attention is deployed, clear evidence was obtained indicating attentional guidance by multiple features.

Similar evidence supporting attentional guidance by multiple features within a dimension has emerged from paradigms using target features that remain the same throughout the experiment and likely depend on LTM rather than VWM (Carlisle et al., 2011). In a modified version of the paradigm from Folk et al. (1992), Irons et al. (2011) found attentional capture by multiple task relevant feature cues, but no capture to an irrelevant feature cue, suggesting that the two relevant features were able to influence attentional guidance but the irrelevant feature was not. When participants were presented with two pairs of objects – one on the vertical meridian and one on the horizontal meridian – Grubert and Eimer (2015) demonstrated that there was a minimal delay to deploy attention to a new cue-matching item compared to the second presentation of an initial cue-matching item. In other words, shifting attention from a red item to a blue item is almost as fast as shifting attention from one red item to another red item when both red and blue are cued as task relevant. Critically, this effect persisted when the cued colors varied from trial to trial (Grubert, Carlisle, & Eimer, 2015), similar to results demonstrating capture by multiple cued colors in an RSVP-style task (Roper & Vecera, 2012). These results demonstrate converging evidence in support of the MIT hypothesis.

However, several other studies have suggested that, although attentional guidance by multiple VWM representations may be possible, it is less efficient than guidance by a single item in VWM (Barrett & Zobay, 2014; Menneer et al., 2007; Stroud, Menneer, Cave, & Donnelly, 2011). Menneer et al. (2007) found that it took participants longer to search for either of two different colors than the sum of search for each color individually, suggesting that searching for multiple colors simultaneously is superadditive. Furthermore, Stroud et al. (2011) found that search efficiency decreased as the difference between the two cued colors increased. However, Barrett and Zobay (2014) found that, although there was a cost (increased response times and decreased accuracy) associated with searching for multiple features simultaneously, the observed data were better fit by a “noisy” two-template model than a one-template model. Attentional guidance by multiple VWM representations may be less efficient than guidance by a single template, as these studies suggest, but this does not necessarily mean that guidance by multiple features is not possible. VWM is a capacity-limited system (Luck, 2008), and executing an eye movement further taxes this system (Tas, Luck, & Hollingworth, 2016). Thus, holding multiple features in VWM while also executing eye movements to matching objects may consume most, if not all, VWM resources and impact the efficiency with which search can be conducted.

In sum, results from the current work (Chapters 2 and 3) and several other studies provide converging support for the idea that attentional guidance by content in VWM is not limited to a single item. Consistent with the MIT hypothesis, multiple VWM representations can influence attentional guidance simultaneously.

6.2 Negative Template

The proposal that a VWM representation can be used to bias attention away from matching items (“template for rejection”) lies in direct conflict with the widespread evidence that attention is automatically biased toward memory-matching items, even when they are known to be task irrelevant (Folk et al., 1992; Hollingworth & Luck, 2009; Hollingworth et al., 2013; Olivers et al., 2006; Olivers, 2009; Soto et al., 2005, 2006b). However, several studies have claimed that attentional capture by memory-matching objects can be overridden (Han & Kim, 2009; Moher & Egeth, 2012) or even prevented (Arita et al., 2012; Woodman & Luck, 2007). Furthermore, Moher and Egeth (2012) have proposed a "search and destroy" mechanism such that early capture by a memory-matching item facilitates later avoidance of similar, irrelevant items. Given the mixed results thus far, it is unclear whether a negative template can be established such that attention is guided away from memory-matching distractors.

At least one study with results that support use of a negative template can be explained by recoding the feature cue information into a simple spatial template. Arita et al. (2012) found a reliable response time benefit from a negative feature cue compared to a neutral cue suggesting participants were able to selectively avoid cue-matching objects. However, the search arrays used in their task always segregated the different colored items by hemifield (see Figure 4.1), making it easy to identify which hemifield contained cue-matching objects once the search array appeared so that attention could be shifted to the opposing hemifield. When the different colored items were spatially intermixed, as in Chapter 4 (see Figure 4.5), converting the feature cue information into a simple spatial template was no longer possible and the response time benefit disappeared. These results suggest that a negative attentional template cannot be implemented directly, but the feature cue information can be transformed into a spatial template indicating either which hemifield to avoid or, equivalently, which hemifield to attend, consistent with evidence that participants can benefit from a cued distractor location (Munneke et al., 2008).

Other studies, though, used search arrays that could not be easily spatially recoded and found both initial capture by and later avoidance of a memory-matching distractor when they cued a distractor color and there was a single matching item in the search array (Han & Kim, 2009; Moher & Egeth, 2012). Moher and Egeth (2012) proposed a "search and destroy" mechanism to account for the observed pattern of initial capture and later avoidance. The "search and destroy" characterization suggests that later avoidance is dependent on early capture – a memory-matching distractor is deliberately attended soon after the search array appears in order to facilitate later avoidance. However, because the search arrays only contained a single memory-matching distractor (one experiment increased this to three matching items), it is unclear how the avoidance Moher and Egeth (2012) observed differs from inhibition of return to a previously attended item (Posner, Rafal, Choate, & Vaughan, 2007) or memory of which items have already been searched (Peterson et al., 2007). The "search and destroy" characterization may, in fact, describe two separate processes: 1) rapid attentional capture by a memory-matching item, 2) indirect avoidance of memory-matching items via transforming the cued distractor feature into either relevant spatial locations or features. End-of-trial measures such as accuracy and manual response time may be obscuring the time course of these two processes and whether later avoidance is dependent on initial capture by memory-matching distractors.

To examine feature-guided avoidance directly, participants were presented with a distractor color and instructed to perform a search task while eye movements were recorded (Chapter 5). Similar to Moher and Egeth (2012), the eye movement data revealed evidence of both initial attentional capture by and later avoidance of memory-matching items. Furthermore, initial capture by a memory-matching distractor persisted even when the delay between appearance of the cue and the search array was increased to 2000 ms, a post-cue delay at which avoidance had previously been observed, suggesting that establishing a negative template did not simply require a greater amount of time. Although initial capture by a cue-matching distractor was robust, it did not occur on every trial, and avoidance of cue-matching items later in a trial was not dependent on attentional capture by a cue-matching item early in a trial. Thus, the current results do not support a functional relationship between early capture and later avoidance. The more parsimonious account is that rapid memory-driven attentional capture occurs as participants are independently implementing a slower change in attentional control settings so as to deprioritize cue-matching items.

Consistent with previous work (Chapter 4), the results from Chapter 5 suggest that a negative template cannot be implemented directly, but must be implemented indirectly by transforming the cued distractor information into either relevant spatial locations or relevant features to attend. Because the search arrays used in Chapter 5 were intermixed (similar to Experiment 2 in Chapter 4), it seems unlikely that participants transformed the feature cue into a spatial template, but further work will need to be done in order to rule out this possibility. However, like spatial recoding, transforming the negative feature cue into potentially relevant features could not occur until the search array appeared as the relevant features could not be predicted based on the cued distractor feature. Holding the negative cue in VWM but not being able to complete this transformation into relevant features until the search array was visible may have left open a window during which participants were vulnerable to rapid attentional capture by a memory-matching distractor. This is consistent with previous work demonstrating that memory-based attentional capture occurs automatically (Olivers et al., 2006; Soto et al., 2005), unless another feature can be prioritized over the item held in memory that is not relevant for search (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, 2009). Thus, the effects of early capture and later avoidance characterized by “search and destroy” (Moher & Egeth, 2012) may not be functionally related, but could be two separate processes that frequently overlap in time. In this manner, early capture could occur prior to but is not necessary for transforming the negative cue into location or feature information that can be used to direct attention toward relevant items.

In sum, results from the current work (Chapters 4 and 5) offer a reinterpretation of previous studies and suggest that feature-guided avoidance cannot be implemented directly. Instead, successfully avoiding cue-matching distractors may require converting the cued distractor feature into either relevant locations or features toward which attention can be directed, suggesting a fundamentally facilitatory relationship between VWM and attentional guidance.

6.3 Implications for Theories of Visual Attention

Visual search tasks have been used extensively to inform on how visual attention is deployed both in highly constrained search arrays and in real-world scenes. Here I will focus on two prominent theories of visual attention that explicitly account for search behavior and make predictions regarding guidance of attention in the context of typical laboratory visual search tasks. Specifically, I will discuss how the Guided Search Model (Wolfe, Cave, & Franzel, 1989) and the Theory of Visual Attention (Bundesen, 1990) may or may not accommodate guidance by multiple VWM representations (multiple templates) and feature-guided avoidance (negative template).

Guided Search Model. The Guided Search Model (GSM) proposes that feature information from objects in the search array can be detected in parallel via categorical “channels” for each stimulus dimension (color, orientation, etc.) and assembled into “feature maps” (Wolfe, 1994). The task-relevant feature maps can be selected and combined to generate a global priority map. Attention is deployed or guided to locations within the priority map beginning with the greatest peak of activation and proceeding to the next in descending order of activation. The GSM can account for a wide range of visual search behaviors such as efficient or “pop-out” search versus inefficient or “serial” search, search asymmetries (search for a tilted line among vertical lines is more efficient than search for a vertical line among tilted lines), and conjunction search (search for a black, vertical target among black, horizontal and red, vertical objects). The question here is whether the GSM, in its current instantiation, can accurately simulate guidance by multiple templates or a negative template.

On the face of it, it seems that the GSM could accommodate attentional guidance by multiple VWM representations. However, the GSM stipulates that, for each feature map, only a single broadly tuned channel (e.g., “red” for color) can be included in the global priority map (Wolfe, 1994, 2007). This limitation precludes guidance based on “red” and “green” simultaneously and would predict that participants would search red items first, then green, or vice versa. Given the mounting evidence in support of attentional guidance by multiple features (Chapters 2 & 3; Barrett & Zobay, 2014; Grubert & Eimer, 2015, 2016; Irons et al., 2011; Roper & Vecera, 2012), the GSM may need to be modified to account for this behavior. One possible modification would be to allow multiple channels from a given feature map to feed into the global priority map. However, because the feature channels defined in the GSM are broadly tuned and categorical in nature, it is unclear whether simply increasing the number of channels allowed will completely account for the observed search patterns. On the other hand, perhaps the use of categorical channels can account for the discrepancy in the literature between studies that find efficient guidance based on multiple features and typically use categorical stimuli (Chapters 2 & 3; Barrett & Zobay, 2014; Grubert & Eimer, 2015, 2016; Irons et al., 2011; Roper & Vecera, 2012), and studies that find inefficient guidance based on multiple features but typically used stimuli with more continuous variation (Menneer et al., 2007; Stroud, Menneer, Cave, Donnelly, & Rayner, 2011; Stroud, Menneer, Cave, & Donnelly, 2011). In sum, the current version of the GSM cannot account for attentional guidance by multiple features within the same dimension; further work is needed to determine how the GSM will need to be modified to accommodate visual search based on multiple templates.

In terms of feature-guided avoidance, the GSM does not explicitly address how known irrelevant features might influence attentional guidance. It does stipulate that the weight assigned to a particular feature can be set to zero if that feature is uninformative in terms of discriminating target and distractor items (Wolfe, 1994, 2007). It is unclear how weights for other features would be set when the possible target features are unknown and only a distractor feature is known. Even though the weight for a distractor feature could be set to zero, the observed data suggest that this might not occur prior to the appearance of the search array. In Chapter 5, we repeatedly found evidence of attentional capture to a cue-matching object early in the trial. If the weight for the cued feature could have been set to zero in between presentation of the cue and the appearance of the search array, we should not have observed attentional capture early in the trial. The observed data do suggest, however, that attentional weights can be quickly adjusted to prioritize other potentially relevant features over the known irrelevant feature, as participants were able to avoid cue-matching objects later in the trial. This online configuration would not be initiated until the search array appeared and all uncued features could be detected and assigned non-zero weights. In this manner, the GSM could potentially account for the pattern of initial capture by and later avoidance of cue-matching objects when a distractor feature is cued. As this type of search situation occurs very rarely, if at all, in real world visual search scenarios, it is unclear whether the ability of the GSM to account for the observed data will be rigorously examined.

Theory of Visual Attention. The Theory of Visual Attention (TVA; Bundesen, Vangkilde, & Petersen, 2014; Bundesen, 1990) is based largely on the principle of biased competition (Desimone & Duncan, 1995) but extended such that competition among candidate objects is biased by attentional weights and pertinence values that are set according to task demands. Each visual category (i.e., feature) is assigned a pertinence value – a nonnegative value that reflects the importance of that particular feature for the current task. Attentional weights are calculated for each item in the array and are a product of pertinence values and strength of category membership. For example, if a high pertinence value is assigned to red and there is a red item and a pink item in an array, the pertinence value for each item will be equivalent, but the red item will end up with a greater attentional weight because it is a better example of the "red" category. According to TVA, the first stage of processing involves calculating an attentional weight for each item present in a search array. In the next stage, there is competition for encoding into VWM, such that objects with greater attentional weights are likely to be selected or encoded sooner. In this way, TVA can also account for a wide range of visual search behaviors. The key question here is whether TVA can accommodate attentional guidance by multiple templates or by a negative template.

As it stands, TVA could accommodate attentional guidance by multiple VWM representations by assigning equal pertinence values to both “red” and “green”, which would result in red and green items competing for selection simultaneously (Bundesen et al., 2014; Bundesen, 1990). Currently, there does not appear to be a limit on the number of features that can be assigned non-zero pertinence values; in fact, in the first wave of processing TVA computes attentional weights for each element present in the array, suggesting that each feature present has an associated pertinence value. Given that, when the target feature varies from trial to trial, the target template specifying the target feature is thought to depend on a VWM representation (Carlisle et al., 2011; Gunseli et al., 2014; Woodman & Arita, 2011), this implies that the number of features that could guide attention simultaneously would be limited to the number of features that can be held in VWM concurrently, typically 3-4 (Luck, 2008). In the current version of TVA, there is no clear mechanism for imposing this limit. Any limitation due to the capacity of VWM is currently implemented during the second stage of processing when objects compete for selection as long as at least part of VWM is unoccupied. It could be that a VWM capacity-limited bottleneck at the selection stage is sufficient to account for search patterns that result from guidance by multiple relevant features. It seems likely that TVA could accommodate guidance by multiple templates, but further work will need to be done in order to determine whether any constraints need to be imposed on the number of features that can be assigned equivalent pertinence values.

Less directly, TVA could also potentially account for feature-guided avoidance by assigning a pertinence value of zero to the cued irrelevant feature and assigning pertinence values greater than zero to all other features present in the search array (Bundesen et al., 2014; Bundesen, 1990). However, as in GSM, this may overestimate actual ability to deprioritize certain feature values prior to the appearance of the search array. If it was possible to set “red” to zero and all other colors above zero immediately after the cue information was presented, we would have expected to see immediate avoidance of red items once the search array appeared. According to TVA, pertinence values can be assigned prior to appearance of the search array so that relevant features can be prioritized, but attentional weights are not computed until the first wave of processing that occurs after the search array has appeared. It could be that holding the negative feature cue in memory assigns a nonzero pertinence value to that feature at least until the first wave of processing is complete and the cued feature pertinence value can be adjusted down while the uncued, potentially relevant features can be detected and their associated pertinence values adjusted up accordingly. Although it is possible that TVA could implement guidance based on a negative template, the observed data (Chapters 4 and 5) suggest there are constraints on how this process should be accommodated by TVA.

6.4 Possible Neural Mechanisms

As yet, the neural mechanisms of memory-guided visual search are not fully characterized. Items maintained in VWM can be reliably decoded from primary visual cortex for a single (Harrison & Tong, 2009; Serences et al., 2009) and multiple (Emrich et al., 2013) representations. These patterns of activation could interact with incoming sensory processing of the search array to bias attention toward matching items. If multiple representations can remain active simultaneously, it is unclear why the resulting attentional bias should be limited to a single representation. On the other hand, the SIT hypothesis has proposed that prefrontal structures may impose a gating mechanism that controls which VWM representations interact with perceptual selection and could limit this guidance to a single “active” representation, relegating all other representations in VWM to an “accessory” state that cannot influence selection (Olivers et al., 2011).

Patients with frontal lobe damage demonstrated greater interference from a memory-matching distractor when performing a visual search task, suggesting that frontal lobe structures might be involved in discriminating between task relevant and irrelevant information (Soto, Humphreys, & Heinke, 2006a), or determining which VWM representations are assigned to an “active” or “accessory” state. Similar to previous studies, patients (and matched controls) were presented with a colored outlined shape to hold in memory, then instructed to search for a shape that contained a tilted line among other shapes that contained vertical lines. Patients made slower responses when the memory-matching distractor contained a vertical line (invalid condition) than when it was not present in the array (neutral condition). However, on a third of the trials, when the memory-matching item appeared in the search array, it had a tilted line and was the target item (valid condition), so there could have been some benefit from attending to a memory-matching item in the search array. Or, at the very least, there was little incentive to avoid attending to memory-matching items in the search array. Thus, patients may have preferred to maximize the potential benefit on valid trials rather than minimize the potential cost on invalid trials.

When an fMRI version of the same task was run with healthy young participants, the resulting patterns of brain activity suggested that some regions (including both frontal and occipital structures) responded to the presence of a memory-matching item during search, regardless of whether it was task relevant (valid vs. invalid; Soto, Humphreys, & Rotshtein, 2007). These results suggest that these structures could potentially be responsible for attentional capture by memory-matching items. When the memory load was varied between one and three items, they found functional connectivity between frontal and occipital regions in the low load, but not in the high load condition, consistent with the response time measures showing interference under low load, but not under high load (Soto et al., 2012). These results were interpreted as supporting the SIT hypothesis that only a single VWM representation could be in an "active" state and influence attentional guidance. However, as mentioned previously, examining interference from items in memory during a search task is a better test of automaticity than ability. When a single item is held in VWM, it may automatically influence attentional guidance, but when multiple items are held in VWM, they may not automatically influence attentional guidance. To better understand the neural mechanisms of the relationship between VWM and attentional guidance, this functional connectivity between frontal and occipital regions will need to be reevaluated using a task that successfully motivates the use of multiple VWM representations to guide attention.

On the other hand, this work demonstrating attention capture by memory-matching items regardless of task relevance (Soto et al., 2012, 2007) might help to explain the pattern of initial capture and later avoidance observed in the studies presented in Chapter 5. When the cue indicated a distractor feature in the upcoming search array, participants presumably held this feature cue in VWM, since they could not predict what the relevant features would be until the search array appeared. Holding this single item in VWM may automatically bias attention toward matching objects until that bias signal can be overridden by loading other features into VWM once the search array appears. To better understand how implementing a negative template results in initial capture but also later avoidance, this coupling between frontal and occipital regions will need to be evaluated under conditions that motivate participants to avoid memory-matching items completely.

Although the contents of VWM may be maintained in sensory cortex (Emrich et al., 2013; Harrison & Tong, 2009; Serences et al., 2009), the biasing signal that determines which VWM representations are elevated to an “active” state and which remain in an “accessory” state may arise from frontal regions (Soto et al., 2012, 2006a, 2007). It is not clear, however, that this bias signal is necessarily limited to a single VWM representation, particularly given the growing evidence in support of guidance by multiple VWM representations.

6.5 Conclusion

To fully characterize the nature of the attentional template and the relationship between VWM and attentional guidance, it is important to determine whether multiple VWM representations can influence attentional guidance simultaneously, and whether a VWM representation can be used as a negative attentional template yielding feature-guided avoidance. In both a traditional visual search task and a gaze-contingent paradigm, I have found results in support of attentional guidance by multiple simultaneously active VWM representations (multiple templates). On the other hand, feature-guided avoidance (negative template) appears to occur indirectly, by converting the cued feature information into a spatial template or, possibly, by translating the known irrelevant feature into relevant feature(s). In sum, the work presented here is consistent with a fundamentally facilitatory relationship between VWM and attentional guidance, a relationship that can span multiple items in VWM.

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