The relationship between working memory and the dual-target cost in visual search guidance

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Abstract

Searching for two targets produces a dual-target cost compared with single-target search, with reduced attentional guidance towards targets (Stroud, Menneer, Cave, & Donnelly, 2012). We explore the effect of holding a color in working memory (WM) on guidance in single-target search. In Experiments 1 and 2, participants searched for a T of a specific color while holding one of the following in WM: a color patch, a letter, a dot pattern, or an oriented bar. Only when holding a color in WM was guidance in single-target search affected as strongly as it is in dual-target search. In Experiment 3, the target changed color from trial to trial. A color in WM reduced guidance, but not to the extent of dual-target search. However, search and WM error rates were high, suggesting interference and incomplete engagement with the combined task. We conclude that the guidance cost in dual-target search is not solely due to attentional capture by the WM-color, because the WM-color can be effectively separated from search color, with little confusion between the two. However, WM load does cause substantial interference in guidance when both tasks involve color. These results illustrate the complex interactions between working memory and attentional guidance.

Keywords: working memory, attention, visual search, search guidance, eye movements.

Public Significance Statement

When searching for two different target objects (e.g., guns and bombs in airport security screening), observers look at objects that are different from either target, which makes search much less efficient than search for a single target. The need to hold two items (rather than one) in working memory could contribute to this failure to keep irrrelevant objects from being attended.

Introduction

Visual search for two dissimilar targets shows a reliable cost in accuracy and sometimes in response time relative to search for single targets (Barrett & Zobay, 2014; Hout & Goldinger, 2010; Menneer, Barrett, Phillips, Donnelly, & Cave, 2004, 2007; Menneer, Cave, & Donnelly, 2009; Menneer, Donnelly, Godwin, & Cave, 2010; Sobel, Puri, & Hogan, 2015; Walenchok, Hout, & Goldinger, 2016). This dual-target cost is underpinned by a reduction in search guidance, as evidenced by fewer fixations to target-similar items or seemingly unnecessary examination of items that are not similar to either target (Menneer et al., 2012; Stroud et al., 2012; Stroud, Menneer, Cave, Donnelly, & Rayner, 2011; Stroud, Menneer, Kaplan, Cave, & Donnelly, Under revision; see also Grubert & Eimer, 2013, for related evidence using ERPs). Attentional guidance for a single target can be very accurate and effective, and the cost in searching for two targets shows that guidance is compromised when the system must represent two different targets. Understanding this disruption in guidance could lead to a better understanding of the limits of attentional control. The deterioration of visual search also has practical implications for tasks such as security search for multiple threat items (e.g., Menneer et al., 2009). The purpose of the current study is to assess the role that working memory limitations could play in the dual-target cost.

The dual-target cost is surprising, because much work using a variety of paradigms has shown that the attention system can successfully maintain two separate target templates (Beck & Hollingworth, 2017; Beck, Hollingworth, & Luck, 2012; Grubert & Eimer, 2015, 2016; Irons, Folk, & Remington, 2012; Stroud et al., 2012), and in some limited circumstances, it is possible for attention to be guided by an even larger set or a range of colors (Stroud et al., Under revision). What, then, leads to the reduction of guidance in dual-target search and the dual target cost? Despite being able to represent multiple search targets, the representation is less precise in dual-target search than in single-target search (Barrett &

Zobay, 2014), resulting in less specificity in attentional guidance. There is also evidence that only one target representation is selected as the current focus (Buttaccio, Lange, Thomas, & Dougherty, 2015; Houtkamp & Roelfsema, 2009; Moore & Weissman, 2011, 2014; Olivers, Peters, Houtkamp, & Roelfsema, 2011; van Moorselaar, Theeuwes, & Olivers, 2014)[1], leading to switch costs in multiple-target search (Dombrowe, Donk, & Olivers, 2011) and competition between the active and passive items (Grubert & Eimer, 2013).

The current question of interest is how memory, or more specifically working memory, might play a role in the dual-target cost. Dual-target search studies typically use the same two targets across trials, which are often referred to as consistently mapped targets (CM). It might be thought that this repetition of the same targets over many trials would allow them to be transferred from working memory (WM) into long term memory, eliminating the role for WM in dual target search (Carlisle, Arita, Pardo, & Woodman, 2011; Oh & Kim, 2003; Olivers, 2009; Olivers et al., 2011; Woodman, Carlisle, & Reinhart, 2013;

[1] However, see Cowan (2011) for a multiple-item account of attentional focus in working memory, and Godwin, Walenchok, Houpt, Hout, and Goldinger (2015) for evidence of unlimited capacity in rejection of distractors in dual-target search.

Woodman, Luck, & Schall, 2007). However, the evidence suggests that the dual-target cost results from imprecision in representation, capacity limitations, or interference between representations, and these constraints would not be expected if targets were stored purely in long-term memory (LTM). It therefore seems likely that WM has some role in search for CM targets. In this study we test the role of working memory (WM) in dual-target search with targets that are consistent and also with targets that vary from trial to trial (variably mapped, VM), which should prevent the targets being stored in long term memory.

A large body of literature has linked items held in WM with attentional capture (Downing, 2000; Schwark, Dolgov, Sandry, & Volkman, 2013), the representations used to guide attention (Gunseli, Meeter, & Olivers, 2014; Huang & Pashler, 2007; Woodman & Arita, 2011; Woodman & Luck, 2004), the inhibition of attention (Barrett, Shimozaki, Jensen, & Zobay, 2016; Dube, Basciano, Emrich, & Al-Aidroos, 2016), disruption of eye-movement control (Solman, Allan Cheyne, & Smilek, 2011), disruption of visual search (Oh & Kim, 2004) and susceptibility to distraction/interference (de Fockert, Rees, Frith, & Lavie, 2001). Specifically, there is evidence that items in WM attract attention during visual search (Dalvit & Eimer, 2011; Hollingworth & Luck, 2009; Kumar, Soto, & Humphreys, 2009; Olivers, Meijer, & Theeuwes, 2006; Olivers et al., 2011; Woodman et al., 2007). However, there is counterevidence that search and WM are not intrinsically linked. Some research has shown no adverse effect on visual search or target detection when distractors match an item held in WM (Downing & Dodds, 2004; Peters, Goebel, & Roelfsema, 2009; Woodman & Luck, 2007; Woodman et al., 2007; Woodman, Vogel, & Luck, 2001), suggesting that the item in WM does not hold the same status as the search target (Houtkamp & Roelfsema, 2006).

In addition, successful search for up to 100 target items (hybrid search, Cunningham & Wolfe, 2014; Drew, Boettcher, & Wolfe, 2016; J. M. Wolfe, 2012; J. M. Wolfe, Cain, Ehinger, & Drew, 2015) suggests that search-target storage can extend beyond the limited capacity of working memory and can rely partly on long-term memory. If a search target is stored in long-term memory, we might expect it to be protected from interference from items in working memory, although the relationship between working memory and long-term memory is potentially complex, and definitions of working memory and the roles assigned to it differ from study to study(e.g., see Cowan, 2017).

In our study, the WM process engaged is that employed to remember an item for a short time. Previous findings of interference between visual search and such a WM-task (as reviewed earlier) suggest the same WM process is employed to remember a search target. The aim in our study is to understand whether the interference in dual-target search is similar to that found between search and a WM-task.

In the current study, performance in single-target and dual-target search is compared with performance in single-target search combined with a WM task. The data for the single- and dual-target search conditions are taken from Stroud et al. (2012). These search arrays included a wide range of colors, which made it possible to use fixation data to get a detailed picture of how attentional guidance by color differed across conditions. Stroud et al.'s search conditions used CM targets such that visual search targets remained constant across trials. The new experiments include both CM and VM search targets. In the WM task, the targets are variably mapped, because for a meaningful test of WM, items need to vary across trials.

Comparison of the single-target and single-target plus WM conditions provides a new and detailed look at how a WM task interferes with single-target search. If WM is contributing to attentional guidance in single-target search, then the single-target search plus WM task should produce less effective guidance to search targets than the single-target search condition. Such reduction in guidance would be in line with and would expand on the many previous studies showing effects of a WM task on search.

Comparison of dual-target and single-target plus WM task is more complicated. If the dual-target search condition relies on WM, then replacing search for one of the two targets with a WM task should be a minimal change for participants. However, the search target in Stroud et al. (2012) is consistently mapped (CM), while the memory item replacing it is variably mapped (VM). If the VM memory task places greater load on WM than the CM search task, then guidance will suffer in the WM condition more than in dual-target search. If the WM task places no greater load on WM than does the second target in dual-target condition, then guidance in the dual-target and single-target plus WM tasks should be equivalent. Some differences in previous findings regarding attentional capture of a WM-item in visual search (as outlined above; e.g., Olivers, 2009; Woodman et al., 2007) have been argued to arise from CM versus VM search targets. Therefore, in the final experiment, we aim to better equate this potential load difference by using VM targets in the visual search tasks.

In summation, the key comparisons between conditions will test how guidance when performing the single-target plus WM task condition compares to single-target search and dual-target search: Is guidance in the single-target search plus WM task similar to that in single-target search, dual-target search, somewhere between the two, or less efficient than both single- and dual-target search conditions?

In all the experiments we report, participants searched for a colored T target while also holding some type of visual stimulus in WM. In the first experiment, the item to be held in WM was a color, while in the second experiment different types of visual memory items (letter, orientation, spatial pattern) were used. Previous work has established a cost in search guidance by measuring fixation rates to distractor colors as a function of their similarity to the target color(s), and revealing that more fixations are made to target-dissimilar colors in dual-target search than single-target search (Menneer et al., 2012; Stroud et al., 2012; Stroud et al., 2011). In the current study, the same measure is used to determine whether these misguided fixations to target-dissimilar distractors arise when an extra item is simply held in WM. If holding a color in WM influences search guidance, we will explore whether misguided fixations are directed specifically to distractors that are similar in color to the WM-item, which would suggest that the WM-color is directing eye movements as if it were a search target. On the other hand, there may be a more generalized disruption (i.e. more fixations) to all colors, which would suggest that the presence of the WM-color weakens the guidance for the search-target color but without becoming a search target. The results suggest that both effects are occurring to some extent.

Unlike some previous studies (e.g., Olivers, 2009; Woodman & Luck, 2007), we utilize an ordered range of colors in the search tasks. This approach allows us to examine the fixation rates as a function of color, and examine guidance patterns at a higher resolution than in previous studies. We examine the fixation rate to each color as a function of its similarity to the search target color (e.g., Stroud et al., 2012) as well as its similarity to the WM-item color. In order to compare the search guidance functions, a sigmoidal function is fit to the empirical data. The parameters required to fit the function allow us to characterize the influences on guidance and to compare them across conditions.

Experiment 1: Does An Item in Working Memory Diminish Search Performance and Guidance in the Same Manner As Adding An Additional Search Target (Consistent Target)?

The purpose of Experiment 1 was to compare attentional guidance across single-target search, dual-target search, and single-target search plus a WM-task. Search targets were defined by color, and were consistent from trial to trial for a given subject. The item to be held in WM was also a color. Attentional guidance was observed by using an ordered range of colors in the search displays to provide a function of fixation rates across color-distance from the search target(s). Is guidance in the single-target search plus WM task similar to that in single-target search, or to that in dual-target search, or somewhere between the two, or less efficient than both single- and dual-target search conditions? Determining this relationship provides evidence as to whether the guidance cost in dual-target search could be accounted for by attentional capture from, and competition between, both of the target colors when held in WM.

Method

There were three conditions: (a) single-target search, (b) dual-target search and (c) single-target search combined with a second task that required holding a color in WM (WM-color search). In the WM-color search condition, the WM-color was selected independently from the search target color; thus they were usually different colors (240 trials), but were occasionally the same (16 trials). The data from the single-target search and the dual-target search conditions have already been reported in detail as the 4-step separation condition in

Stroud et al. (2012)[2] as part of an examination of the dual-target and split-target costs. The experiments were conducted in accordance with ethical guidelines and approval from the Institutional Review Board of the University of Massachusetts.

The primary analyses presented across Experiments 1, 2 and 3 were in the form of a mixed-design ANOVA comprising three factors. The first factor was between-participants with 2 or 5 levels (Search-condition: single-target, dual-target, WM, etc.)[3], the second was a within-participant factor with 2 levels (Target-presence: target-absent vs. target-present trials), and the third was a within-participants factor with 7 or 9 levels (Color-step distance of the fixated distractor from the search-target color). The two analyses of primary interest were comparison of single-target and dual-target searches against WM-color search, and

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[2] The reduction in guidance in dual-target search has also been evident with x-ray images (Menneer et al., 2012), and in more recent, but currently unpublished, experiments. Given the replicability of the cost in guidance, we consider that the Stroud et al. (2012) data provide a valid representative sample for comparison, and that, despite already being published, re-use of the data does not pose risks that can be associated with re-use (e.g., increased false positives).

[3] Given that two of these conditions (single-target and dual-target) have already been conducted (Stroud et al., 2012), a between-participants design was most appropriate for the Search-condition.

differences in color guidance across the search conditions. A power analysis was conducted for each of these analyses using G*Power 3.1 (Faul, Erdfelder, Lang, & Buchner, 2007) for *F* tests with a mixed-design.

The first comparison of interest was the main effect comparing search conditions. A power analysis was conducted with 2 between-participants levels and 2 within-participants levels. The lowest number of levels was chosen for each type of factor in order to be liberal in estimating the sample size. The effect size and correlation between the repeated measures were set to the empirical values arising from the data presented in Stroud et al. (2012). The analysis relevant to the current study was the 2×2×7 ANOVA on the guidance measure (i.e., fixation rates) comparing 4-step dual-target search with single-target search, which comprised the same factors as used in the current study (Search-condition: single-target vs. dual-target; Target-presence: target-absent vs. target-present trials; Color-step distance of the fixated distractor from the search-target color(s)). The effect size for the main effect of Search-condition was $\eta_p^2 = .18$ and the correlation between target-present and target-absent fixation rates was $r = .91$. Given that G*Power 3.1 requires the f for the effect size, we used η_p^2 to give an estimate of $f = .47$. The f and r values were used in the power analysis to predict the sample size required to achieve our desired *a priori* power level of .70, resulting in a sample size of 30 participants across two groups or 50 participants across five groups.

The second comparison of interest was the interaction between the Search-condition and the Color-step, which would reveal any differences in color guidance for one search condition over the other. The power analysis was conducted using the effect size from Stroud et al. (2012), $\eta_p^2 = .20$, which gave an estimate of $f = .50$, and the largest correlation between all color steps, $r = .98$, in order to encourage a liberal sample size estimate. These values were again used to predict the sample size required to achieve our desired power level of .70, resulting a sample size of 28 across two groups or 45 across five groups.

To facilitate counterbalancing of the 16 stimulus colors, we increased the sample size inferred from the power analyses to have 16 participants per group. We recalculated the power analyses using this larger sample size, which both resulted in estimated power > .74 for effects of the size observed by Stroud et al. (2012).

Participants.

Sixteen University of Massachusetts undergraduate students (12 female, 4 male, age range 17–25 years[4], M = 19.9, SD = 2.2) participated in the WM-color search condition. The data from one additional participant was lost due to a technical problem. All participants self-reported normal or corrected-to-normal vision and were tested for normal color vision (Ishihara, 1917). Some of the participants had prior experience with visual search tasks, although none participated in the conditions from Stroud et al. (2012), and none had prior experience with the stimuli. All participants were unaware of the purpose of the experiment. Participants received academic credit for their participation and were fully informed about the nature of the task. There were 32 participants total in the single-target and dual-target

[4] One participant chose not to report her age.

search conditions (16 in each condition), as reported in Stroud et al. (2012). The sample consisted of 25 females and 7 males with ages range 18–22 years (*M* = 19.53; *SD* = 1.23).

Apparatus.

Stimuli were presented on a 17-inch Vision Master Pro 514 iiyama CRT monitor with a resolution of 800 × 600 pixels and a refresh rate of 85Hz. Eye movements were recorded with an Eye-Link II eye tracking system with a sampling rate of 250 Hz. The tracker was calibrated using a 9-point display to be within a maximum of 0.55° visual angle error. Viewing was binocular although only the participant's right eye was tracked, and a chin-rest was used to minimize head movements at a viewing distance of 57cm from the display. Default and recommended settings were used for the Eyelink parameters to define the fixations and saccades. A saccade onset was demarcated when the spatial separation of samples indicated an eye movement with a velocity that exceeded 30° per second or an acceleration that exceeded 8000° per second-squared. If these criteria were not met, then successive samples were assumed to comprise the current fixation. Manual responses were recorded using a Microsoft gamepad controller.

Stimuli.

The items making up the search arrays were Ts (targets) and offset Ls (distractors), as used by Stroud et al. (2012). Each stimulus was 2.5° of visual angle at the widest point, and the thickness of the lines was 0.5°. The lines met at the bisector point for the T-shape, with symmetrical offsets of 1.0°, and for the L-shape, the lines were joined asymmetrically giving offsets of 1.7°and 0.3°. The offset was chosen to reduce target-distractor discriminability and thus encourage fixations. Each object appeared in one of sixteen colors spaced in a ring in CIExyY space (see Figure 1; Menneer et al., 2007). In these experiments, as in Stroud et al.

(2012), the differences between two colors can be measured in terms of the number of steps between them on the color ring.

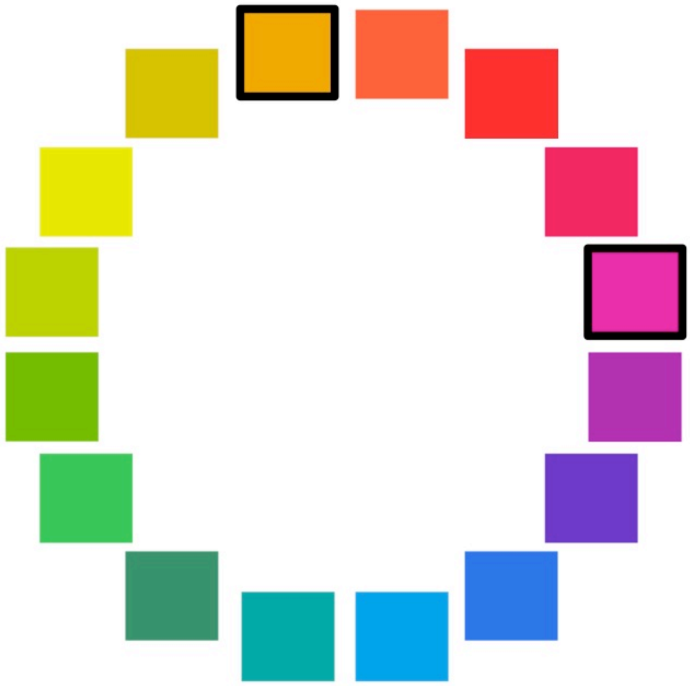

Figure 1. Color stimulus space, as created by Menneer et al. (2007). The colors marked with a black border indicate the target pair for one of the 16 participants in the dual-target condition. In the dual-target condition, all target pairs were separated by 4 steps in the color space. Color versions of the figures are available in the online version of the manuscript.

Each display contained ten objects on a white background. All were Ls, except one that was a T on target-present trials. Objects were evenly spaced on a circle with a radius of 7.3° visual angle, and appeared at orientations of 0°, 90°, 180°, or 270°. Distractor items (Ls) were selected at random, with no restriction other than the same number of each color and orientation were presented over the 256 experimental trials.

Figure 2 provides an example display. The whole display subtended a visual angle of 39.2° × 29.0°.

The stimuli for the WM task were the same 16 colors as used in the visual search task. After the search array and response, all 16 colors were presented in a circular array of visual angle 22.6° x 24.6°. Each of these colors was presented as a filled circle of 2.8° diameter.

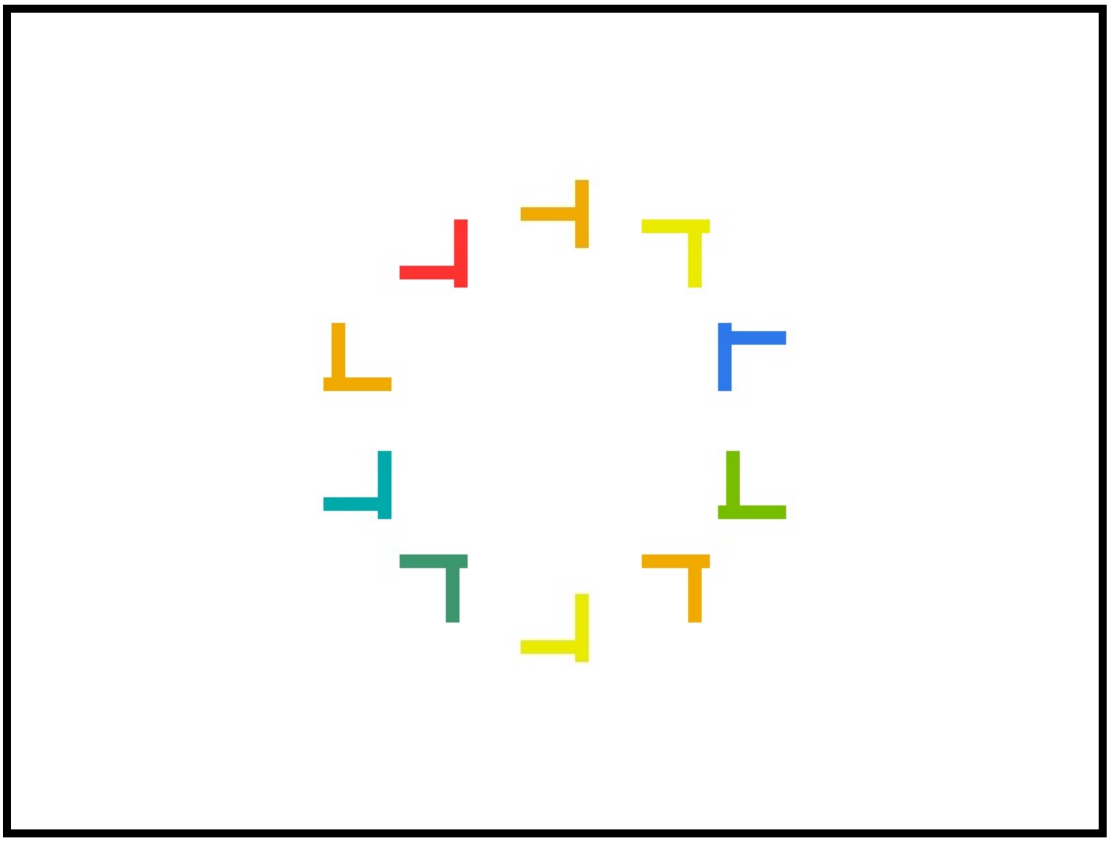

Figure 2. An example search display with T target present.

Procedure.

Each participant completed 256 experimental trials preceded by 5 practice trials of a single type of search. The search task was to respond to the presence or absence of a search target (T) within the display. Each of the three groups of 16 participants performed a different search condition: (a) single-target search for a T-shape that remained a consistent color throughout the experiment, (b) dual-target search for targets that were separated by 4 steps in the stimulus color space (see Figure 1), and (c) WM-color search, which was single-target search while holding a color in WM.

In all conditions, a target was present on half of the trials. In dual-target search (from Stroud et al., 2012), at most one target appeared on any trial. Each of the participants in single-target search and WM-color search was assigned a single search-target color. Each of the dual-target participants was assigned two target colors, with half of the targets appearing in each color. In both conditions, the search-target color(s) remained the same for each participant throughout the experiment (CM). Target colors were balanced across the participants in each search condition.

The trial procedure for the WM condition is shown in Figure 3. A single color that was to be remembered was presented centrally for 1000 ms. Unlike the target colors, the color used for the WM task changed from trial to trial. The memory color presentation was followed by a fixation dot for 500 ms, then a reminder of the search target for 1000 ms, and a further fixation dot for 500 ms. The search display was then presented until a response was made indicating target-present or target-absent. The memory test display then appeared, comprising a circle of the 16 possible colors used in the WM task. Participants were asked to fixate the item they held in WM for 1 second and press the response button. 'Target-present', 'target-absent' and 'memory item fixated' responses were made using three different buttons. No feedback was provided for either task.

In the single-target and dual-target conditions, the procedure was similar (see Stroud et al., 2012), except that no memory color was presented at the beginning, no memory test was presented at the end, and the dual-target preview showed two possible search targets that were presented side by side, separated by 2.5° visual angle at the shortest distance. The dual-target preview was presented for same duration as the target previews in the other search conditions.

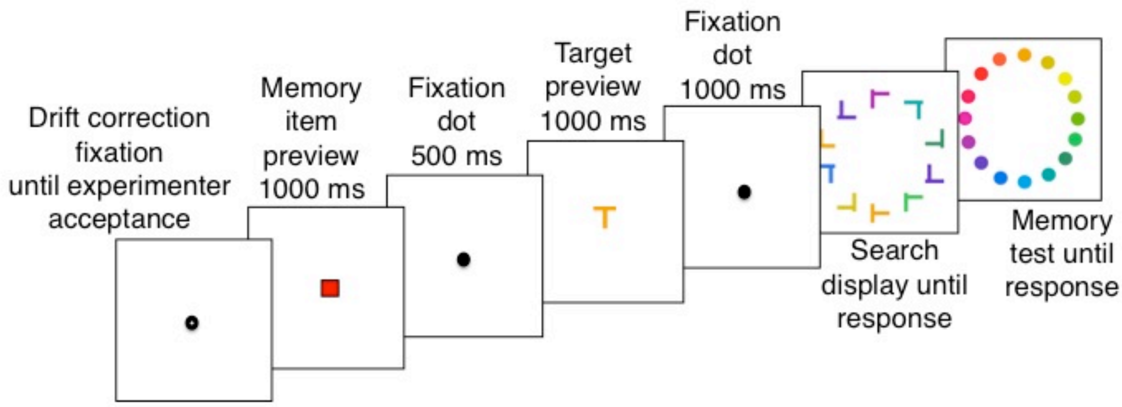

Figure 3. Trial procedure for Experiment 1.

The WM-color was varied from trial to trial to ensure that it would be stored in WM and not become learned independently of WM throughout the course of the experiment. Conversely, in Experiments 1 and 2, the search targets remained consistent throughout the experiment. Dual-target search and WM-color search in these experiments are therefore not exactly equated due to the potential for the search targets to be maintained independently of WM. Differences between the two conditions therefore lean towards more disruption from the WM-color than the extra target in dual-target search. We will return to this point in Experiment 3 and in the General Discussion.

Eye movements were tracked. A central fixation dot (default drift correction stimulus for the Eyelink II), was presented before each trial began to allow for eye-movement calibration accuracy to be checked, and was displayed until the experimenter was satisfied with the accuracy of the fixation (around 500 ms). Recalibration was conducted if the error in fixation was greater than 0.55°.

Results

The purpose of this study was to examine color guidance in search. The clearest evidence on search guidance in these tasks comes from the fixation rates to distractors of different colors. However, before presenting the fixation rates, we will first report search error rates and response times (RT). In the WM task, 'correct' was defined as being within one color step of the WM-item in stimulus space. Resulting error rates in the WM task are presented in Figure 4. Participants were unaware that adjacent items were to be deemed correct; rather the decision was made post-hoc because identification of the precise WM-item resulted in 36% error rate, suggesting participants did not always have a precise representation of the WM-item. Using colors within one step of the WM-item captured trials in which participants were nonetheless engaging with the WM task, and avoided discarding a large number of trials.

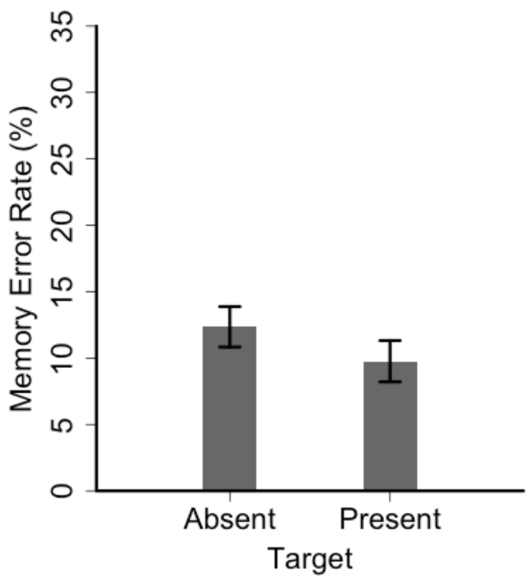

Figure 4: Error rates in reporting the working-memory color in the WM-color search condition. Error bars represent one standard error.

The primary focus of interest in Experiment 1 was guidance in the search for a target color when a second color must be stored in WM. Comparison of the WM-color search task guidance with that in single-target search and in dual-target search was conducted separately. Guidance was measured with respect to fixation rates to different colors during search. In addition, we also analysed whether or not a color in WM attracted fixations. Fixation rates were calculated using only those fixations that occurred during the presentation of the search array and that fell within regions of interest (ROIs). ROIs were defined as the smallest rectangle to contain each stimulus.

The rate of fixating any given distractor color was calculated as the number of distractors with that color that were fixated at least once in a trial divided by the number of distractors of that color that were presented over the course of the experiment. These data were analysed in two ways. First the fixation rates were analysed using traditional ANOVAs. Second they were modelled to provide estimates for parameters relating to search.

Models of fixation data in visual search are typically used to understand what attracts eye movements and guides attention (e.g., Henderson, Malcolm, & Schandl, 2009; J. Wolfe & Gancarz, 1997; Zelinsky, 2008), or to understand the processes driving eye movement behaviour (e.g., Godwin, Reichle, & Menneer, 2014; Williams, Pollatsek, & Reichle, 2014). In contrast, with our model, we wished to characterize the parameters influencing the guidance of attention towards colors in the display as a function of the color-similarity to the target. We are not aware of any other model that examines fixation data in this way. Our data allow this function to be estimated because we use an ordered range of colors with a resolution that allows us to examine the fixation rate as a function of target-distractor color similarity.

In all the experiments presented here and in similar earlier studies, the fixation rates across the different colors follow a similar pattern. The target colors and colors very similar to them are fixated at a high rate, and the fixation rate drops gradually for colors that are more and more different from the target colors, until it levels off at a low level for colors that are very different from the targets. When the fixation rate is plotted by color, with the target color on the left and colors most dissimilar to the target on the right, all the experiments produce a descending curve with the same basic shape, but with some important differences from one experiment to the next. The model used here is based on a sigmoidal function, because the sigmoid function provides the S-shape curve apparent in these data (see also Cave, Menneer, Kaplan, Stroud, & Donnelly, In preparation). We started with a simple sigmoid function, and found that three parameters were required in order to characterize search, and to best fit the range of patterns across participants' fixation data. The equation for the function is as follows, where *e* is Euler's number:

$$f = u + (1 - u)\left(\frac{1}{1 + e^{sc-t}}\right)$$

c is the color of the fixated item, defined in steps from the target color in stimulus color space; *u* is the unguided fixation rate; *s* is the selectivity; *t* is the target color.

Unguided fixation rate (*u*). Even in guided search, participants exhibit a baseline fixation rate to all distractors, including those that are maximally different to the target. *u* defines the ratio of unguided to guided fixations (see Figure 5, left-hand panel). As *u* increases, the rate of fixations guided towards the target color (i.e., for low values of color step at the left of the graph) increases only slightly, while the part of the function that represents fixations to colors that are dissimilar to the target color (i.e., many color steps away from the target, on the right of the graph) rises more so. This rise in fixation rates towards non-target colors represents more unguided fixations.

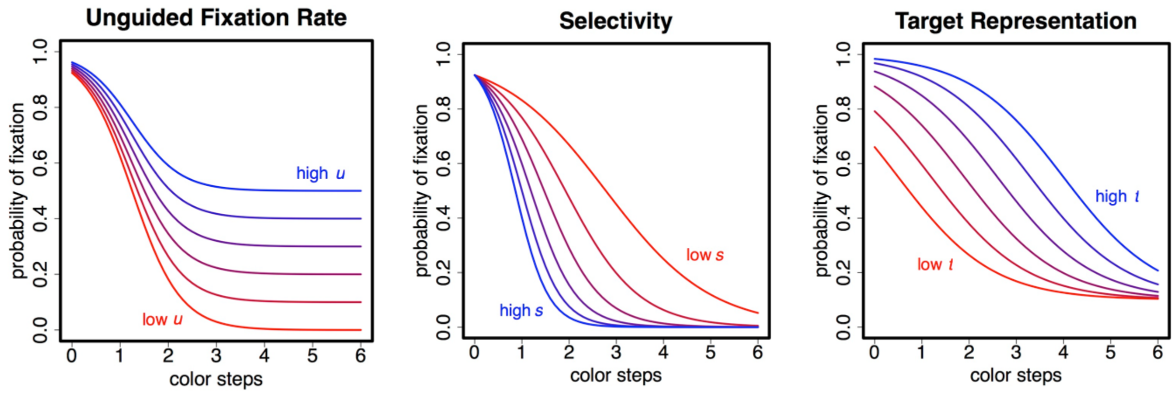

Figure 5: Graphs to illustrate the effects of changing the three parameters. Higher values of the unguided fixation rate (left-hand panel) cause the fixation rate to level off at higher levels for large color differences. Higher values for selectivity (middle panel) produce steeper drop-offs. Higher values for target representation (right-hand panel), move the entire curve to the right, leading to higher fixation rates for the target and similar colors.

Selectivity (*s*). Participants may vary in their ability to distinguish the target colors from other colors in the display. If discriminability is high, then there will be a steep drop-off from the high fixation rate for the target to the low fixation rates for colors that are very different from the target. If discriminability is low, then many colors that are somewhat similar to a target color will have a fairly high fixation rate, and the curve in the graph will descend more gradually from left to right. A high value for the selectivity parameter produces a guidance curve that drops off steeply, while low selectivity produces a shallow drop-off (see Figure 5, middle panel).

Target representation (*t*). When we look at the data across participants, we also see variation in the highest fixation rates, and the range of colors receiving those high rates. In some cases, colors a step away from the target may produce a fixation rate near 1.0. In other cases, especially for target-color distractors when a target is present, the fixation rate can be well below 1. This variation can be captured with a third parameter, called Target Representation. With a high value for Target Representation, the fixation rate is near 1 for the target color and for other colors similar to it. For low values of Target Representation, even the peak fixation rate at the target color can be fairly low. In the equation below, *t* represents this parameter. The effect of *t* on the curve is very simple; it simply shifts the curve to the left or the right. When the curve is shifted to the left, the fixation rate for the target can be well below 1. When it is shifted to the right, then the fixation rates for nontarget colors that are similar to the targets can be almost as high as the target color fixation rate (see Figure 5, right panel).

In some respects, these parameters can be paralleled with parameters in mixture models of visual working memory (e.g., Bays, Catalao, & Husain, 2009; Suchow, Brady, Fougnie, & Alvarez, 2013), which use a combination of Gaussian distributions to model the matching of an item with one held in working memory. Such models can be used (e.g., Barrett et al., 2016) to estimate a measure of precision of memory, which is a similar concept to the *t* parameter here, a guess rate, which is similar to the *u* parameter here.

For each participant, values for the three parameters were generated by fitting the model to the participant's fixation rates using the optim() function in R to minimize the root mean square error (RMSE) between the data points and the model predictions. We used the L-BFGS-B method, which allows upper and lower bounds to be set for each parameter. The parameter *u* was constrained to fall between 0 and 1, and the parameter *s* was constrained to be above 0. Parameter t was unconstrained. Separate fits were calculated for target-present and target-absent trials. The model fits for each participant were evaluated by visual inspection and appeared to be satisfactory overall.

RT and eye-movement data were included in the analyses only from those trials in which the search task and the WM-task responses were deemed correct[5]. Search error rates, on the other hand, were calculated over all trials, regardless of WM-task errors. RT data were otherwise untrimmed, and median RTs from each participant were analysed to minimize the effect of skew.

In all analyses, Greenhouse-Geisser corrected degrees of freedom were used when the assumption of sphericity was violated. All *t*-tests were post-hoc, with Bonferroni correction to the *p*-value, and adjusted degrees of freedom when Levene's test showed a violation of equality of variances. Effect sizes are reported using partial-eta-squared (η_p^2) for factorial ANOVAs, eta-squared (η^2) for one-way ANOVAs and Cohen's *d* for independent sample *t*-tests.

[5] Analyses were also conducted with working memory task errors remaining, and results showed very similar patterns. Differences are described in footnotes.

Search Error Rates and RTs.

While guidance in search is our focus, we report the analyses of the search error rates and RTs to allow a complete overview of performance. Search error rates and RTs were each analyzed in separate ANOVAs with factors of Search-condition (single-target vs. WM-color or dual-target vs. WM-color) and Target-presence (target-present, target-absent). Search-condition was a between-participants factor and Target-presence was a within-participants factor.

Search error rates. There was no significant main effect of Search-condition when comparing single-target search and WM-color search, but error rates were significantly higher in dual-target search than WM-color search, $F < 1$, $\eta_p^2 = .01$, and $F(1,30) = 22.66$, $p < .001$, $\eta_p^2 = .430$ respectively (see Figure 6). The main effect of Target-presence was significant when comparing both single-target search and dual-target search with WM-color search, $F(1,30) = 31.47$, $p < .001$, $\eta_p^2 = .51$, and $F(1,30) = 92.08$, $p < .001$, $\eta_p^2 = .75$ respectively, with more errors on target-present trials than target-absent trials.

The interaction between Search-condition and Target-presence did not reach significance when comparing single-target search with WM-color search, $F(1,30) = 1.55$, $p = .22$, $\eta_p^2 = .05$. However it did reach significance when comparing dual-target search and WM-search, $F(1,30) = 21.96$, $p < .001$, $\eta_p^2 = .42$. In this case, error rates were high in dual-target search than WM-color search on target-present trials, but not target-absent, $t(30) = 4.96$, $p < .001$, $d = 1.75$ and $t(30) = 1.41$, $p = .34$, $d = 0.50$ respectively.

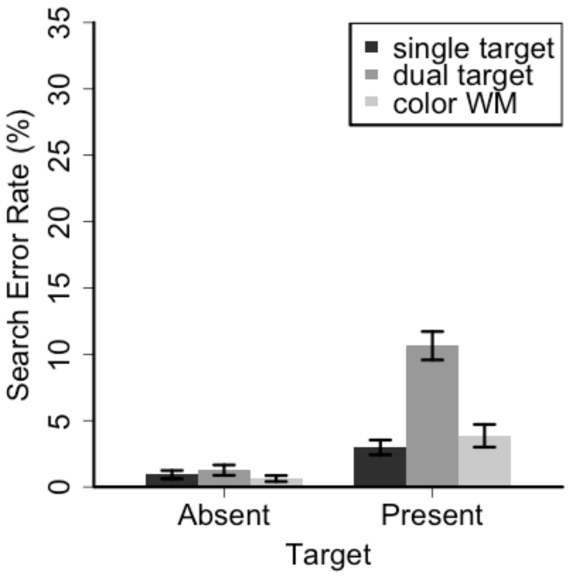

Figure 6: Error rates in the search tasks. Error bars represent one standard error.

Response times. RTs were slower in WM-color search than in single-target search, but the main effect of Search-condition was not significant when comparing dual-target search and WM-color search, $F(1,30) = 22.70$, $p < .001$, $\eta_p^2 = .43$ and $F(1,30) < 1$, $\eta_p^2 = .002$ respectively (see Figure 7). RTs were faster on target-present then target-absent trials. when comparing both single-target search and dual-target search with WM-color search (main effect of Target-presence: $F(1,30) = 41.74$, $p < .001$, $\eta_p^2 = .58$; $F(1,30) = 67.88$, $p < .001$, $\eta_p^2 = .69$ respectively).

The interaction between Search-condition and Target-presence was significant when comparing single-target and WM-color search but not when comparing dual-target search and WM-color search, $F(1,30) = 8.13$, $p < .001$, $\eta_p^2 = .21$ and $F(1,30) = 1.41$, $p = .24$, $\eta_p^2 = .05$ respectively. Despite the interaction, RTs were consistently slower in WM-color search than single-target search across both target-present and target-absent trials, $t(18.8) = 5.18, p < .001, d = 1.83$ and $t(20.5) = 4.35, p < .001, d = 1.54$ respectively.

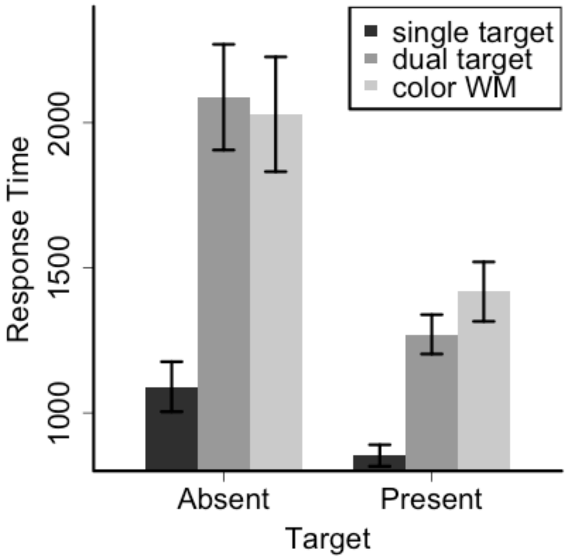

Figure 7: Response times in the search tasks. Error bars represent one standard error.

Guidance.

Our primary focus in this study was examination of search guidance across the different search conditions. Guidance was assessed in two ways. First the fixation rates were analysed using traditional ANOVAs. Second, parameters to characterize search guidance were estimated from the modeled fixation rates and compared across search conditions.

In those first two sets of analyses, we found that guidance is affected by holding a color in WM. We therefore include a third set of analyses to explore more about that interference.

Fixation rates. The fixation rates are shown in Figures 8 and 9. For comparison with single-target search, the ANOVA for the fixation rates comprised the factors of Search-condition (single-target, WM-color), Target-presence, and Color-step (0 to 8). For comparison with dual-target search, the ANOVA for the fixation rates comprised the factors of Search-condition (dual-target, WM-color), Target-presence, and Color-step (0 to 6). Color-step is defined as the number of steps in the ring of 16 stimulus colors between the fixated distractor color and the target color, and thus it represents the distance of the distractor from the target color in stimulus space. For the dual-target search analysis, fixation rates for the three colors between the two search targets were not included. Two of these colors are one step away from a target, and the third color is halfway between both targets (two steps from each). Fixations to these three colors comprised 24% of the fixations made on target-absent trials, and 25% of the fixations on target-present trials. Results are again focused on differences across Search-condition.

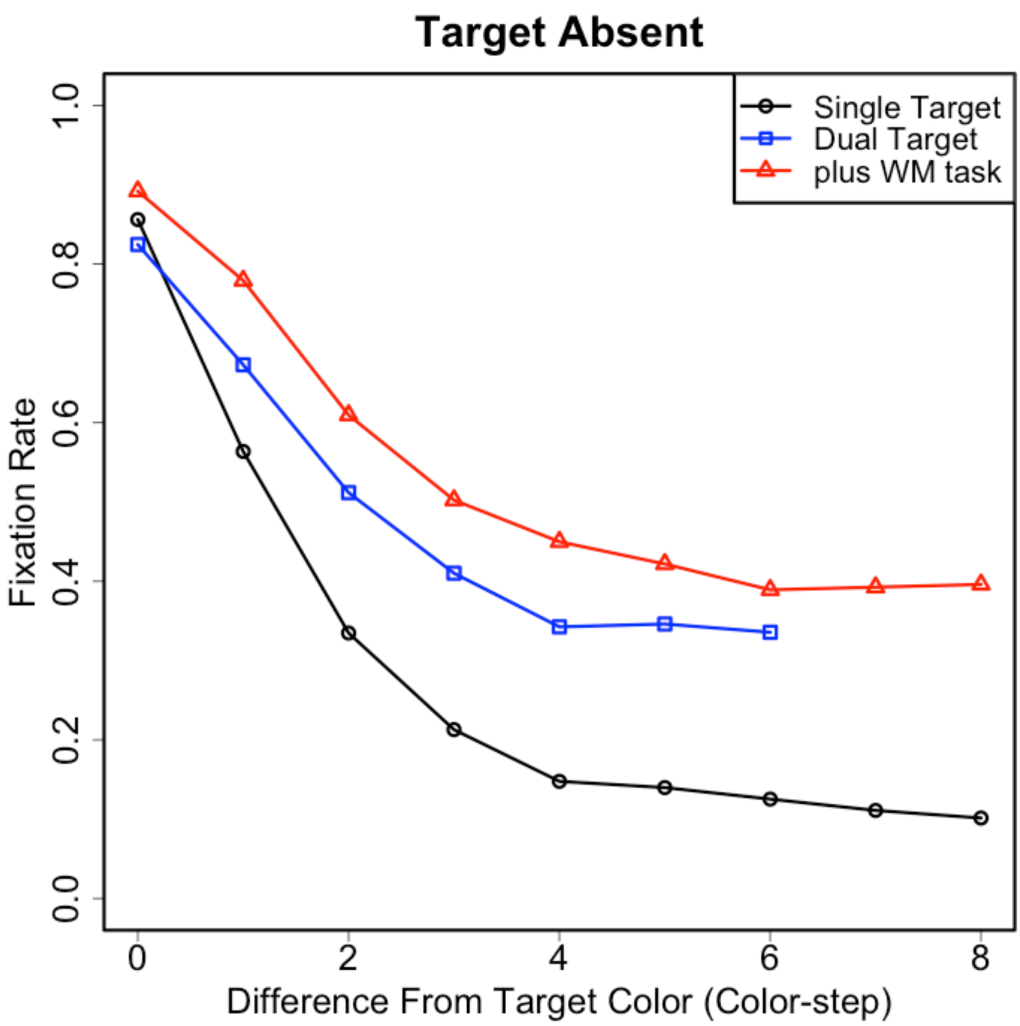

Figure 8: Fixation rates on target-absent trials for each color as a function of its difference from the target color. The difference in color is measured by the number of steps between the two colors in the stimulus color space. Each line represents a different search condition: Single-target, dual-target, and WM-color (single-target search with the WM task). In the dual-target search, the color difference is measured between each color and the more similar target color.

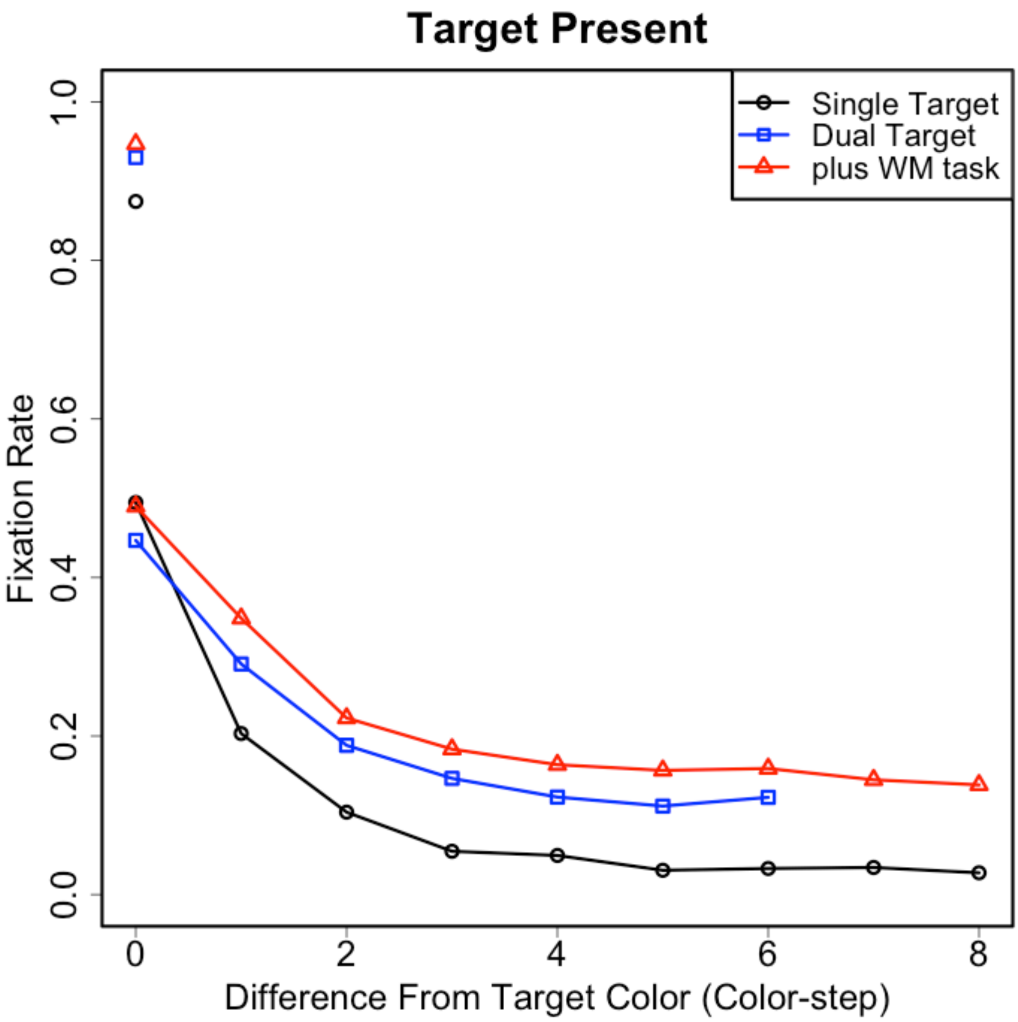

Figure 9: Fixation rates for the target-present trials of Experiment 1. The target color is represented at the left of the graph, where Color-step = 0. The points on the lines represent distractors (Ls) with the target color, while the unconnected points at the top left of the graph represent targets (Ts). Each line represents a different search condition: Single-target, dual-target, and single-target search with the WM task.

Compared with single-target search, fixation rates were higher in WM-color search, $F(1,30) = 19.18$, $p < .001$, $\eta_P^2 = .39$. Fixation rates were higher on target-absent than target-present trials, $F(1,30) = 180.32$, $p < .001$, $\eta_P^2 = .86$, and decreased monotonically with Color-step, $F(2.1,62.4) = 200.75$, $p < .001$, $\eta_P^2 = .87$.

All three interactions involving Search-condition were significant, with the two-way interactions embedded in the three-way Search-condition × Target-presence × Color-step interaction, $F(3.3,98.2) = 2.70$, $p = .05$, $\eta_P^2 = .08$. More fixations to non-target colors were made in WM-color search than single-target search, with this pattern being stronger on target-absent than target-present trials. See Figures 8 and 9. This pattern is also observed in the later analyses on the model parameters.

For dual-target search versus WM-color search, there was no effect of Search-condition, $F(1,30) = 1.65$, $p = .21$, $\eta_P^2 = .05$. Fixation rates were higher on target-absent than target-present trials, $F(1,30) = 217.10$, $p < .001$, $\eta_P^2 = .88$, and decreased monotonically with Color-step, $F(1.7,51.9) = 135.05$, $p < .001$, $\eta_P^2 = .82$. There were no significant interactions with Search-condition, all $F < 1.09$, $p > .30$, $\eta_P^2 < .04$.

Model parameters. In order to estimate parameters for the unguided fixation rate (*u*), selectivity (*s*), and target representation (*t*), fixation rates for Color-steps 0 to 6 were modeled for all search conditions using the sigmoidal function, as described earlier, towards the start of this Results section. The parameter values are presented in Figures 10 and 11. The parameter values were M = 0.19, SD = 0.21 for *u;* M = 1.75, SD = 2.51 for *s;* M = 0.67, SD = 1.35 for *t*. RMSE values for the model fit were M = 0.077, SD = 0.040.

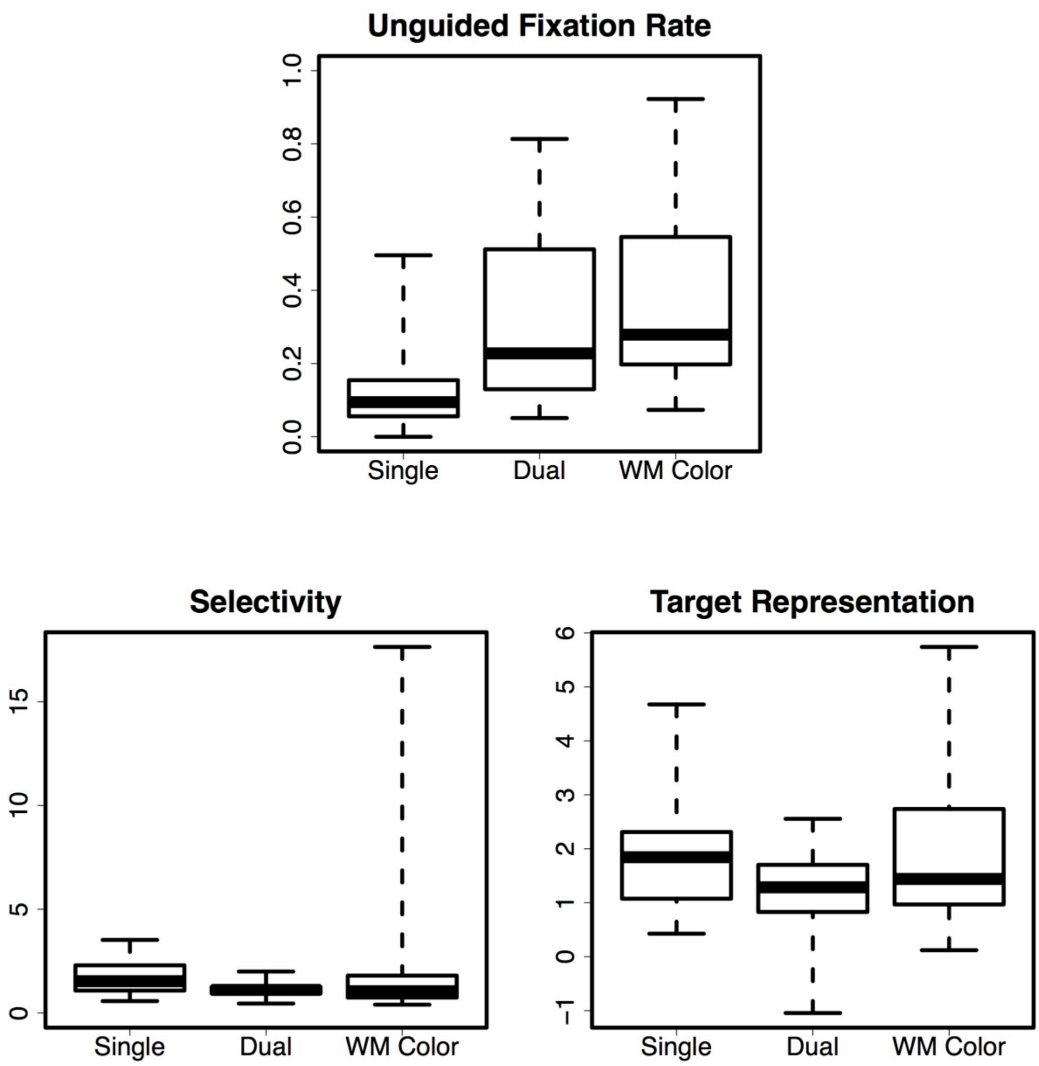

Figure 10: Box and whisker plots showing the Unguided fixation rate (*u*), Selectivity (*s*), and Target representation (*t*) parameters for the target-absent trials in single-target search, dual-target search and WM-color search in Experiment 1.

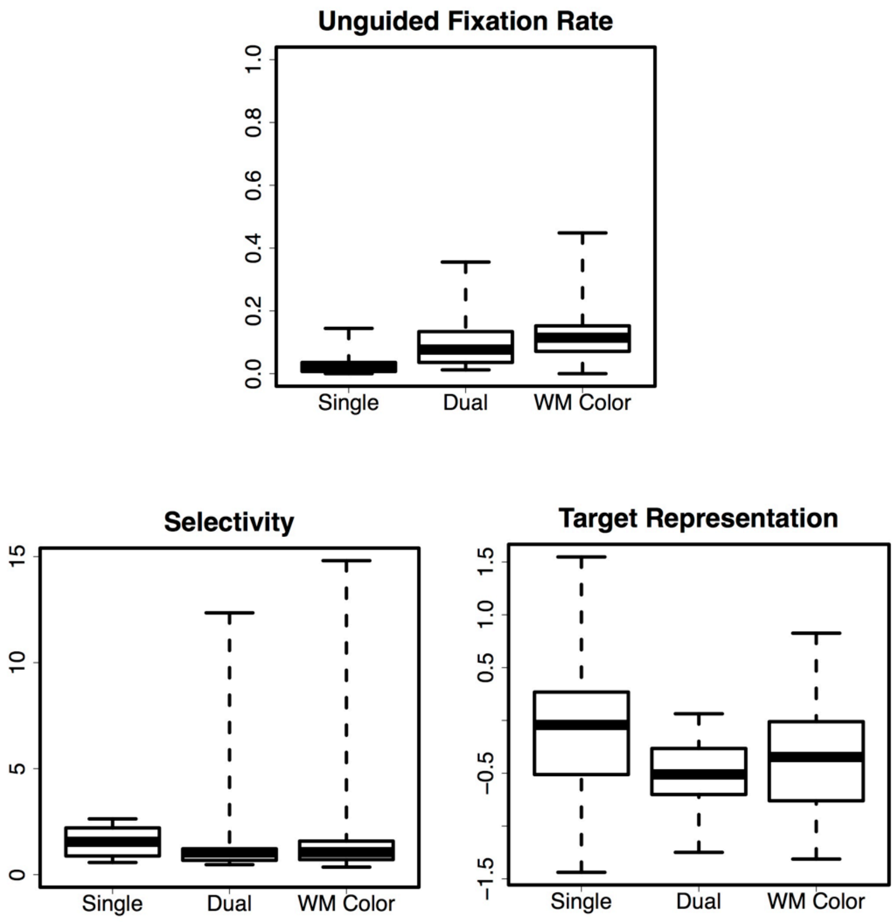

Figure 11: Box and whisker plots showing the Unguided fixation rate (*u*), Selectivity (*s*), and Target representation (*t*) parameters for the target-present trials in single-target search, dual-target search and WM-color search in Experiment 1.

Estimates for unguided fixation rate (*u*), selectivity (*s*), and target representation (*t*) were subjected to separate ANOVAs comprising two factors: Search-condition (single-target or dual-target vs. WM-color) and Target-presence. Analyses were conducted separately for single-target versus WM-color searches and for dual-target versus WM-color searches.

Single-target search resulted in lower *u* than WM-color search, $F(1,30) = 12.09$, $p = .002$, $\eta_p^2 = .29$. Search-condition interacted with Target-presence, $F(1,30) = 7.86$, $p = .009$, $\eta_p^2 = .21$, but *u* remained consistently lower for single-target search than WM-color search on both target-present and target-absent trials (both $t(30) > 3.29$, $p < .005$, $d < 1.20$). There were no significant differences for *s* and *t*, nor significant interactions for Search-condition, all $F < 1$, $p > .35$, $\eta_p^2 < .03$.

For dual-target search, given no effects of Search-condition in the fixation rate data, little difference was expected across model parameters. Indeed, there were no differences across Search-condition, nor a significant interaction, for any of the parameters, all $F < 2.55$, $p > .12$, $\eta_p^2 < .08$, except a trend towards an interaction between Search-condition and Target-presence for *t*, $F(1,30) = 3.67$, $p = .07$, $\eta_p^2 = .11$. The interaction stemmed from a trend towards a larger *t* in WM-color search that dual-target search on target-absent trials, $t(30) = 1.79$, $p = .08$, $d = 0.63$.

For both comparisons (single-target vs. WM-color and dual-target vs. WM-color), *u* and *t* were both larger on target-absent than target-present trials, all $F > 45.43$, $p < .001$, $\eta_p^2 > .60$, presumably driven by a larger number of fixations on target-absent trials.

Memory Item Attentional Capture. Finally, given that guidance is affected by holding a color in WM, we explore more about that interference. Given the analyses are exploratory in nature, the results are summarised here allowing the reader to skip to the

Summary and Discussion section for Experiment 1 if preferred. The analyses presented in this section address the following three questions. Firstly, does the color held in working memory attract fixations? We find that it does. We secondly ask, does the WM-color attract as many fixations as a search target? We find that it does not. Given the WM-color attracts fixations, our third question is whether that effect can explain all the cost in guidance. We find that it cannot, because there is still a cost in guidance even when the WM-color is the same as the search-target color.

In the first set of analyses, we ask whether the WM-color attracts fixations. It is important to note that the data were from the WM-color search task only[6]. The data were

[6] It is important to note that the search conditions were not designed to explicitly investigate this question, and therefore the number of data points contributing to each value can be fairly low. On average, the number of presentations of each distractor color that matched each memory-step and each color-step (distance between the target color and distractor color) was around 4 to 16 items for each participant. There were 162 possible combinations (9 Color-steps x 9 Memory-color-steps x 2 target-present and target-absent), and there were four participants who were presented zero items for one of these combinations. These four participants were excluded from the reported analysis. However, the analysis was repeated with these missing values

organised according to the distance in color space (number of color steps) between the WM-color and the fixated distractor color. Like the number of color steps between the target color and the distractor, the distance between the WM-color and the distractor is measured in color steps in stimulus color space. Here we refer to this distance as Memory-color-step to distinguish it from the Color-step factor. If colors similar to the memory color attract more fixations, then fixation rates will be higher for low values of Memory-color-step. There are nine levels of Color-step included in this analysis, allowing distractors to fall up to eight steps from the target color in all conditions. Fixation rates were analysed using a Memory-color-step (0 to 8) x Color-step (0 to 8) x Target-presence repeated-measures ANOVA.

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replaced by the mean value across the remaining participants, which gave the same pattern of results as the analyses reported unless otherwise noted.

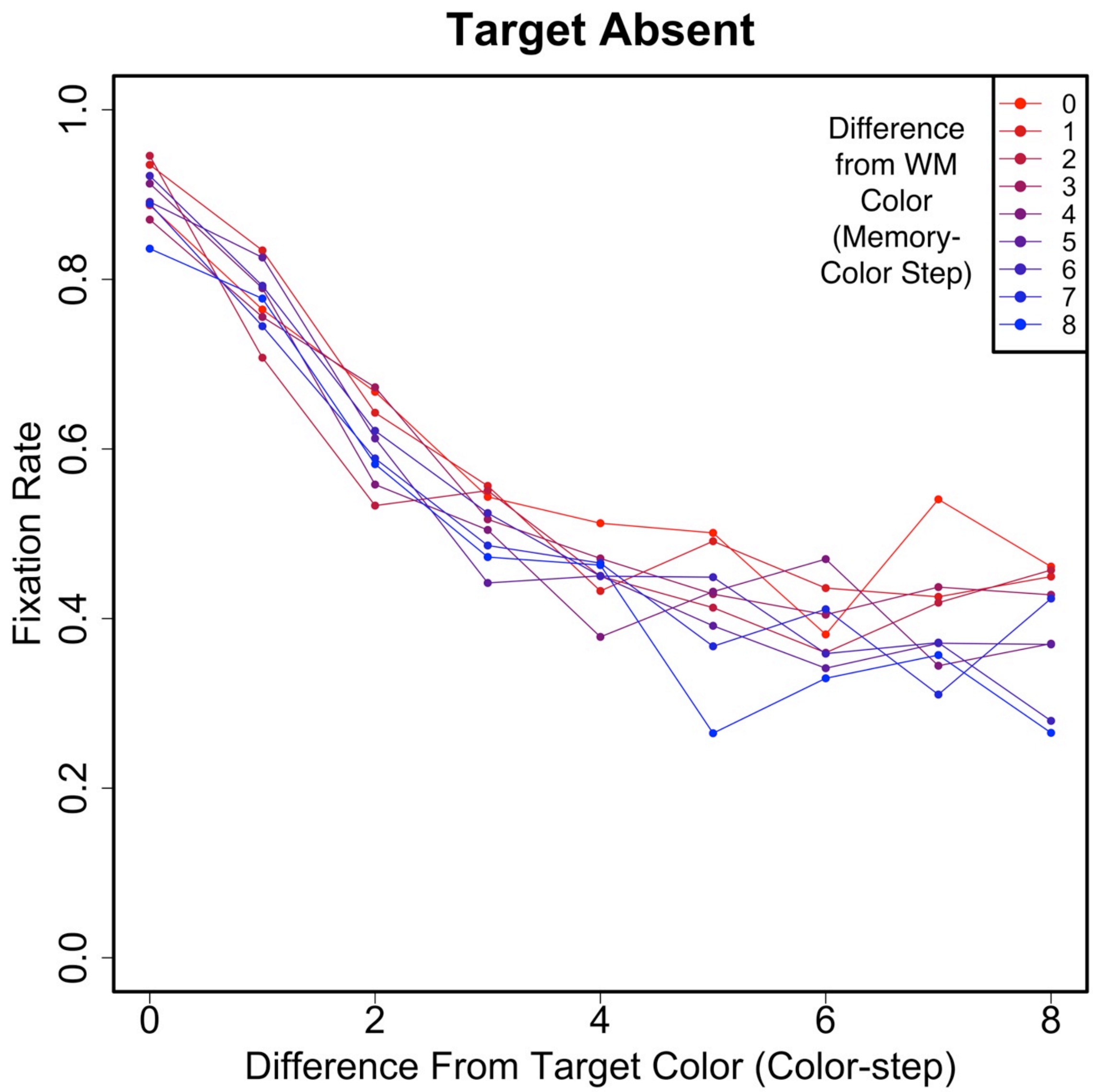

Figure 12: Fixation rates for the target-absent trials in the WM-search condition of Experiment 1, broken down by the similarity of the fixated color to the color held in working memory. The number associated with each line is the number of steps to the memory color (Memory-color-step). Red lines show fixation rates for items identical or similar to the memory color. Blue lines show fixation rates for items very different from the memory color.

Figure 12 shows fixation rates broken down by Memory-color-step when the target is absent, and Figure 13 shows the results when the target is present. Fixation rates generally decreased, although not monotonically, as Memory-color-step increased, $F(3.0,33.1) = 8.76$, $p < .001$, $\eta_p^2 = .44$. Fixation rates decreased monotonically as Color-step increased, $F(1.5,16.2) = 33.15$, $p < .001$, $\eta_p^2 = .75$. Fixation rates were higher for target-absent than target-present trials, $F(1,11) = 61.89$, $p < .001$, $\eta_p^2 = .85$.

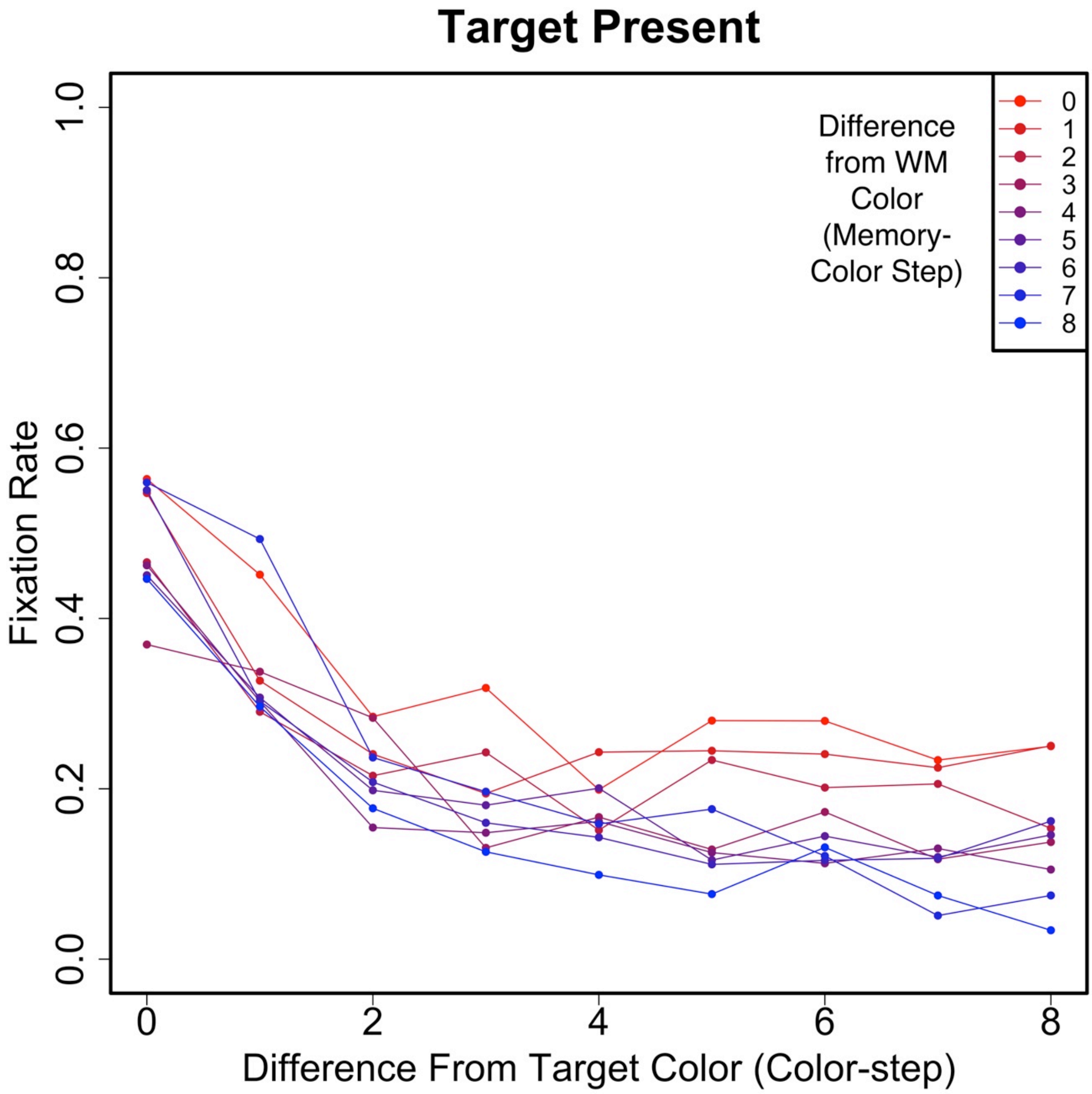

Figure 13: Fixation rates for the target-present trials in the WM-search condition of Experiment 1, broken down by the similarity of the fixated color to the color held in working memory (Memory-color-step). As in the previous graph, similarity to the memory color tends to bring the fixation rate up, especially for items that are not similar to the target color.

Crucially, Memory-color-step interacted with Color-step, $F(64,704) = 1.33$, $p = .05$, $\eta_p^2 = .11$. Figures 12 and 13 show that the effect of Memory-color-step is smaller for target-color distractors (Color-step 0) than target-dissimilar distractors (Color-step 8). Further ANOVAs were therefore conducted to test for the effect of Memory-color-step for Color-steps 0 and 8 separately[7]. There was no effect of Memory-color-step for Color-step 0, $F(8,96) = 1.47$, $p = .18$, $\eta_p^2 = .11$ [8], for which fixation rates were generally high, and a significant effect for Color-step 8, $F(4.0,55.9) = 3.99$, $p = .006$, $\eta_p^2 = .22$, for which fixation rates were generally lower. Thus, the analysis provides some evidence that items that would normally not be fixated much because they are very different from the search target may be fixated

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[7] There was a missing value for three participants in the analysis for Color-step 0 and one participant in the analysis for Color-step 8. These participants were excluded from the respective analyses.

[8] For the analysis with missing values replaced by the mean value and including WM-task errors, there was a trend towards the effect of Memory-color-step, $F(8,120) = 1.83$, $p = .08$, $\eta_p^2 = .11$.

more because they are similar to the memory color. There were no other significant interactions involving Memory-color-step, both $F < 1.45$, $p > .08$, $\eta_p^2 < .12$[9].

In the second analysis, given that the WM-color attracts fixations, we asked whether the WM-color attracts as many fixations as a target in dual-target search. Data were selected from the WM-color search and the dual-target search conditions. We examined the effect of the WM-color when it was the same distance from the search target as the distance between the two dual-target search targets. Specifically, fixation rates to the WM-color when it was 4 steps from the target were compared to the fixation rates to the search-target colors in dual-target search (which are separated by 4 steps in stimulus color space). There were no missing values in this dataset. Search-condition (dual-target-target-color, 4-step-WM-color) and Target presence were factors in the ANOVA. Fixation rates were higher to the target color in dual-target search (M = .636) than to the color in WM when it was 4 steps from the target (M = .320), $F(1,30) = 35.21$, $p < .001$, $\eta_p^2 = .54$. The interaction with Target presence was not

[9] As noted above, these analyses were repeated with all participants included, and with missing values replaced by the mean. In this version of the analyses, the interaction Memory-color-step x Color-step x Target-presence was significant, both with WM-task errors included and excluded, $F > 1.38$, $p < .04$, $\eta_p^2 > .08$.

significant, $F < 1$, $\eta_p^2 = .03$. The results show that a color held in WM does not receive the same attentional guidance as a search target.[10]

In the third analysis, given that a color held in WM attracts fixations, we investigate whether holding a color in WM interferes with search even when it is the same color as the search target. It could be that a color held in WM disrupts search only because fixations are attracted towards the WM-color and away from the search-target color. If that is the case then the disruption to single-target search would disappear when the color in WM is the same as the search-target color because the two colors are no longer competing for attention. Single-target search data (from Stroud et al., 2012) are used as a baseline for search in which there is no interference from a WM-color or an additional search target.

Fixation-rate data were compared across single-target search and WM-color search, using only the data for trials in which the WM-color was the same as the search target.

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[10] The effects of the WM-color on search were not estimated using the model because the interaction between the target color and the WM-colors is dominated by the relatively large effects of the target color. Effects of the WM-color are therefore difficult to isolate and subsequently interpret using these model parameters.

Search-condition (single-target, WM-color=target-color), Color-step (0-8 steps of distractor color from the target color) and Target presence were factors in the ANOVA.

Fixation rates were higher when WM- and target-color were the same than when there was no WM color, $F(1,30) = 10.39, p = .003, \eta_p^2 = .26$, demonstrating an influence on guidance by the WM-color. Search-condition did not interact with Color-step, $F(4.6,140.0) = 1.43, p = .22, \eta_p^2 = .05$, but did interact with Target presence, $F(1,30) = 10.83, p = .003, \eta_p^2 = .27$, with a stronger effect of Search-condition on target-absent than target-present trials ($\eta_p^2 = .29$ and .12 respectively).

This third step in these exploratory analyses shows that holding a color in WM affects search guidance more than would be expected from just the extra fixations to the WM-color. The extra burden of holding another color in WM interferes with search guidance independently of any attentional capture by the specific color held in WM.

To summarise this set of analyses on attentional capture by the memory item, we found that the color held in working memory does attract fixations, but not as many fixations as a search target. However, the attraction of fixations cannot explain all of the guidance cost that we observed when comparing WM-color search and single-target search, because there is still a cost in guidance even when the WM-color is the same as the search-target color. It is important to again note that this third set of analyses was exploratory in nature, given low numbers of data points in some cases because the conditions were not designed to directly address these questions.

Summary and Discussion

In Experiment 1, the biggest effect of holding a color in WM is in the fixation rates. They clearly show that a color held in WM reduces visual guidance relative to a single search target baseline. Holding a color in WM influences fixations made during search, with more unguided fixations than in single-target search alone.

The results of our exploratory analyses indicate that fixation rates to distractors similar to the WM-color were higher than they would otherwise be if no color was stored in WM, suggesting that the color stored in WM attracts fixations. However, it appears that holding an item in WM does not disrupt guidance only by attracting fixations to that color; it also interferes with guidance more generally, given that guidance was impaired even when the WM-color was the same as the target color. One explanation for this general disruption in guidance is the load of maintaining a variable color in WM, even when it is the same color as the search target.

Overall, it is clear that the presence of a color in WM increases unguided fixations and thus increases fixations to items that are markedly different to the color of search targets.

Experiment 2: Search-Relevant versus Search-Irrelevant Working Memory Items

In Experiment 1, we found that holding a color in WM while searching for a target defined by color caused an increase in unguided fixations. This interference might only occur because the item in WM is in a feature dimension that is relevant to the search task (i.e., color).

In Experiment 2, the effect of holding items in WM that cannot be search targets was investigated. Searching for a single color target while holding a color in WM was compared with performing the same search task while holding a letter, an oriented line or a simple dot pattern in WM. Only when the item in WM was a color was it on the same feature dimension as the search target. We compared the model parameters for WM searches with single-target search to assess whether there is an overall cost in guidance (unguided fixation rate, u) of holding any item in WM or whether the cost to guidance is found only when the item in WM and the search target are in the same feature dimension.

The single-target search condition data in Experiment 2 are from the single-target search condition in Experiment 1 and in Stroud et al. (2012). The WM-color search data in Experiment 2 are from the same condition in Experiment 1. There was no dual-target search condition in Experiment 2.

Method

There were three new conditions that each required holding an item in WM while conducting single-target search. The WM-item was an oriented line, a letter or a simple dot pattern (WM-letter search, WM-orientation search, and WM-dot-pattern search). The WM-color condition and single-target search (from Stroud et al., 2012), both from Experiment 1, are also included in the analyses.

Participants.

Forty-eight University of Massachusetts undergraduate students participated in the three new WM-search conditions, with 16 participants in each. The sample consisted of 40 females and 8 males with age range 18 – 44 years (M = 20.33; SD = 3.74). Some of the participants had prior experience with visual search tasks, but none of these participants was in any of the conditions in Experiment 1, and none had prior experience with the stimuli. All participants had self-reported normal or corrected-to-normal vision. Normal color vision was once again verified through the Ishihara test of color deficiency.

Apparatus, Stimuli and Procedure.

The apparatus, stimuli and procedure were identical to Experiment 1 except that a different type of item was used for the WM task.

Three different participant groups each received a different type of stimulus in the WM task. The letter items were letters from the alphabet from A to P, presented at 2.1° × 2.1° maximum visual angle. The orientation stimuli were 16 oriented ovals starting at vertical, and equally spaced with 11.25° rotation between one orientation and the next. Each oval was 4.0° × 0.3° visual angle. The memory dot patterns were generated to contain three randomly located dots falling within a centrally-placed square that was approximately two-thirds the height of the screen. Each dot had a diameter of 2.3° visual angle.

The stimulus to be stored in WM was presented prior to the search array, as in Experiment 1. The memory test display was presented as in Experiment 1 for the letter and orientation WM tasks, but contained 16 letters or 16 orientations. For the dot pattern WM task, participants were presented with a single dot on the screen, and indicated whether or not the dot location was the same as one of the dots in the memory display. Examples of the memory stimuli and memory test displays for all three tasks are shown in Figure 14.

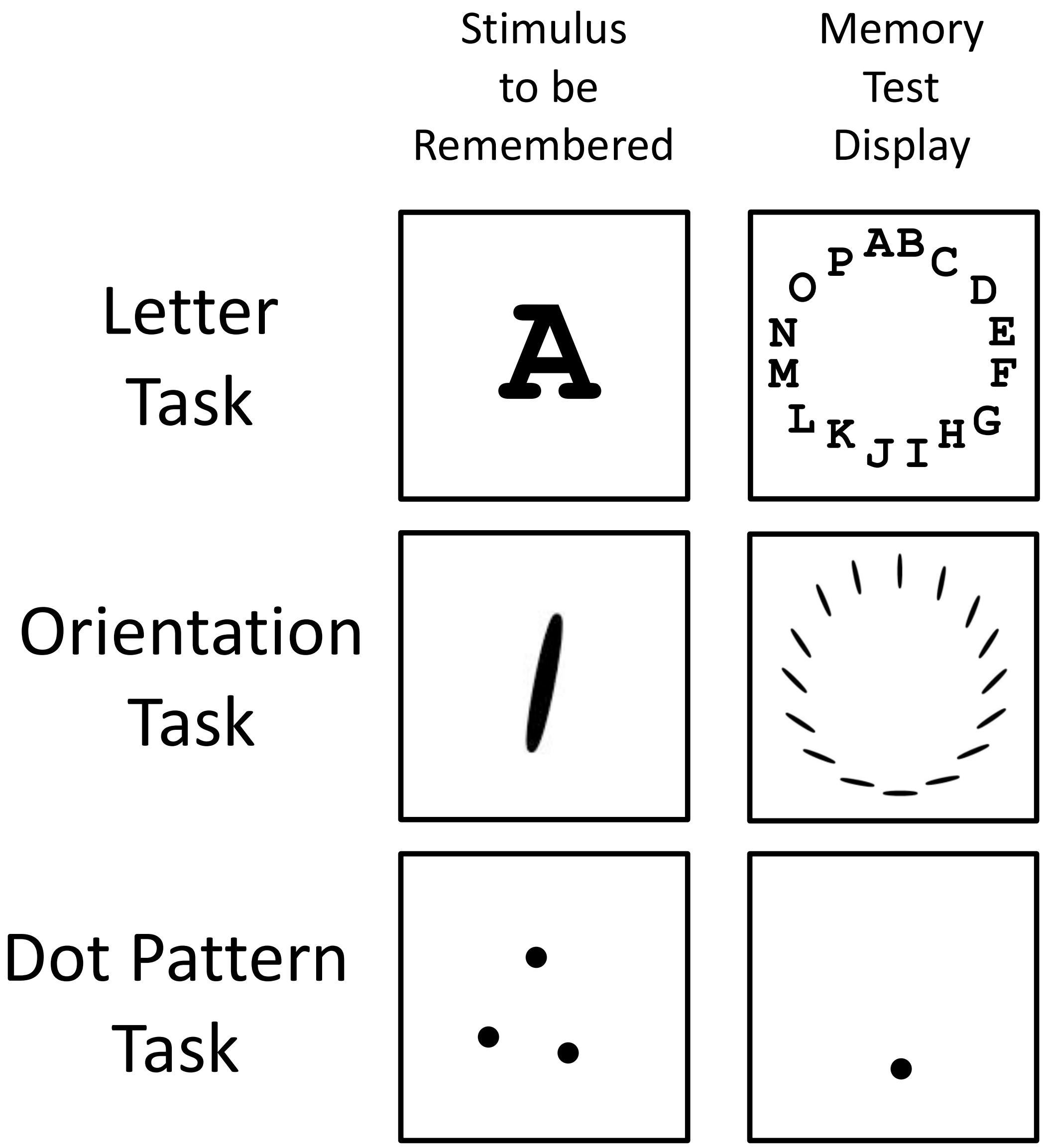

Figure 14. An example memory stimulus and memory test display for each of the three new (noncolor) working memory tasks introduced in Experiment 2.

Search condition varied across five groups of 16 participants each: (a) single-target search (from Stroud et al., 2012), (b) WM-color search (from Experiment 1), (c) WM-letter search, which was single-target search while holding a letter in WM (d) WM-orientation search, and (e) WM-dot-pattern search.

Results

The primary purpose of Experiment 2 was to determine whether the decrement in guidance produced by a color in WM that was found in Experiment 1 generalizes to WM tasks with non-color items. We compare single-target search with search while holding an item in WM (a color, a letter, an oriented line or a dot pattern). The analyses are designed to explore whether a WM-item causes a cost in search, relative to the single-target baseline, only when it has the same feature dimension as the search target. We also compare differences in the unguided fixation rate (*u*), selectivity (*s*) and the target representation (*t*) to help determine the source of any cost for a WM-color in search relative to holding other types of items in WM.

As before, for completeness we start by reporting analyses of search error rates and RTs. The same data trimming and analysis procedures were used as in Experiment 1.

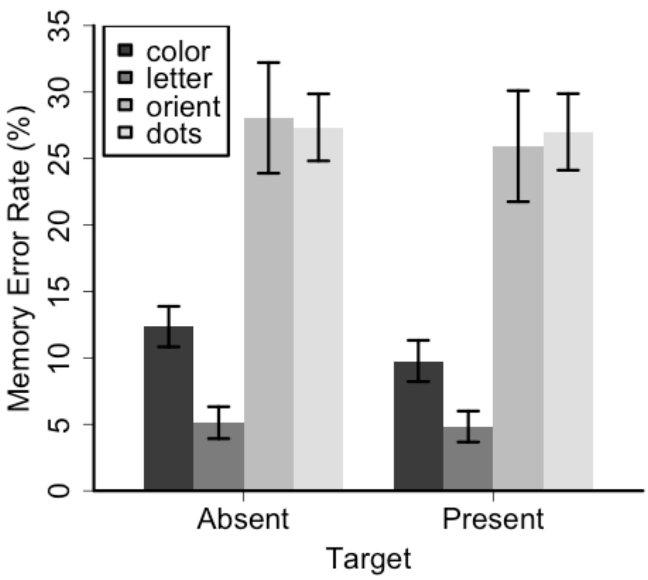

Figure 15. Error rates for reporting the working memory item across the WM-color search condition from Experiment 1 and the three new WM search conditions in Experiment 2. Error bars represent one standard error.

Search Error Rates and RTs.

Error rates in the WM tasks are presented in Figure 15. For the letter and orientation WM-items, as with color, 'correct' was defined as fixating the object within one item either side of the WM-item in stimulus space[11]. For the dot pattern WM-item, there were only two response options, and only one was correct. Accepting the different definitions of 'correct' across the conditions, Figure 15 shows that color is at an intermediate level of difficulty. Given the differences in performance on the memory tasks, any differences in search between WM-color and the other WM conditions cannot be attributed to the overall load placed on WM.

[11] Error rates when only the precise WM-item was considered correct were 13% for letters and 61% for orientation.

As before, search error rates and RTs were each analyzed in separate ANOVAs with factors of Search-condition (single-target, WM-color, WM-letter, WM-orientation, WM-dot-pattern) and Target-presence (target-present, target-absent). Search-condition differs in the levels used for the previous analyses (five levels as opposed to two), but remained a between-participants factor, and, as before, Target-presence was a within-participants factor. Figures 16 and 17 present the data.

Search error rates. There was no effect of Search-condition on error rates and no significant interaction, both $F(4,75) < 1.68, p > .16, \eta_p^2 < .09$. There were more errors on target-present trials than target-absent trials, $F(1,75) = 37.10, p < .001, \eta_p^2 = .33$.

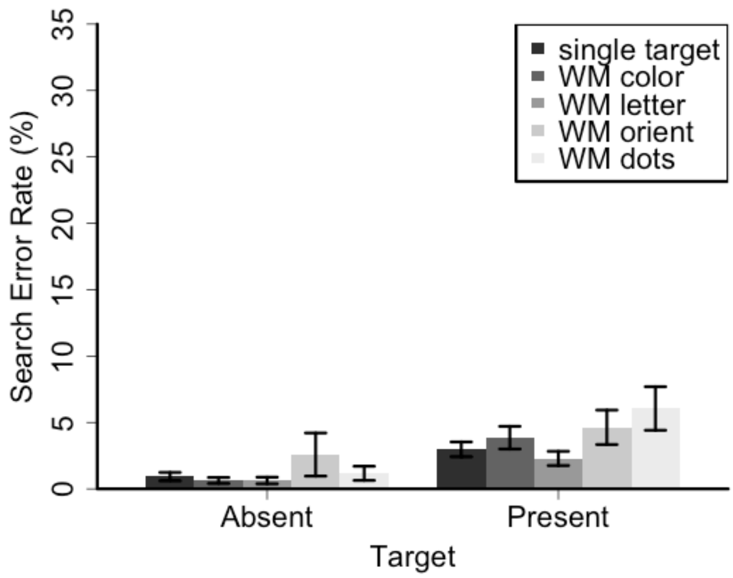

Figure 16. Error rates for the search task, including the single-target condition from Stroud et al. (2012) and the WM-color search condition from Experiment 1. Error bars represent one standard error.

Response times. RT was dependent on Search-condition, $F(4,75) = 8.00$, $p < .001$, $\eta_p^2 = .30$. RT was slower on target-absent trials than target-present trials, $F(1,75) = 62.34$, $p < .001$, $\eta_p^2 = .45$. The interaction was also significant, $F(4,75) = 3.29$, $p = .02$, $\eta_p^2 = .15$.

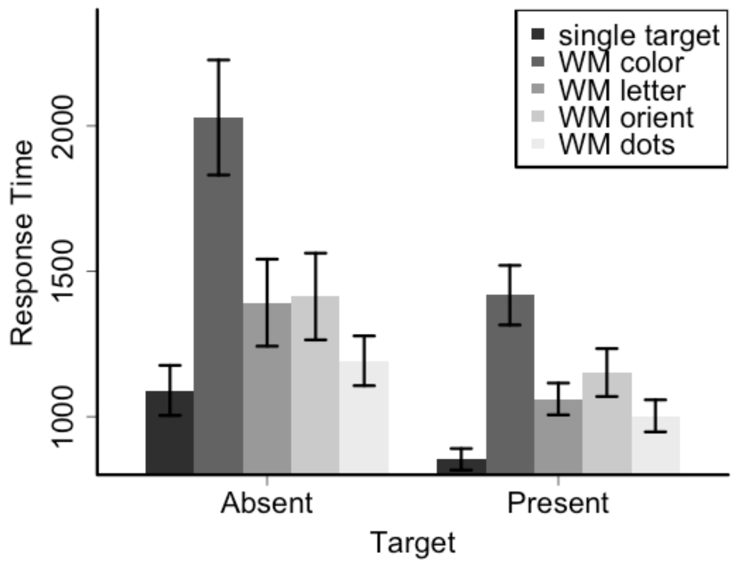

Figure 17. Response times in the search task, including the single-target condition from Stroud et al. (2012) and the WM-color search condition from Experiment 1. Error bars represent one standard error.

The numerical ordering by Search-condition from fastest to slowest is single-target, WM-dot-pattern, WM-letter, WM-orientation, WM-color, and this ordering held across absent and present responses. The effect of condition was more striking on absent than present trials (see Figure 17).

Guidance.

As in Experiment 1, search guidance was assessed firstly by analysing the fixation rates as a function of Color-step, and secondly by analysing parameter estimates for the modeled fixation rates. We found that guidance was unaffected by non-color items in WM and therefore did not conduct any further analyses.

Fixation rates. The main ANOVA for the fixation rates comprised the factors of Search-condition (single-target, WM-color, WM-letter, WM-orientation, WM-dot-pattern), Target-presence, and Color-step (0 to 8).

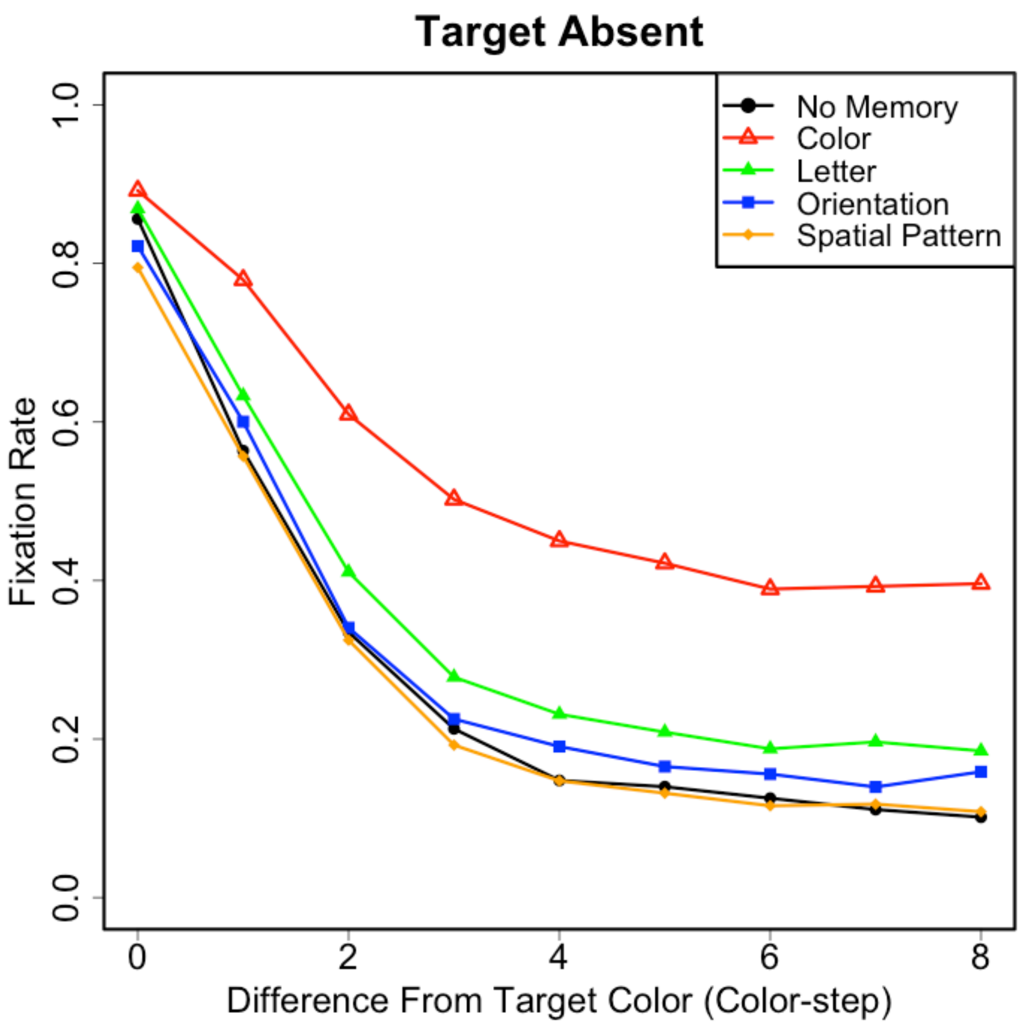

Figure 18. Rates of fixating each distractor color as a function of its distance from the target color, for each Search-condition (separate lines) for target-absent trials. The condition labelled “No Memory” is the single-target condition (from Stroud et al. (2012). The “Color” condition is WM-color condition from Experiment 1.

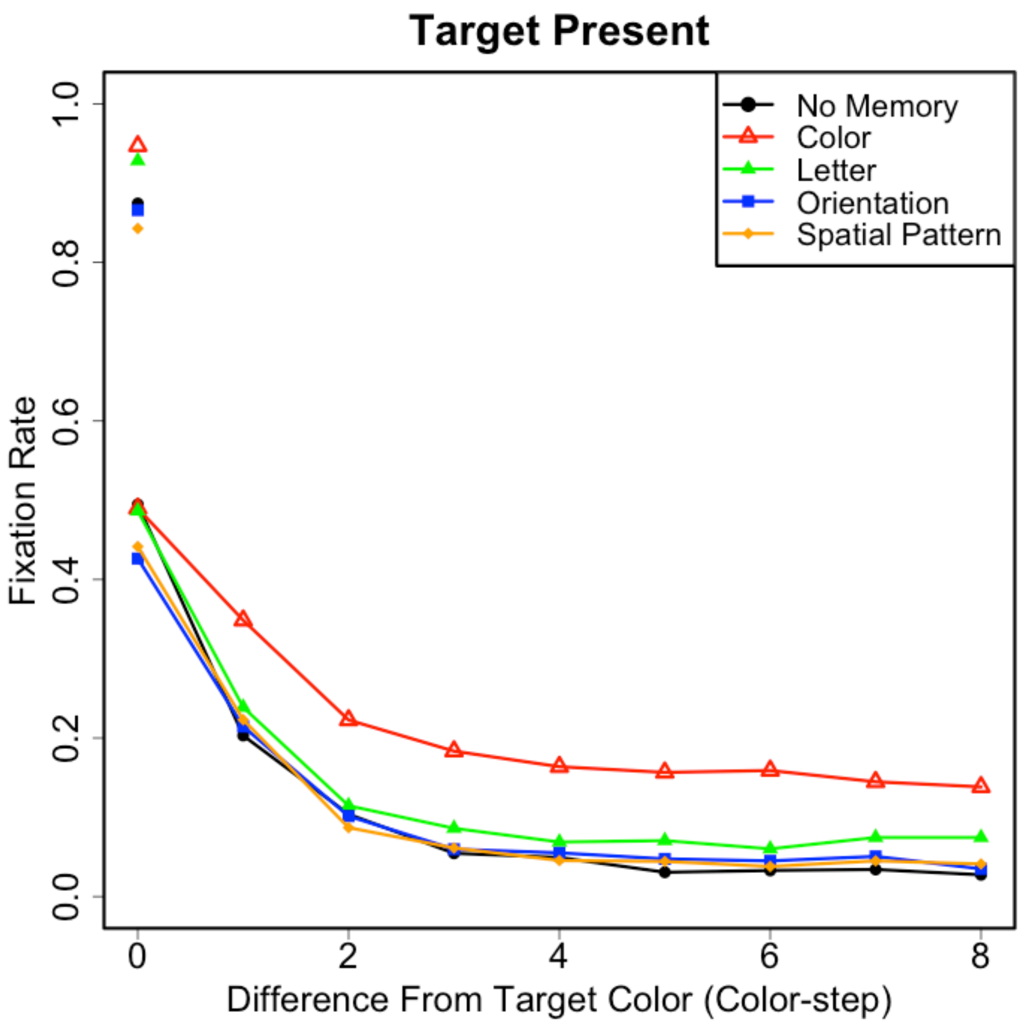

Figure 19. Fixation rates for the target-present trials of Experiment 2. As in Figure 9, the points on the lines represent distractors (L’s), with Color-step = 0 representing the target color, while the unconnected points at the top left of the graph represent targets (T’s).

Fixation rates were dependent on Search-condition, $F(4,75) = 8.44$, $p < .001$, $\eta_P^2 = .31$, were higher on target-absent than target-present trials, $F(1,75) = 341.35$, $p < .001$, $\eta_P^2 = .82$, and decreased monotonically as Color-step increased, $F(8,600) = 513.19$, $p < .001$, $\eta_P^2 = .87$.

The effect of Search-condition was caused by higher fixation rates in the WM-color condition than the other four conditions, evidenced by no effect of Search-condition when analysing the other four conditions only (single-target, WM-letter, WM-orientation, WM-dot-pattern), $F(3,60) = 1.01$, $p = .39$, $\eta_P^2 = .05$ (see Figures 18 and 19). The lack of effect suggests that holding an item in WM that is irrelevant to the search task does not affect guidance compared with conducting the search task alone.

Search-condition interacted with Target-presence, $F(4,75) = 5.54$, $p < .001$, $\eta_P^2 = .23$, with a stronger effect on target-present than target-absent trials, $F(1,75) = 411.18$, $p < .001$, $\eta_P^2 = .33$ and $F(1,75) = 421.60$, $p < .001$, $\eta_P^2 = .29$, respectively. There was a trend towards Search-condition interacting with Color-step, $F(8.9,168.7) = 1.68$, $p = .10$, $\eta_p^2 = .08$[12], and no significant three-way interaction, $F(13.1,246.5) = 1.34$, $p = .19$, $\eta_p^2 = .07$.

Model parameters. The analysis of the fixation rates again reveals the reduction in guidance in WM-color search compared with single-target search, as from Experiment 1, and compared with the searches while holding a non-color item in WM. However, it reveals no reduction in guidance for when holding a non-color item in WM. In order to characterize the different aspects of search guidance, the unguided fixation rate (*u*), selectivity (*s*), and target representation (*t*), were estimated from the fixation data for Color-steps 0 to 8. The parameter values are presented in Figures 20 and 21. The parameter values were M = 0.12, SD = 0.16 for *u;* M = 1.57, SD = 1.19 for *s;* M = 0.75, SD = 1.33 for *t*. RMSE values for the model fit were M = 0.084, SD = 0.045. Each parameter was subjected to a separate ANOVA comprising factors of Search-condition (single-target, WM-color, WM-letter, WM-orientation, WM-dot-pattern) and Target-presence.

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[12] This trend was slightly stronger in the analysis that included trials with an error on the WM task, $F(8.9,167.8) = 1.85$, $p = .06$, $\eta_p^2 = .09$.

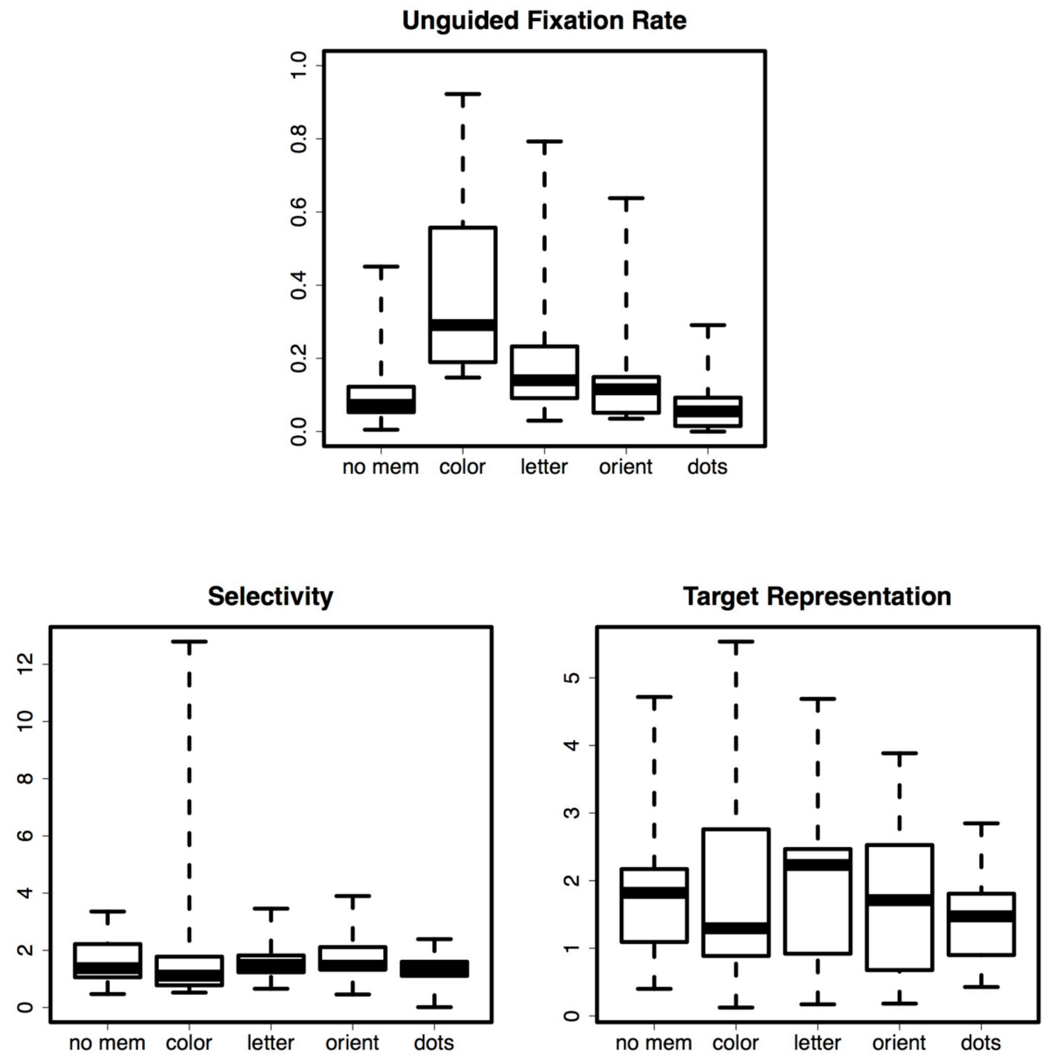


Figure 20: Box and whisker plots showing the Unguided fixation rate (*u*), Selectivity (*s*), and Target representation (*t*) parameters for the target-absent trials in single-target search and in WM-search with four different types of memory items in Experiment 2.

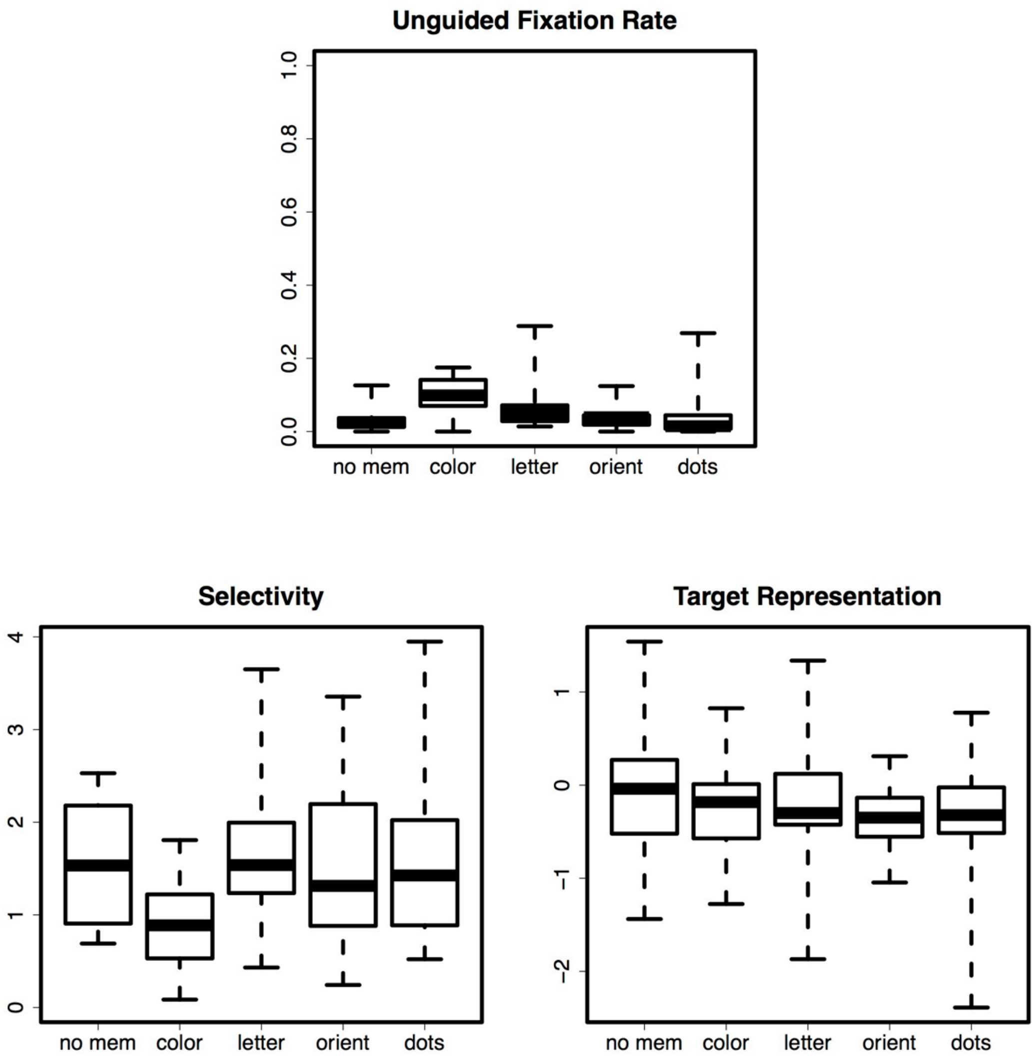


Figure 21: Box and whisker plots showing the Unguided fixation rate (*u*), Selectivity (*s*), and Target representation (*t*) parameters for the target-present trials in single-target search and in WM-search with four different types of memory items in Experiment 2.

Unguided fixation rate (u). There was a main effect of Search-condition, $F(4,75) = 9.16$, $p < .001$, $\eta_p^2 = .33$, reflecting a larger *u* in the WM-color condition compared with the other conditions. A further ANOVA without the WM-color condition showed no effect of Search-condition, $F(3,60) = 2.09$, $p = .11$, $\eta_p^2 = 10$, supporting this conclusion. In the main ANOVA, *u* was higher on target-absent trials than target-present trials, $F(1,75) = 57.28$, $p <$

.001, $\eta_p^2 = .43$. The interaction was significant, $F(4,75) = 6.18$, $p < .001$, $\eta_p^2 = .25$, although ANOVAs split by Target-presence revealed that the effect of Search-condition remained on both target-present and target-absent trials ($F(4,75) = 5.34$, $p = .001$, $\eta^2 = .22$. and $F(4,75) = 8.30$, $p < .001$, $\eta^2 = .31$, respectively), and disappeared on both when WM-color was removed from the analysis (both $F < 2.25$, $p > .09$, $\eta^2 < .11$).

Selectivity (s). There were no significant effects or interaction for *s* (all $F < 1.64$, $p > .17$, $\eta_p^2 < .09$).

Target representation (t). There was no effect of Search-condition, nor a significant interaction (both $F < 1$, $\eta_p^2 < .03$), but, as in Experiment 1, *t* was again larger on target-absent than target-present trials, $F(1,75) = 307.53$, $p < .001$, $\eta_p^2 = .80$.

Summary and Discussion

In contrast to the null effects of holding an oriented oval, letter or dot pattern in working memory (WM), holding a color in WM during visual search for a colored target caused an increase in RTs on target-absent and target-present trials, and an increase in the unguided fixation rate of all distractors. Color selectivity and the precision and breadth of the search-target representation were unaffected by holding a color in WM. The elevated unguided fixation rate, relative to that found in single-target search and non-color WM-item searches, has shown that holding a color in WM affects overall color guidance, but that holding a non-color item in WM does not.

Experiment 3: Does An Item in Working Memory Diminish Search Performance and Guidance in the Same Manner As Adding An Additional Search Target (Varying Target)?

Experiment 3 used the same experimental procedure as used in Experiment 1 except that the search targets varied from trial to trial. As before, WM-color search was compared with both dual-target search and single-target search. The goal of Experiment 3 was to explore how color in WM might influence guidance when the search targets vary across trials such that they too must rely completely on WM.

Method

Except for the variation in target colors across trials, the methods were as described in Experiment 1, and again comprised single-target search, dual-target search and WM-color search conditions.

Participants.

Forty-eight University of Massachusetts undergraduate students participated in the three conditions (single-target search, dual-target search and WM-color search), with 16 participants in each. The sample consisted of 40 females and 8 males with ages range 17 – 37 years (M = 20.33; SD = 2.86). All participants self-reported normal or corrected-to-normal vision and were tested for normal color vision (Ishihara, 1917). Some of the participants had prior experience with visual search tasks, but were not part of any of the conditions in Experiments 1 and 2, and none had prior experience with the stimuli.

Apparatus, Stimuli and Procedure.

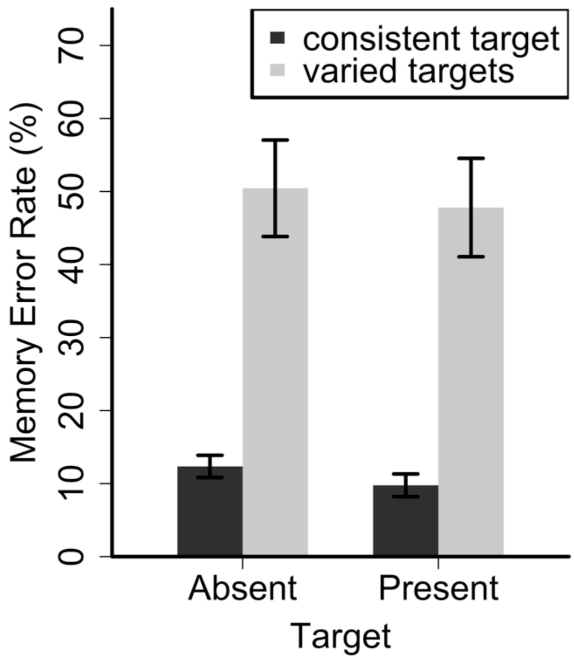
The apparatus, stimuli and procedure were identical to Experiment 1 except that the color of the search target(s) varied from trial to trial. Search condition varied across three groups of 16 participants each: (a) single-target search, (b) dual-target search, and (c) WM-color search. In the WM-color search condition, each WM-color was paired once with each search-target-color, such that there was one trial for each WM-color and search-target-color combination (16 WM-colors × 16 search-target-colors = 256 trials).

Results

All the analyses were conducted similarly to those for Experiment 1. We firstly review the WM-task error rates, then present the analyses of search error rates and RTs, and finally present the analyses of guidance measures comprising fixation rates and guidance parameters.

Figure 22 includes the error rates on the WM-color task along with the consistent-target WM-task error rates from Experiment 1. When the WM demands of the search task are increased by varying the target color from trial to trial, performance drops considerably for the WM-task.

As in Experiment 1, RT and eye-movement data were included in the analyses only from those trials in which the search task and the WM-task responses were deemed correct[13]. Search error rates were calculated over all trials, regardless of WM-task errors.



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[13] Analyses were also conducted with working memory task errors remaining, and results showed very similar patterns. Differences are described in footnotes.

Figure 22: Error rates in reporting the working-memory color in the WM-color search condition. Error bars represent one standard error.

Search error rate and response times.

As for Experiment 1, Search error rates and RTs were each analyzed in separate ANOVAs. There were two sets of comparisons, the first comparing single-target with WM-color and the second comparing dual-target search with WM-color. The ANOVAs comprised factors of Search-condition (single-target vs. WM-color or dual-target vs. WM-color) and Target-presence (target-present, target-absent). Search-condition was a between-participants factor and Target-presence was a within-participants factor.

Search error rates. WM-color search resulted in more search errors compared with single-target, but not dual-target search, $F(1,30) = 5.59$, $p = .03$, $\eta_p^2 = .16$ and $F < 1$, $\eta_p^2 = .01$ respectively (see Figure 23). The effect of Target-presence and the interaction did not reach significance when comparing WM-color search with either single- or dual-target search, all $F < 1.54$, $p > .22$, $\eta_p^2 < .05$.

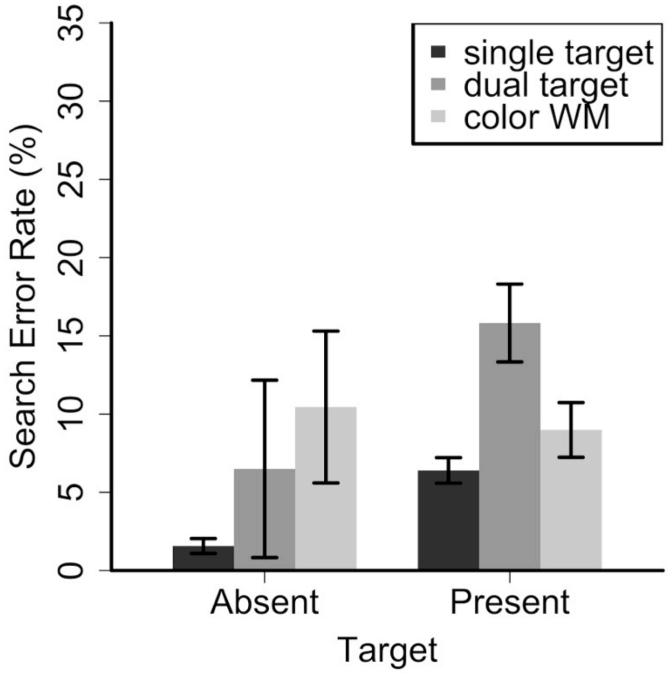

Figure 23: Error rates in the three search tasks with varying targets for Experiment 3. Error bars represent one standard error.

Response times. RTs were slower in WM-color search than in single-target and faster in WM-color search than in dual-target search, $F(1,30) = 7.33, p = .01, \eta_p^2 = .20$ and $F(1,30) = 19.84, p < .001, \eta_p^2 = .40$ respectively (see Figure 24). RTs were slower on target-absent than target-present trials when comparing WM-search with single-target and with dual-target search, $F(1,30) = 32.84, p < .001, \eta_p^2 = .52$ and $F(1,30) = 95.63, p < .001, \eta_p^2 = .76$ respectively.

The interaction between Search condition and Target-presence was not significant when comparing WM-search with single-target search but was when comparing WM-search with dual-target search, $F < 1, \eta_p^2 = .01$ and $F(1,30) = 21.18, p < .001, \eta_p^2 = .41$ respectively. Despite the interaction, RTs remained faster in WM-color search than in dual-target search on both target-present and target-absent trials, $t(30) = 3.13, p = .004, d = 1.11$ and $t(30) = 4.93, p < .001, d = 1.74$ respectively.

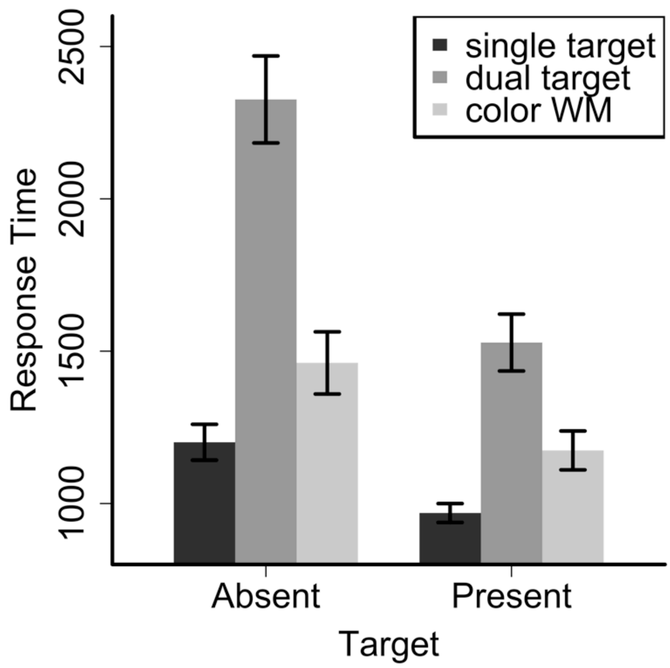

Figure 24: Response times in the three search tasks with varying targets for Experiment 3. Error bars represent one standard error.

Guidance.

As before, search guidance was examined firstly by analyzing fixation rates as a function of Color-step of the distractor from the target color, and secondly by analyzing the estimated guidance parameters from the modeled fixation rates.

Given that these first two analyses revealed differences in color guidance across search conditions, we also conducted a third analysis aimed at exploring what is attracting fixations in the WM-color search.

Fixation rates. The fixation rates are shown in Figures 25 and 26. Analyses were the same as in Experiment 1. Specifically, for comparison with single-target search, the ANOVA for the fixation rates comprised the factors of Search-condition (single-target, WM-color), Target-presence, and Color-step (0 to 8). For comparison with dual-target search, the ANOVA for the fixation rates comprised the factors of Search-condition (dual-target, WM-color), Target-presence, and Color-step (0 to 6). In the comparison with dual-target search, fixation rates to the three colors that fall between the two targets were not included in the analysis. Fixations to these colors comprised 24% of fixations made in the target-absent trials, and 25% of the fixations in the target-present trials.

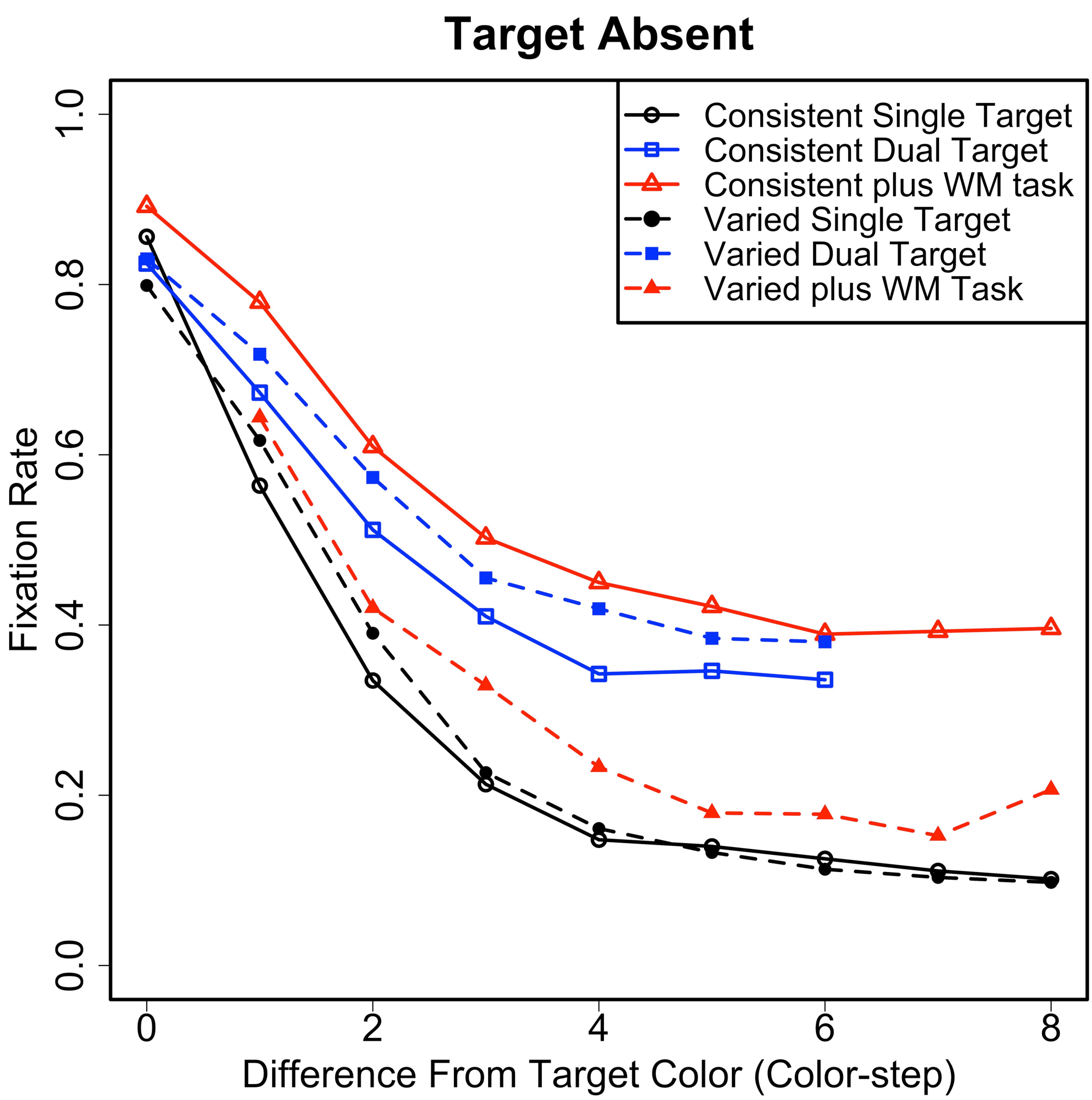

Figure 25: Fixation rates on target-absent trials for each color as a function of its difference from the target color. The difference in color is measured by the number of steps between the

two colors in the stimulus color space. Each line represents a different search condition: Single-target, dual-target, and single-target search with the WM task. In the dual-target search, the color difference is measured between each color and the more similar target color. Data from the corresponding consistent-target conditions of Experiment 1 are included for comparison.

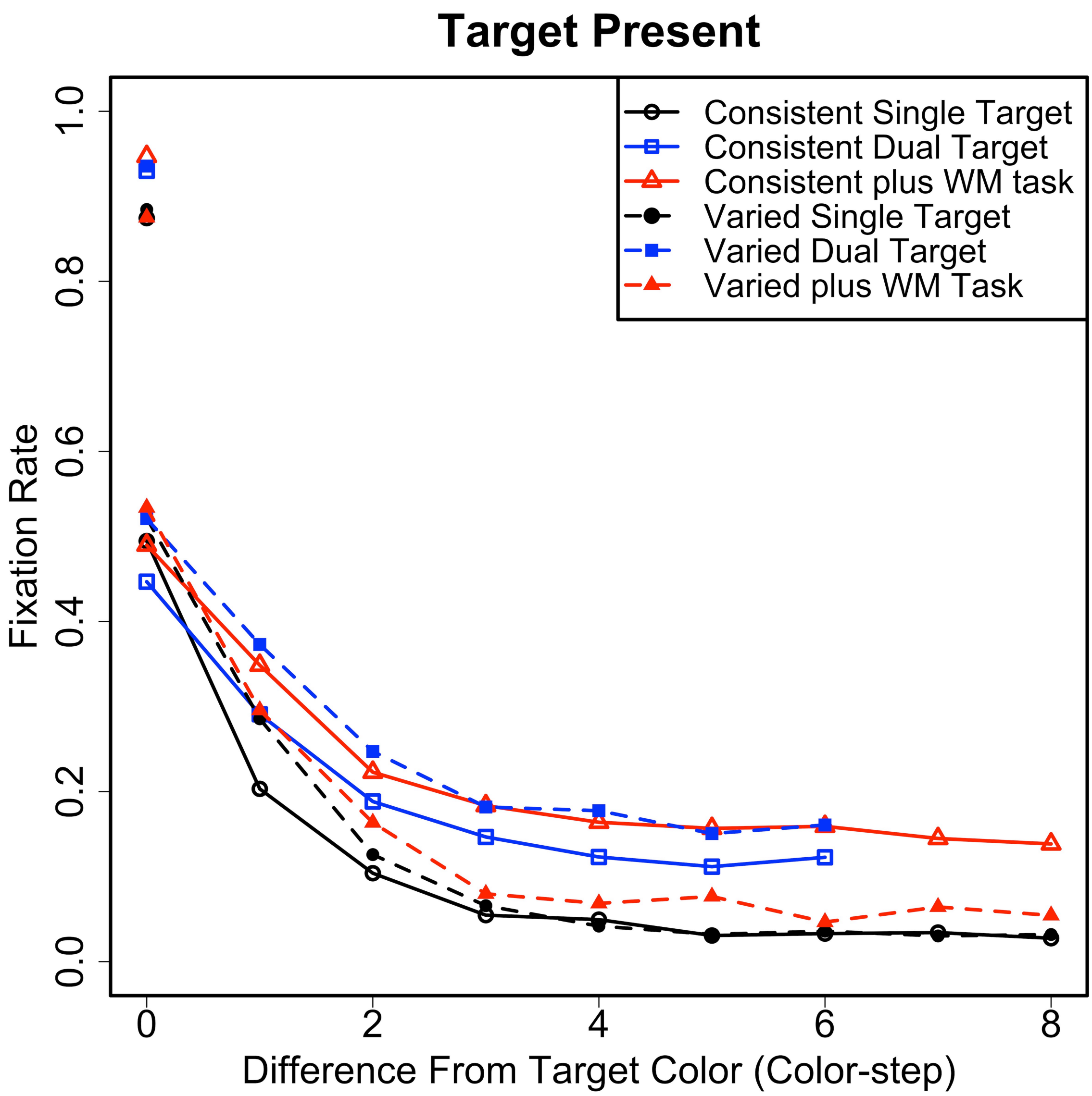

Figure 26: Fixation rates for the target-present trials of Experiment 3, along with the corresponding fixation rates from Experiment 1. The target color is represented at the left of the graph, where Color-step = 0. The points on the lines represent distractors (Ls) with the target color, while the unconnected points at the top left of the graph represent targets (Ts). Each line represents a different search condition: Single-target, dual-target, and single-target search with the WM task.

Fixation rates were higher in WM-color search than single-target search, $F(1,30) = 5.00$, $p = .03$, $\eta_p^2 = .14$, and on target-absent than target-present trials, $F(1,30) = 326.32$, $p < .001$, $\eta_p^2 = .92$, and decreased monotonically with Color-step until Color-step 7 (7 = .094, 8 = .088, 9 = .098), $F(2.2,65.9) = 385.59$, $p < .001$, $\eta_p^2 = .93$. There were no significant interactions with Search-condition, all $F < 2.48$, $p > .12$, $\eta_p^2 < .08$.

Fixation rates were higher in dual-target search than WM-color search, $F(1,30) = 8.82$, $p = .006$, $\eta_p^2 = .23$, and on target-absent than target-present trials, $F(1,30) = 392.80$, $p <$

.001, $\eta_p^2 = .93$, and decreased monotonically with Color-step, $F(2.0,60.3) = 274.43$, $p < .001$, $\eta_p^2 = .90$.

The two two-way interactions involving Search-condition were significant, but the three-way interaction was not, $F(2.0,60.3) = 1.26$, $p = .29$, $\eta_p^2 = .04$[14]. With regard to the Search-condition × Color-step interaction, $F(2.0,59.4) = 5.31$, $p = .008$, $\eta_p^2 = .15$, the effect of Search-condition emerged as the distance from the target-color(s) increased (at Color-step 0, $F < 1$, $\eta_p^2 = .003$; at Color-step 6, $F(1,30) = 13.69$, $p = .001$, $\eta_p^2 = .31$). In other words, the increased fixation rate in the dual-target search was driven by colors different from the target color. The Search-condition × Target-presence interaction, $F(1,30) = 6.33$, $p = .02$, $\eta_p^2 = .17$, reflected that the effect of Search-condition was larger for target-absent, $F(1,30) = 9.60$, $p = .004$, $\eta_p^2 = .24$, than target-present trials, $F(1,30) = 6.34$, $p = .02$, $\eta_p^2 = .17$.

Model parameters. As in Experiment 1, the unguided fixation rate (*u*), selectivity (*s*) and target representation (*t*) were estimated using a sigmoidal function on the fixation data

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[14] In the analysis with WM-task error trials included, the interaction showed a trend towards significance, $F(3.0,90.2) = 2.57$, $p = .06$, $\eta_p^2 = .08$.

from Color-steps 0 to 6. The fixation data for one participant in WM-color search did not include any fixations to target-color distractors on target-absent trials, so the function for that participant was not modeled and therefore not included in the analysis[15]. The parameter values are presented in Figures 27 and 28. Parameter values were M = 0.13, SD = 0.15 for *u;* M = 1.07, SD = 0.46 for *s;* M = 0.67, SD = 0.92 for *t*. RMSE values for the model fit were M = 0.07, SD = 0.04. Values were subjected to separate ANOVAs comprising factors of Search-condition (single-target vs. WM-color or dual-target vs. WM-color) and Target-presence.

The unguided fixation rate, *u*, was higher in WM-color search than single-target search, $F(1,30) = 4.38$, $p = .05$, $\eta_p^2 = .13$, and was higher in dual-target search than WM-color search, $F(1,30) = 10.81$, $p = .003$, $\eta_p^2 = .27$. For both analyses, *u* was higher on target-absent than target-present trials, both $F > 30.92$, $p < .001$, $\eta_p^2 > .51$. The interaction was significant in the comparison with dual-target search only, $F(1,30) = 4.76$, $p = .04$, $\eta_p^2 = .14$,

[15] In the analysis with the WM-task error trials included, the participant was retained.

but *u* remained higher in dual-target search than WM-color search on both target-present and target-absent trials, both $t(29) > 2.21$, $p < .04$, $d > 0.79$.[16]

Selectivity (*s*) was higher in WM-color search than dual-target search, $F(1,30) = 5.21$, $p = .03$, $\eta_P^2 = .15$[17]. There were no other significant effects or interactions for *s* across either of the analyses, all $Fs < 1$, $p > .53$, $\eta_P^2 < .02$.

For target representation (*t*), neither analysis revealed an effect of or interaction with Search-condition, all $Fs < 2.08$, $p > .15$, $\eta_P^2 < .07$. The only significant findings were as follows. In both comparisons, *t* was larger on target-absent than target-present trials, both $Fs > 82.24$, $p < .001$, $\eta_P^2 > .73$. As in Experiment 1, these differences across Target-presence are likely to be driven by the higher number of fixations on target-absent trials.

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[16] In the analysis with the WM-task error trials included, the interaction was also significant in the comparison with single-target search, $F(1,30) = 4.12$, $p = .05$, $\eta_P^2 = .12$

[17] In the analysis with the WM-task error trials included, this effect only exhibited a trend towards significance, $F(1,30) = 3.32$, $p = .078$, $\eta_P^2 = .10$

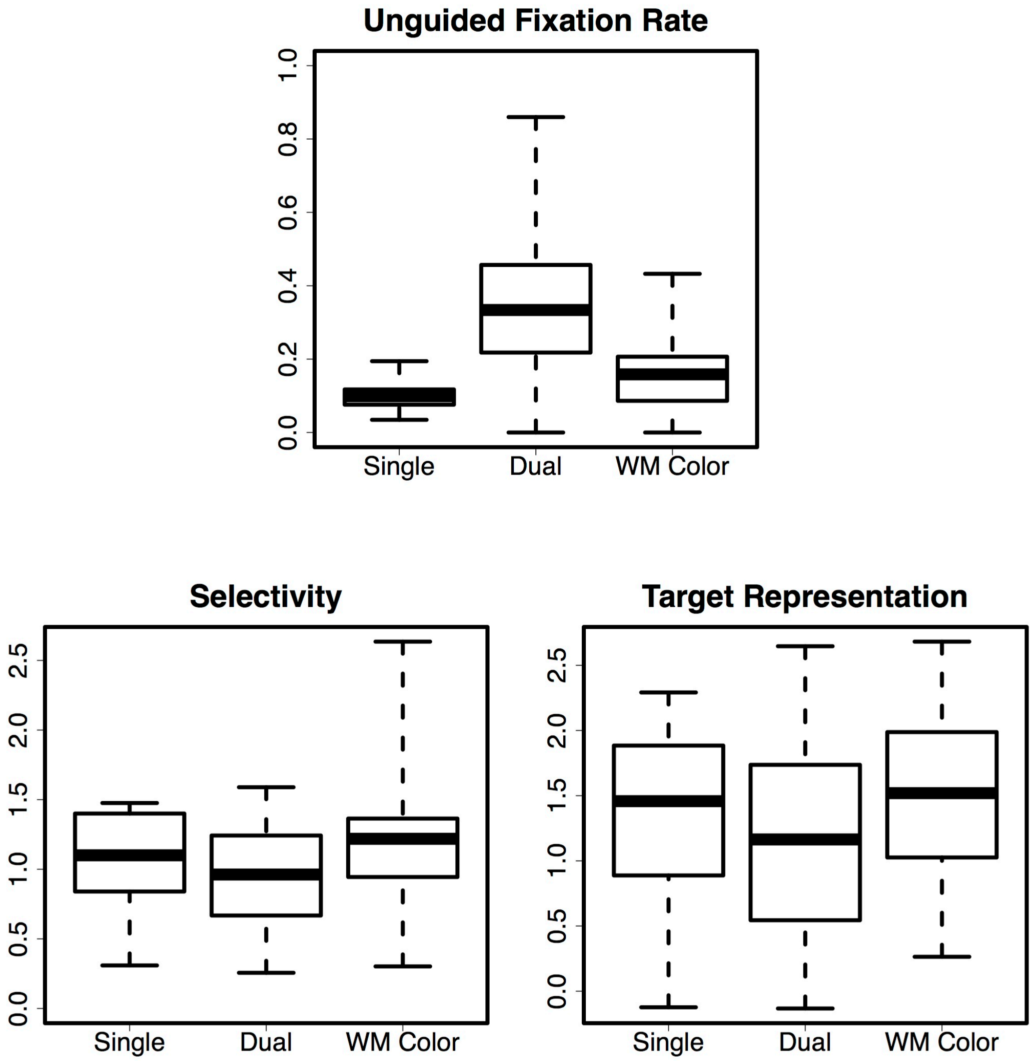

Figure 27: Box and whisker plots showing the Unguided fixation rate (*u*), Selectivity (*s*), and Target representation (*t*) for the target-absent trials in single-target search, dual-target search and WM-color search in Experiment 3. The horizontal black band in the middle of each box indicates the median, and the top and bottom of each box mark the first and third quartiles. The ends of the whiskers indicate the extreme values.

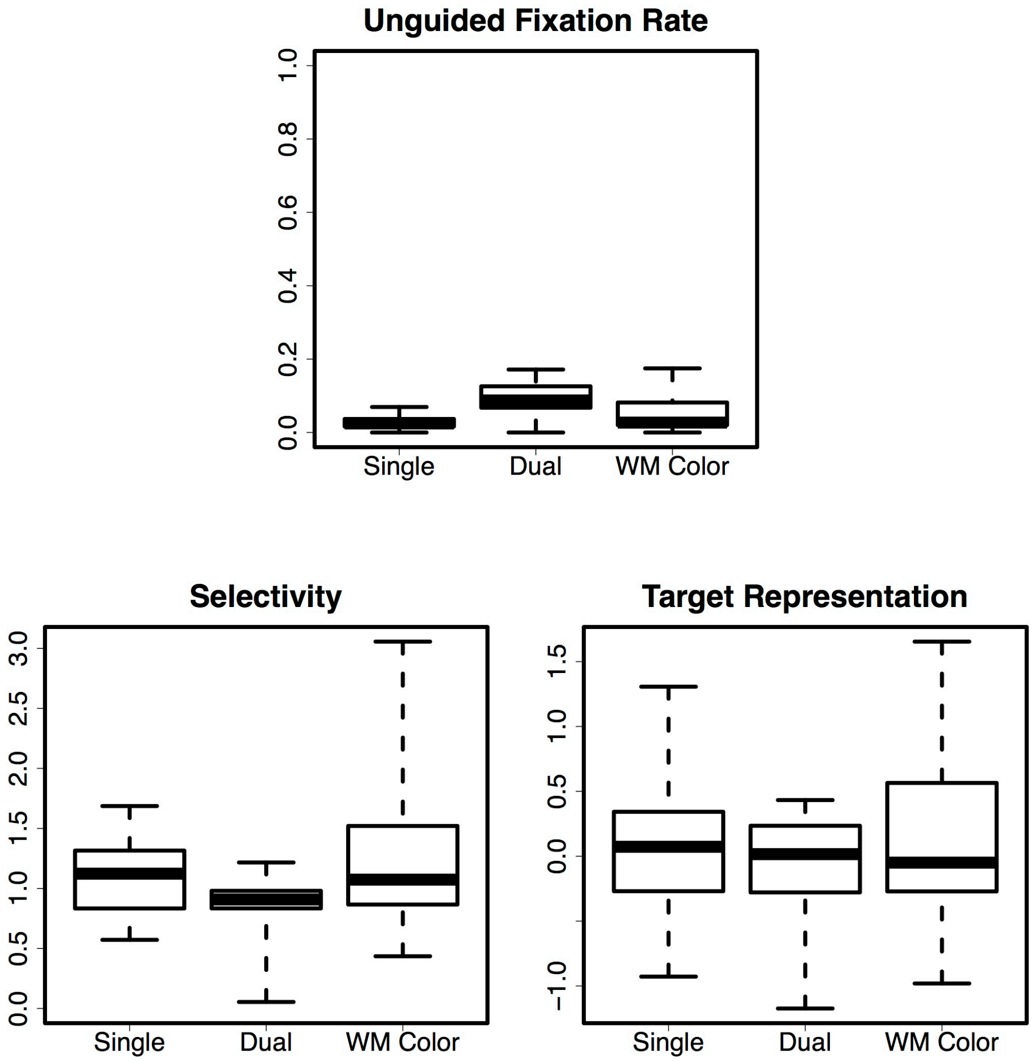

Figure 28: Box and whisker plots showing the Unguided fixation rate (*u*), Selectivity (*s*), and Target representation (*t*) parameters for the target-present trials in single-target search, dual-target search and WM-color search in Experiment 3.

Memory Item Attentional Capture. As in Experiment 1, we conducted a third analysis on the fixation rate data, which was exploratory. We tested whether distractors that match the color held in WM have higher fixation rates than distractors that are dissimilar to the color in WM. In short, there was minimal evidence that the WM-color attracted fixations. As before, the data were from the WM-color search task only, and were split according to Memory-color-step. However, in the current WM-search condition, there were high numbers of errors in search and on the WM task, resulting in a high number of missing values, so we do not present the data in the main body of the text (see Appendix A).

Summary and Discussion

Guidance in WM-color search fell between that in single-target search and that in dual-target search. The fixation rate in WM-color search was higher than in single-target search and lower than in dual-target search, with the differences being based mainly in the unguided fixation rate, with some effect on selectivity, but not the representation of the target.

On the surface, these findings with varying search targets differ from those with consistent targets, given that in Experiment 3 guidance in WM-search was not the same as in dual-target search. However, in Experiment 3, the error rate in the WM task was high (see Figure 22), indicating that the WM-color was often forgotten during the search process. In WM-color search, search error rates were higher with varying targets (Experiment 3, M = .10, Figure 23) than with consistent targets (Experiment 1, M = .02, Figure 6), $F(1,30) = 9.545$, $p = .004$, $\eta_p^2 = .241$. These high error rates suggest that WM-color search with varying targets was very difficult and often not conducted correctly. The implications of the raised error rate with varying relative to consistent search targets are discussed in the General Discussion.

General Discussion

Dual-target Search and Working Memory

These experiments demonstrate that holding a color in working memory causes a general disruption in attentional guidance to a color target, similar to that observed in dual-target search. These results differ from those of previous working memory studies in that they show elevated fixation rates to all distractor colors. This increase in unguided fixations is surprising because it makes search much less efficient. It is consistent with a reduced reliance on color to guide search, with participants perhaps instead using the common target property (T-shape) to identify the target. This shift away from color guidance may also explain the disrupted guidance in dual-target search: Preliminary analysis of data from further experiments using targets defined by color only, so that the T-shape cannot be used to complete the search, show that the dual-target cost in search guidance is much more limited under those conditions (Cave et al., In preparation).

There was some evidence that, in addition to general disruption in guidance when an item is held in working memory, the specific WM-color attracted fixations during search. The fixations to WM-colors are evidence of colors in WM competing for attention. Fixations to the WM-color were apparent when the search target was consistent, but there was minimal evidence of the WM-color attracting attention when the search target varied. This difference may emerge because when a search target is consistent, its representation can be facilitated by (or even transferred to) LTM, thereby freeing up WM for the WM-color. Remembering the WM-color becomes a more pressing task than remembering the search target. With the WM-color active in WM, it can attract fixations. However, when the search target is varying, holding the search target in WM becomes the more pressing task, and WM needs to be applied to the target representation at the expense of the WM-color. Therefore the WM-color does not attract fixations, and there are many more errors in the WM test.

These accounts are in line with previous research identifying differences in the effects of WM items in search for varying and consistent targets. Woodman et al. (2007) found that search for a shape target was less efficient when WM was fully occupied with an array of colors, but only when the search target varied from trial to trial. They concluded that a variable target is stored in WM while a consistent target is not; therefore, the variable target is subject to a cost when WM is already occupied. In contrast, Olivers (2009) looked more specifically at whether attention during search is diverted when a distractor matches an item held in working memory. He only found attention diverted to stimuli matching the contents of WM when the target was consistent from trial to trial. Olivers (2009) discusses why his more specific WM effect is consistent with Woodman et al.'s more general effect, and he argues that when no target needs to be remembered in WM (consistent target), the contents of WM can be active and therefore affect search. A variable target, on the other hand, requires WM, so competing WM content is deprioritized and suppressed (Oh & Kim, 2003; Olivers, 2009). Olivers' results are generally consistent with the new results presented here: the color in working memory only diverts eye movements when the target is consistent (Experiment 1) and not when it varies across trials (Experiment 3). Our new experiments illustrate additional complexities in the interaction between attentional guidance and working memory, as seen in the rise in the fixation rate to *all* colors, not only to the WM-color, especially when the search target was consistent, and in the high error rate in the WM-task when the search target varied.

The Relevance of Working Memory Items for Search

The second aim of this study was to test whether the interference from the item in WM occurs generally, for any type of memory item, or specifically for items with search-relevant properties. When the item in WM was not relevant to the search task, interference only slowed response time on target-present trials, but not on target-absent trials, and there was no evidence of interference in accuracy or search guidance. These results suggest that the interference from non-colors only affects target identification. Guidance in search, specifically the unguided fixation rate, for a consistently colored target was affected only when the item in WM was relevant to the search task; in other words, when it was a color. This difference in results for color versus other items cannot be attributed to difficulty of the WM task because the orientation and spatial pattern tasks led to more errors than the color task. The only effect on search by the non-color items (orientation, letter or spatial pattern) was an increase in RTs when a target was present.

Some previous studies produced a different sort of pattern. They show search interference from WM-items that are unrelated to the visual search task and that do not share relevant properties with items in the search array; for example, using a search target that is defined by shape when colors are to be held in WM (Woodman et al., 2007, for varied targets). Other studies have used a property to be held in WM that is present in the search array (e.g., Dowd & Mitroff, 2013; Downing & Dodds, 2004; Kumar et al., 2009).

The findings are inconsistent across the different types of studies as to whether there is an interference effect of the WM property, demonstrating that relevance to the search task is unlikely to account for differences in results. One particularly interesting study shows that a property of the WM-item interferes with search even when that property does not have to be recalled; specifically, the WM-item's color interfered with search even when only its size needed to be recalled (Hollingworth & Luck, 2009). It is therefore difficult to determine when an irrelevant property of a WM-item interferes with search.

Our findings suggest that while items in WM can cause interference in search, the interference is severe when the WM-item properties are relevant to search, but interference is minimal or absent when the properties in WM are not present in the search display. Relating back to dual-target search, our findings are consistent with findings in which dual-target search for targets defined in different feature dimensions (color and orientation) showed reduced costs in accuracy compared with same-dimension targets and no cost in speed of search (Menneer et al., 2007) (see also Biderman, Biderman, Zivony, & Lamy, 2017; J. M. Wolfe et al., 1990). Our findings also suggest some separation in WM resources for different types of visual information (Vogel, Woodman, & Luck, 2001).

The Relationship Between the Working-Memory Cost and the Dual-Target Cost

As noted above, the increase in the unguided fixation rate that comes from holding a color in WM in Experiment 1 is similar to the increase in unguided fixation rate that comes from adding a second color search target. The similarity in these patterns suggests a possible linkage between the WM cost and the dual-target cost, although the exact nature of that relationship is difficult to work out. It is not always necessary to store all search target representations in WM, as demonstrated by experiments in hybrid search, which have too many potential targets to fit in WM (Cunningham & Wolfe, 2014; J. M. Wolfe, 2012; J. M. Wolfe et al., 2015). Even if we assume that the one or two targets in the experiments presented above are always stored in WM, we cannot explain either the dual-target cost or the WM cost by assuming that storing these two colors fills up all of the storage capacity of WM, because in many other WM tasks, four colors can often be stored successfully, along with additional object properties. Grubert, Carlisle, and Eimer (2016) used a different attentional measure, the N2pc, to show that dual-target search impaired attentional guidance, and that the impairment was independent of the WM load, as measured by the contralateral delay activity (CDA), which again suggests that the impairment in guidance is not simply a result of the WM load. These costs seem to reflect some difficulty in attentional guidance that arises when two colors are held in WM. The experiments presented here show that simply holding an additional color in WM interferes with color search guidance, even when that color is not relevant to search, and thus reveal a new aspect of the link between working memory and attentional control. While the similarities between the dual-target cost and the WM cost suggest that a single explanation may cover both of them, there are some key differences that pose challenges to such a unified account.

The WM cost and the dual-target cost look very similar when the target is consistent from trial to trial: adding either a second target color or a working memory color raises the unguided fixation rate substantially. However, there is a striking difference in the two costs when the target varies; in that case, the unguided fixation rate for WM-search is much lower than for dual-target search. Does this difference mean that the two costs have different explanations?

It may be possible to produce a unified account of the dual-target cost and the WM cost if we make certain assumptions about how WM capacity is used in these tasks. These assumptions would produce behavior that is consistent with the current data. These assumptions are illustrated in Figures 29 and 30, which show the different types of information that must be held in WM during the tasks in Experiment 1 and 3. We assume that the different items in WM are ranked by priority, and that if WM is exceeded, the items with the lowest priority are most likely to be lost from WM. In each diagram, the WM information with the highest priority is at the top, and the lowest priority is at the bottom. The height of each segment represents the amount of WM capacity used by each item, and the total WM load for a task is represented by the total height of the stack of items. Note that, in the search task, we do not know whether shape is prioritized over color, nor whether one dual-target color is prioritized over the other, so the order of search colors and shape in the figures is arbitrary; rather the display simply reflects the amount of resources used by each in WM.

One assumption is that WM must hold information defining the current task. For each of the tasks in Figures 29 and 30, we assume that the highest priority information defines the search task, and that the WM-color has lower priority than the search target during the search task. (Note that participants were not instructed to prioritize one task over the other; we assume that search is given higher priority because participants are actively engaged in that task while passively holding the WM-color in storage.)

In the diagram for single-color varying-target search on the left of Figure 29, this search task definition points to two other items in memory. One is the target color (blue in this example), and the other is the shape (T) that defines the target. Because the target color varies from trial to trial, it must be held in WM. However, the shape is consistent, and so it is stored in or supported by LTM, with a pointer to it in WM, so that the T-shape remains an active component of the current task. A second assumption is that this pointer to LTM occupies much less WM capacity than an item that is stored completely within WM. This assumption is supported by Grubert, Carlisle, and Eimer's (2016) finding of a higher CDA in varying-target search than in consistent-target search.

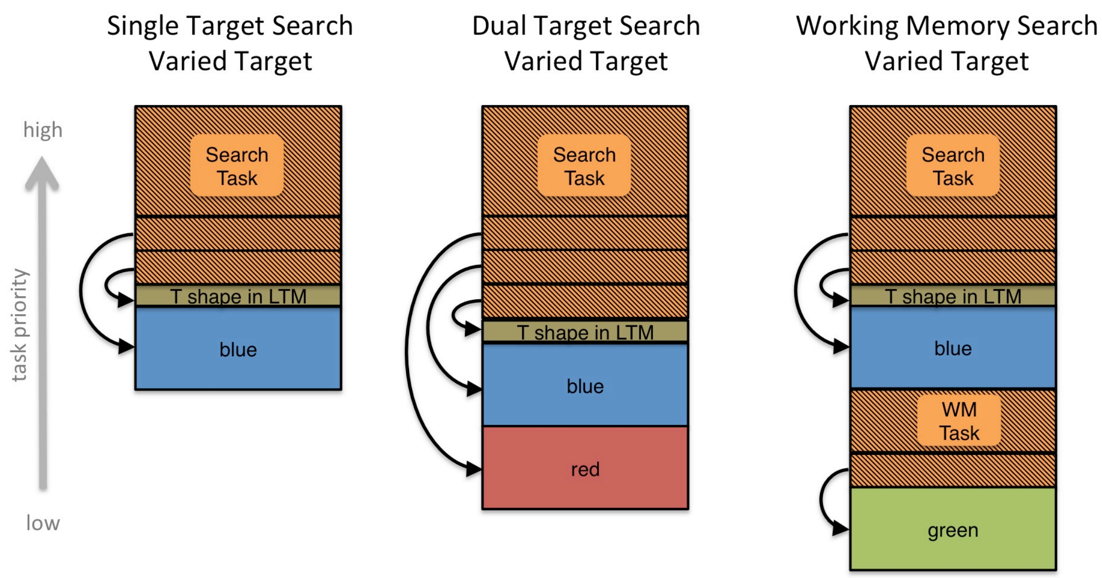

Figure 29: The information that must be held in working memory for the varying-target color search tasks. The boxes labelled "Search Task" and "WM Task" (orange in the color version, shaded pattern in the monochrome version) represent the WM resources devoted to controlling each of these tasks; each of these has pointers to representations within WM of the stimulus colors and shapes that are needed for that task.

The diagram in the middle of Figure 29 illustrates the extra WM capacity that is required for dual-target search. In this case, a second color (*i.e.* red) must be held in WM, and the task definition must be more complex to include the second search target. For WM-search with varying target (on the right side of Figure 29), the WM demands are greater still, because there must be additional information about the separate (WM) task. Figure 30 shows that the WM demands are smaller for all of the experiments with consistent targets, because the colors that were stored in WM in varying-target search are replaced with pointers to target colors in LTM, which take up less WM capacity.

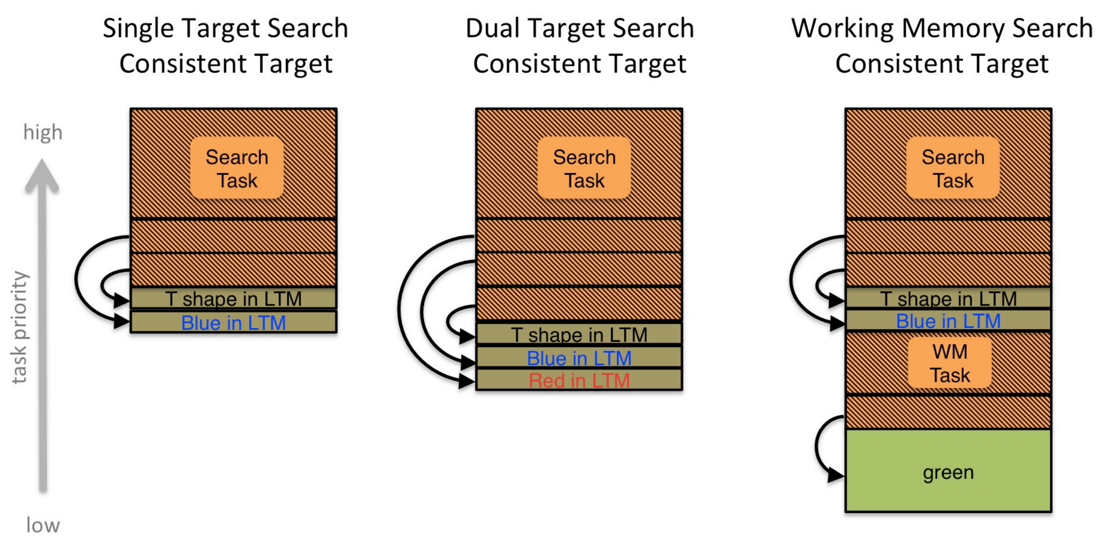

Figure 30: The information that must be held in working memory for the consistent-target color search tasks.

The highest WM demands are in WM-search with varying target, and thus it comes as no surprise that the WM-color is often lost in these searches, since it has lower priority than the search target during the search task. The loss of the WM-color could help to explain why it does not capture attention in the varying-target condition. However, the analysis with the WM error trials removed appears to show that there is no WM-color capture even when the WM-color is still accurately held in WM. Why is it unable to capture attention with varying targets, but it is able to capture attention with consistent targets? In order to capture attention, the WM-color must compete against the search-target-color that is also in WM. Perhaps the very low priority of the WM-color in the varying-target condition makes it less competitive, so that it interferes less with the color search. Also, with a consistent search target, it may be easier for the WM-color to compete against a pointer to an LTM-color than against a color that is stored completely with WM. This last explanation might also apply to findings by Olivers (2009) and by Gunseli, Olivers, and Meeter (2016) that a WM-color only captures attention when the target color is stored in LTM. Thus, the low priority and/or lack of competitiveness for the WM-color in the varying-target condition might explain both the lack of attentional capture and the lower unguided fixation rate in this condition.

The current performance on the search tasks and WM-task are consistent with the assumptions of prioritising the search task over the WM-task described above. Future research could test this account by explicitly manipulating the instructions to participants to prioritize one task over the other. We thank Katherine Moore for this idea.

Relationship to Other Studies on Search and Working Memory

Although this study was motivated mainly to explore the role of WM in dual-target search, the results are also relevant to the role of WM in attentional guidance more generally, which has been the subject of a number of recent experiments. The attentional capture from the passively-held WM-item in Experiment 1 suggests that the color in WM is occasionally used to guide attention. Such influence of the WM-color is not apparent in the experiments by Downing and Dodds (2004), or in the study by Peters et al. (2009) in which the WM-item shows no difference in event-related potentials compared with regular distractors. Rather, our findings are in line with those of Houtkamp and Roelfsema (2006), which suggest that attentional guidance by the WM-item is weak, only interfering with search when the target is absent. In the current data, the accuracy for the WM-search task was higher than in dual-target search when the target was present; the WM-search accuracy only dropped to the level of dual-target search when the target was absent. This reduced (current findings) or minimal (Houtkamp & Roelfsema, 2006) interference when the search target is present is again in line with prioritisation of the search target over the WM-item (Houtkamp & Roelfsema, 2006).

Given the large body of evidence linking attentional guidance and WM (see the Introduction, and for reviews see Olivers et al., 2011; Soto, Hodsoll, Rotshtein, & Humphreys, 2008; Woodman et al., 2013), it is perhaps not surprising that a simultaneous WM task interferes with the visual search process when the search target is consistent and exhibits the same property (i.e., color) as the WM-item. For example, as noted above, Olivers et al. (2011) would predict that we would find WM interference, as we did, for the consistent target because there is not a search target in WM to block the effects of other memory items. Olivers et al. went further, claiming that only one representation in WM could be actively guiding attention at any one time, which would suggest that the dual-target cost is due to target switching. This claim that only a single WM item guided attention was supported by a study by van Moorselaar et al. (2014). Their visual search task showed interference from a color in WM, but that interference disappeared when two colors were held in WM. However, other studies suggest that multiple simultaneous representations are maintained in WM for dual-target search (Barrett & Zobay, 2014; Beck & Hollingworth, 2015; Beck et al., 2012; Grubert & Eimer, 2015, 2016; Irons et al., 2012; Stroud et al., 2012), and the conclusions of van Moorselaar et al. were challenged by Hollingworth and Beck (2016), who were able to find search interference from two WM-colors. Thus, while a search target held in WM with high priority can often block interference from other WM items, it is apparently possible under the right circumstances for two different colors in WM to affect search guidance simultaneously.

The current results show that a search target that is represented at least partly in LTM (Experiment 1) is subject to interference from a color in WM, while a target that is strongly represented in WM (Experiment 3) is not. This pattern is consistent with the claim that only one representation can be active in WM at a time[18], but it is also consistent with the competing claim that two WM items can simultaneously affect attention under the right circumstances. Recent evidence from a similar dual-target search task has suggested that while both targets are simultaneously maintained, one target is weighted over the other at a given moment, but not to the extent that search for one target is completed before search for the other begins (Cave, Menneer, Nomani, Stroud, & Donnelly, 2017). Overall, the evidence

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[18] See the Introduction for references to evidence that one target representation is prioritized as the current focus.

seems to suggest that a target in WM with high enough priority can withstand interference from other WM items. Under this account, however, there is not a hard limit that prevents more than one item from guiding attention.

Another proposal on the role of WM in attentional control comes from Han and Kim (2009), who suggest that WM interference occurs in easy searches when the response time is fast, but that when search is harder, there is time for cognitive control to inhibit selection of the distractor that matches the memory item. From their findings, we might also predict that we would find WM interference, because our participants cannot be certain that the WM-color will never be a target color and so it is not beneficial to inhibit the WM-color.

Olivers et al. (2011) and Han and Kim (2009) might have predicted that attention would be guided to the WM-color in these experiments, but they would probably not have predicted the more profound effect of the WM-color: that it reduces guidance more generally, producing elevated rates of unguided fixations similar to those observed in dual-target search. Importantly, by recording eye movements, this study reveals that search guidance is disrupted generally (even when the color in WM is the same as the target color), and this disruption cannot be explained simply by the WM-color attracting attention. This general deterioration in guidance has not been demonstrated before when search is combined with a WM task; it has only been seen previously in dual-target search.

The Difficulty of Color Discrimination May Change the Use of Working Memory

Our search task differs from many other color search studies in that a large number of different colors were used (16), and discriminating these colors from one another could be difficult. These more difficult discriminations may have led to differences in whether and how WM is employed. For instance, even the consistent target may have required a high level of effort by the searcher to create and maintain the target template, given that it needs to be more precise than in many previous studies that use only a few colors for the search stimuli.

Such maintenance might require an active representation in WM, even when the search-target-color is consistent, and thus prevent the interference from non-color properties (orientation, letter, dot-pattern) held in WM, but not prevent interference from a property within the same feature dimension.

Using Shape Rather Than Color

As alluded to earlier, it is worth noting that although the current task was designed to be a search guided by color, it did allow an unusual alternative approach that is not possible in most experimental search tasks: the target could be identified by searching for a T-shape and ignoring color. When two colors need to be maintained (dual-target search or single-target search plus a color in WM), the results suggest that color is not used to guide search as effectively as in single-target search. In dual-target search and in WM-color search, color guidance might be reduced because the target is defined as a single shape, and not by two colors. It is important to note that the target can be defined solely by shape in all the conditions tested here; there seems to be something about dual-target search and WM-color search that increases the likelihood that targets will be identified only by shape, with no color guidance. Search for a T target would have an extra appeal in dual-target search, because it allows the target representation to consist of a single shape feature that is common to both targets (Menneer et al., 2009; Stroud et al., 2011), avoiding the need to maintain two separate target representations. On these grounds, we might expect that color guidance would be reduced more in dual-target search than in search while holding a color in WM, but our results presented above do not show such a difference. The possibility of abandoning color guidance and using shape will be examined in future work using targets that are defined by color only, and not by shape (Cave et al., In preparation).

Conclusions

Guidance of eye movements to a consistent color target is affected by a color in working memory (WM) as strongly as it is affected in dual-target search for two consistent colored targets. However, with a varying search target, the item in WM appears to be deprioritized, resulting in poor performance on the WM task and less interference with the search task. With both consistent and varied targets, the color held in WM does not hold the same status as a search target, given that it did not attract as many fixations. The reduction in fixations to the WM-color compared with the search-target color suggests that color representations for guiding search and WM tasks are fairly well separated from each other, and the reduction in guidance when the color in WM is the same as the search target indicates that the extra load causes general task interference.

Together these experiments and the earlier experiments in dual-target search demonstrate the different ways in which participants may adjust their performance when they face high demands on visual working memory and attentional guidance. In dual-target search, the difficulty of holding two target representations and using them both to guide attention encourages participants to identify targets by shape rather than color. They can still perform the task this way, but they make many fixations to distractors they could otherwise avoid (Stroud *et al*. 2012). A similar move away from color guidance occurs when the color WM task is added in Experiment 1. However, when the task demands are taken up a notch in the WM condition of Experiment 3 with the search-target color varying from trial to trial, participants shift to a different approach; they deprioritize the WM task, and although they make many errors on the memory task, they are able to guide search fairly accurately. Future experiments might explore how participants decide to use their attention and memory resources in these demanding tasks, and whether they are using these resources as effectively as possible.

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Appendix A

The data for this analysis are from the WM-color search task with varying search targets (from Experiment 3). As in Experiment 1, we tested whether distractors that match the color held in WM have higher fixation rates than distractors that are dissimilar to the color in WM. The data were split according to Memory-color-step. However, in the current WM-search condition, there were high numbers of errors in search and on the WM task, resulting in a high number of missing values. Therefore, the error trials from the WM task and from the search task were not removed from the current analysis in order to allow enough presentations of each distractor color. For three participants, there was one combination of Color-step and Memory-color-step that had no distractors presented, resulting in three missing data points. As in Experiment 1, those participants were excluded from the reported analyses. Analyses were also conducted with a mean-average as a replacement for the missing value, and showed the same patterns except where noted. As before, if colors similar to the memory color attract more fixations, then fixation rates will be higher for low values of Memory-color-step. Figures A1 and A2 present the data.

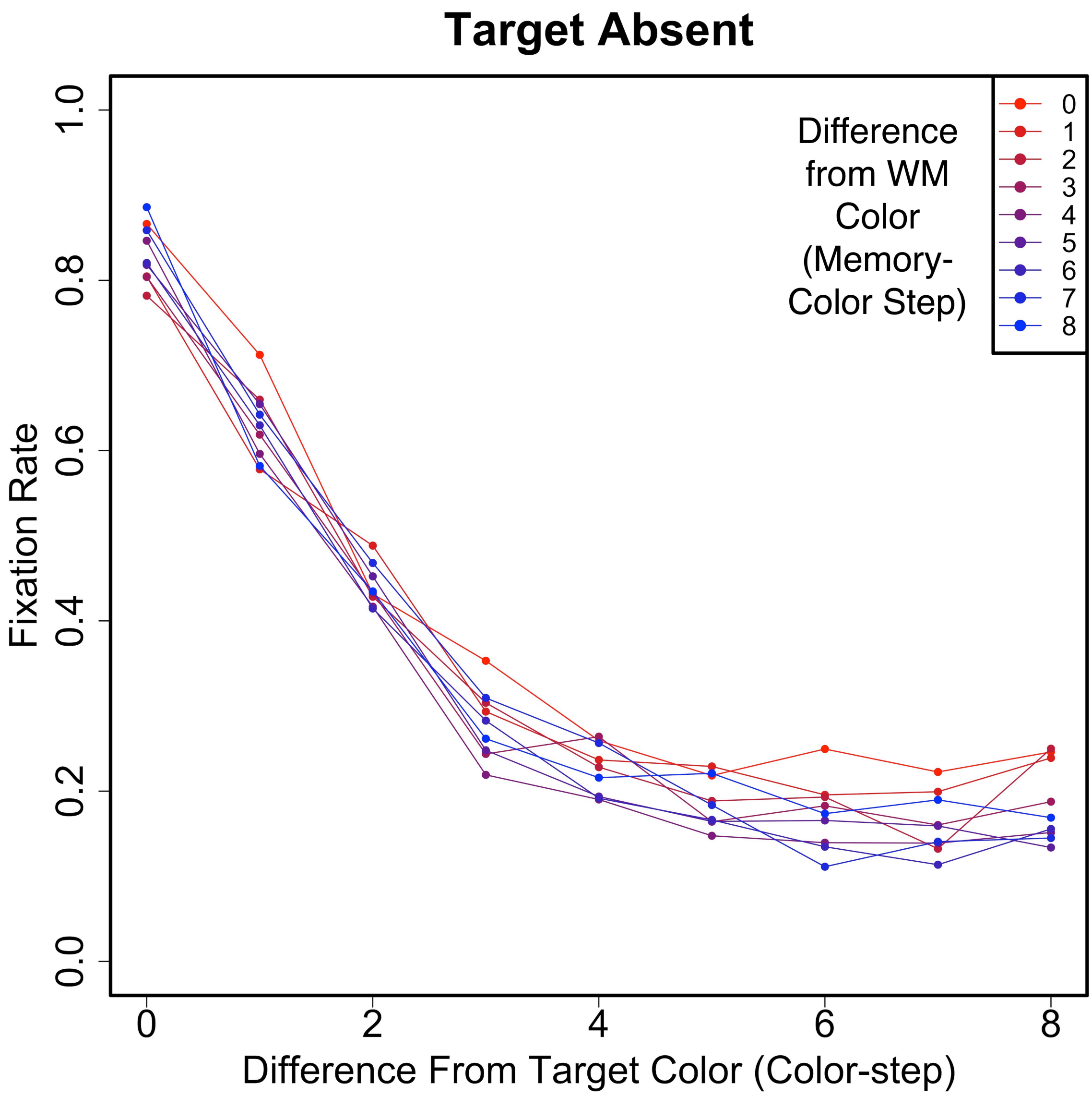

Figure A1: Fixation rates for the target-absent trials in the WM-search condition of Experiment 3, broken down by the similarity of the fixated color to the color held in working memory. The number associated with each line is the number of steps to the memory color (Memory-color-step). Red lines show fixation rates for items identical or similar to the memory color. Blue lines show fixation rates for items very different from the memory color. Error trials are included in the mean values shown in this figure and the next, and also in the appendix analyses, as described in the text.

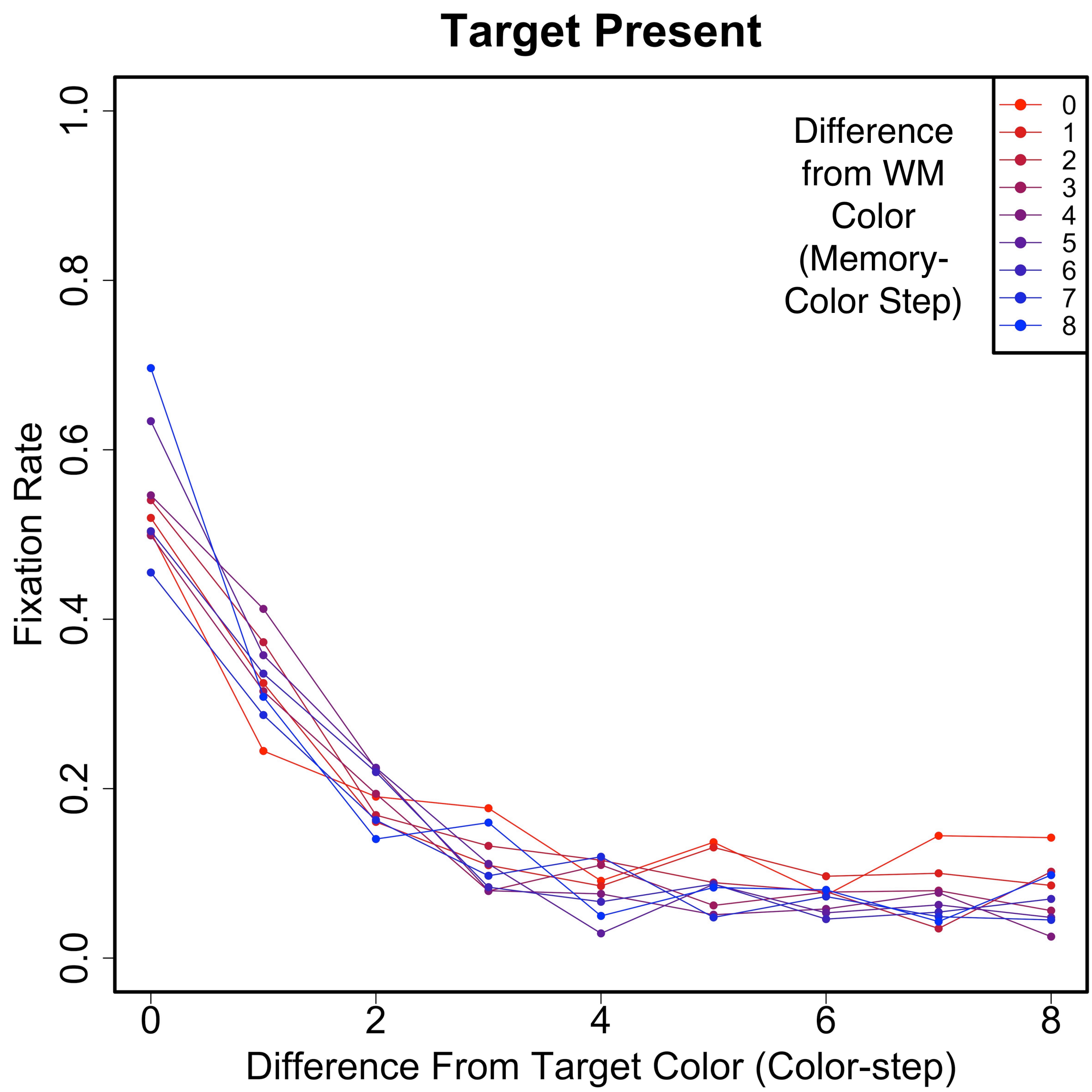

Figure A2: Fixation rates for the target-present trials in the WM-search condition of Experiment 3, broken down by the similarity of the fixated color to the color held in working memory (Memory-color-step). As in the previous graph, similarity to the memory color tends to bring the fixation rate up, especially for items that are not similar to the target color.

Fixation rates were analysed using a Memory-color-step (0 to 8) x Color-step (0 to 8) x Target-presence repeated-measures ANOVA. There was no effect of Memory-color-step, $F(2.7,31.9) = 1.49$, $p = .24$, $\eta_P^2 = .11$[19]. Fixation rates decreased as Color-step increased, $F(2.0,24.2) = 211.58$, $p < .001$, $\eta_P^2 = .95$, and fixation rates were higher on target-absent than target-present trials, $F(1,12) = 52.45$, $p < .001$, $\eta_P^2 = .81$. The Memory-color-step x Target-presence interaction was significant, $F(4.2,50.4) = 2.83$, $p = .03$, $\eta_P^2 = .19$[20]. There were no other significant interactions involving Memory-color-step, both $F < 1.58$, $p > .13$, $\eta_P^2 < .12$.

Given minimal evidence that the WM-color attracted fixations, there is no reason to test whether the WM-color attracted as many fixations as a dual-target search-target, as we did in Experiment 1.

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[19] The analysis with the mean replacement values showed a trend towards an effect of Memory-color-step, $F(2.9,44.1) = 2.46$, $p = .08$, $\eta_P^2 = .14$, with fixation rates generally decreasing as Memory-color-step increased.

[20] The interaction was not significant in the analysis with the mean replacement values, $F(4.9,67.3) = 1.54$, $p = .20$, $\eta_P^2 = .09$.