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Guidance of attention by irrelevant contents of working memory is transient

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Abstract

Information in working memory can have distracting effects on visual search. For instance, a color that is incidentally stored in memory may bias search towards items matching the stored color. We investigated whether attentional guidance by task-irrelevant colors is transient or sustained. To investigate this, we systematically varied the color match between memorized and target colors, as well as the set size of the search display. We found that the match between the task-irrelevant color in memory and the color of the subset with the search target resulted in equivalent reductions of search reaction times across varying set sizes, supporting the hypothesis of a transient effect on attentional guidance. A sustained effect would predict growing differences between matching and nonmatching colors as the number of scanned items increases. Using eye tracking we ruled out postattentional target identification or decision-making as potential explanations. Thus, the content of visual working memory guides attention to matching features even in case of task irrelevance, but this guidance is transient. Possibly, activation of the irrelevant content is suppressed to avoid the prolonged distraction resulting from sustained guidance.

Keywords

visual search, visual working memory, search slope

Public Significance Statement

Keeping things in mind is useful in many situations. However, it may also have unwanted consequences. For example, it may guide visual attention to stimuli that resemble those we have in mind but that are not useful for the task at hand. We investigated whether this involuntary guidance of visual attention occurs continuously or only once. Our results show that involuntary guidance from memory is limited to only a single shift of attention.

Introduction

Working memory allows us to store information for short periods of time. During this time, the information may be manipulated internally, or it may be used in interactions with the external world. In models of attentional guidance and visual search (Desimone & Duncan, 1995; Eimer, 2014; Schneider, 2013; Wolfe, 2021), visual working memory is assumed to have two main functions. First, representations of the target held in working memory enhance sensory processing of features matching the stored representation of the target. This top-down enhancement may subsequently guide attention to candidate target objects. Second, the representation of the target in working memory is used to decide whether a candidate target object is in fact the target. Previous research observed that guidance of attention by visual working memory is not limited to representations of the search target, but that irrelevant representations may introduce similar biases. The memory-capture paradigm was instrumental in exploring these effects (reviews in Olivers et al., 2011; Soto et al., 2008). For instance, Soto et al. (2005) asked participants to memorize the color and shape of a geometrical object shown at the start of a trial. During the retention interval, participants searched for a tilted line among vertical lines. Each line was enclosed in a geometrical shape. Although the memorized object was irrelevant to the search task, response times were shorter when the target line appeared within a shape matching the memorized object's color, revealing that irrelevant features can still guide attention.

Transient vs. sustained effects of irrelevant features

While strong evidence supports attentional guidance by search-irrelevant features in working memory, the temporal dynamics of this influence remain unknown; specifically, whether it is sustained or transient. Because the search-irrelevant features cause distraction, a shorter, transient effect is less detrimental than a longer, sustained effect. Possibly, there is suppression of the irrelevant features in working memory (e.g., Awh & Vogel, 2008) to ensure successful search completion. Similarly, suppression of salient-but-irrelevant stimuli is thought to avoid attentional capture (e.g., Luck et al., 2021). Thus, suppressive mechanisms are consistent with transient effects of irrelevant features on visual search. However, the previous literature does not provide a fair test between transient and sustained effects because the irrelevant feature was never entirely irrelevant.

For instance, the memorized features of the geometrical object shown at the start of a trial in Soto et al. (2005), were search-irrelevant, but they were nonetheless relevant for the memory task at the end of a trial. Many studies used a similar procedure (reviewed by Olivers et al., 2011; Soto et al., 2008). The key drawback is that participants were encouraged to keep the irrelevant feature activated through the search task because it was needed in the subsequent memory task, which favored sustained effects on visual search. To avoid this caveat, we used a variant of a paradigm developed by Foerster and Schneider (2018, 2019, 2020), where the irrelevant feature in memory was not only irrelevant for the search task, but also for the memory task. In our experiments, participants were asked to memorize the shape of a colored object shown at the start. In the memory test at the end of a trial, color was irrelevant because all stimuli were gray. During the search task, color was also irrelevant because participants searched for a shape-defined target. Thus, there was no reason to maintain activation of the irrelevant color feature, providing the opportunity for an unbiased evaluation of transient or sustained effects of the irrelevant color feature on visual search.

Previous studies on the time course of effects of irrelevant features

A previous eye tracking study provides some insights into the temporal dynamics but was not designed to distinguish between sustained and transient effects. Participants in de Groot et al. (2017) first studied a word. Subsequently, they either looked for an object matching the word, or they looked for an object from an unrelated object category, rendering the word irrelevant. On target-absent trials, eye movements were biased toward objects that were visually or semantically related to the word, but this bias was strongly reduced and short-lived when the word was irrelevant. Because of the overall reduction, it is unclear whether the bias was transient or sustained. A short-lived bias is compatible with a transient bias, but also with a weak sustained bias that only reaches significance for a short time. Another study investigated the time course of the influence of the irrelevant feature, but not during execution of the search task, but between encoding of the irrelevant feature and the search task. Dombrowe et al. (2010) found that the time course varied depending on the nature of the color’s memory representation, but mostly, the influence decreased as more time elapsed between encoding and search. This time course aligns with that of search-relevant features. Grubert and Eimer (2018, 2020, 2023) demonstrated that guidance by target features was activated only briefly before the onset of the search display but not sustained during the inter-trial-interval. In contrast to irrelevant features, however, relevant features need to be activated in a sustained manner to ensure successful search completion.

Thus, the extant literature concerning attentional guidance by irrelevant features does not provide a clear answer to our question. However, research on saliency-driven attentional capture predominantly supports the hypothesis of transient effects. For instance, Donk and van Zoest (2008) showed that the eyes are captured by salient-but-irrelevant stimuli only during a short time interval following the onset of the search display. This finding raises the question about the subjective saliency of stimuli matching the irrelevant feature in memory. Using pupil size as dependent variable, Wilschut and Mathot (2022) found that colors matching a color stored in memory were perceived as more salient. Thus, stimuli matching the irrelevant feature in memory could be perceived as more salient, resulting in transient effects on attention. However, the methodological differences between studies prevent a definitive conclusion about the relation between enhanced saliency and transient guidance.

Search functions

To disentangle transient and sustained activation of the irrelevant feature in working memory, we examined the intercept and the slope of search functions. We hypothesized that if irrelevant features are only briefly biasing attentional guidance, they would primarily affect the intercept of the search function. Conversely, if their influence on guidance is sustained, they would influence the slope (e.g., Arita et al., 2012; Song et al., 2025). In general, search functions show RTs for an increasing number of items in the search display. The slope of this function shows how much RTs increase when an item is added to the display (Neisser, 1963; Sternberg, 1966). Search slopes are thought to reflect the attentional guidance toward candidate target objects or the attentional selection of these objects. The flatter the search slope, the better the attentional guidance. For instance, search slopes for finding a single feature (e.g., a red target among green distractors) are close to zero (Treisman & Gelade, 1980), suggesting that attentional guidance was strong. In contrast, search slopes for finding feature conjunctions (e.g., a red horizontal bar among red vertical and green horizontal bars) are large, suggesting that attentional guidance based on the target features was poor and individual items or groups of items had to be inspected serially (Liesefeld & Müller, 2020; Treisman & Gelade, 1980).

If guidance by the irrelevant feature was sustained, each inspection during serial search would be biased toward the irrelevant feature. This would decrease the search slope if the target was among matching items and increase the search slope if it was among nonmatching items. In contrast, transient activation of irrelevant features is expected to bias only a single or very few inspections. For instance, the transient activation of the irrelevant feature may result in a single inspection of matching stimuli, resulting in an RT benefit if the target is contained in a matching stimulus, but an RT cost if the target is contained in a nonmatching stimulus. These unique costs and benefits would be visible in the intercept of the search function. Thus, a sustained bias in the shifts of attention during serial search would be reflected in changes of the search slope, while a transient bias would be reflected in changes of the intercept.

A key challenge to our interpretation is that changes in the intercept are commonly attributed to factors other than shifts of attention, such as the speed of target identification or decision-making (Neisser, 1963; Sternberg, 1966). Therefore, if we observe intercept changes suggesting transient activation of the irrelevant feature, we must carefully distinguish these effects from those arising from postattentional target identification and/or decision-making. We will address this issue by measuring eye movements.

Previous findings concerning search slopes

The previous literature reports mixed results regarding the effects of visual working memory on search slopes. Soto et al. (2005) found that search slopes were shallower when the features of the search-irrelevant stimulus in memory matched the subset of stimuli with the target than when it matched the subset without the target. It should be noted that the memorized features were not useful for finding the target because participants looked for a tilted line, while the memorized object was a colored shape. Similarly, Moriya (2018) found shallower search slopes when the color of a search-irrelevant mental image matched the color of the subset of stimuli containing the target stimulus than when it did not match. Again, color was not useful for finding the target because participants were looking for a square with a vertical gap. Conflicting results were obtained by Olivers (2009) who observed that search slopes were independent of the match between the search-irrelevant memory color and the color of the singleton distractor. Again, color was not useful for finding the target because participants searched for a letter inside a shape. Thus, the results of previous studies concerning the effects of irrelevant features on search slopes are inconsistent.

Experiment 1

The goal of Experiment 1 was to test whether a search-irrelevant color stored in memory would affect attentional guidance or selection in a transient or sustained manner.

Participants memorized the shape of a colored object at the start of a trial. Although irrelevant for the search as well as for the memory task, the color of the object is known to affect an intervening search task, suggesting that it is incidentally memorized (Foerster & Schneider, 2018, 2019, 2020; Kerzel & Andres, 2020; Kerzel & Huynh Cong, 2021). In our experiments, the intervening search task was to look for the letter T among randomly oriented letter L nontargets (Duncan & Humphreys, 1989; Wolfe et al., 1989). Importantly, there were two color subsets of equal size. In the matching subset, the stimulus color was the same as the memorized color whereas in the non-matching subset, the stimulus color was different from the memorized color. The search target was randomly in the matching or non-matching subset and color was therefore not useful. If attentional guidance or selection was biased toward the memorized color in a sustained manner, we expect flatter search slopes for search targets in the matching than in the non-matching color. Statistically, this should result in an interaction of color match and set size. In contrast, if a transient process was affected by the search-irrelevant color in memory, RTs are expected to be shorter if the search target is in the matching than in the non-matching subset irrespective of set size. Statistically, a main effect of color match without interaction should be observed. To rule out low-level color priming, we included a control group where the memory test was omitted (see also Soto et al., 2005; Soto & Humphreys, 2007), and all aspects of the object shown at the start of the trial were therefore irrelevant. To preview the results, we found strong evidence for transient, but no evidence for sustained effects in Experiment 1. With less efficient search in Experiments 2 and 3, there was inconsistent evidence for sustained effects, but strong evidence for transient effects. Finally, eye tracking in Experiment 3 ruled out that transient effects resulted from postattentional target identification and/or decision-making.

Method

Transparency and Openness. All program code and methods developed by others are cited in the text and listed in the references section. This study did not use any data collected by others. The following software was used: MatLab 2022a (The Mathworks, Natick, MA) for data management, aggregation, and plots; IBM SPSS 27 (IBM, Armonk, NY) for statistical analysis; PsychoPy2 (Peirce et al., 2019) for running the experiments. The data and R-scripts (R Core Team, 2024) performing the analyses reported below are available at https://osf.io/mqvyb/ and requests for the code can be sent via email to DK. We report how we determined our sample size, all data exclusions (if any), all manipulations, and all measures in the study. The study's design and its analysis were not preregistered. The study was approved by the ethics committee of the Faculty of Psychology and Educational Sciences and was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki). Informed written consent was given before the experiment started.

Participants. There were 20 datasets in the group with memory task (3 men; age: M = 24 years, SD = 9) and 19 in the group without (2 male; age: M = 20 years, SD = 2). One participant from the group with memory task (initial sample: 21) was excluded due to an exceptionally high error rate of 43%, compared to 5% (SD = 5) for the remaining participants. We were looking for an interaction between color match and group showing that color match had an effect in the group with memory task, but not in the control group without memory task. G*Power 3.1 (Faul et al., 2009) indicated that given our sample size, an alpha of .05 and power of .8, we could detect interactions as small as η_p^2 = .041 with a minimal $F(2, 74) = 3.12$. We additionally looked for an interaction of color match and set size in the group with memory task, which would indicate that matching and non-matching targets had different search slopes in the experimental, but not in the control group. The minimal effect size for this interaction was also η_p^2 = .080 with a minimal $F(2, 38) = 3.24$. Given the effect size of η_p^2 = .360 for the interaction of color match and set size in Moriya (2018, Experiment 3), the current sample size appears conservative. Students participated for class credit and reported normal or corrected-to-normal vision.

Apparatus. The stimuli were displayed on a 22.5-inch LCD monitor (VIEWPixx Lite, standard backlight, VPixx Technologies Inc., Saint-Bruno, Canada). The display frequency was 100 Hz and the pixel resolution was 1,920 × 1,200 pixels. Colors were measured with an i1Display Pro (VPixx Edition) colorimeter by X-Rite (Grand Rapids, Michigan, United States). Head position was stabilized with a chin/forehead rest at a viewing distance of 66 cm. Responses were collected on a RESPONSEPixx Handheld 5-button response box (VPixx Technologies Inc., Saint-Bruno, Canada), which had four buttons arranged in a diamond shape and one button in the center.

Stimuli. In the fixation display, only the fixation cross (0.24° diameter) was shown in the center of the screen. In the memory display, one colored image was shown in the center of the screen. In the memory test display, two grayscale images were shown side by side, at 4.4° to the left and right from the center of the screen. The 510 images used in the memory task were from Brady et al. (2013). The complete collection can be downloaded at https://bradylab.ucsd.edu/stimuli.html. Four versions of the originals were created by rotating the hue of the originals by -30°, 60°, 150°, and 240° in CIELAB-space without changing luminance. The resulting colors were purple, orange-brown, green, and blue. We also created a grayscale variant of each image. The images were square and had a side length of 4.4°.

In the search display, the fixation cross was shown, and 6, 12 or 18 stimuli were arranged on one of three rings with radii of 3.3, 6.6, and 9.8°. The minimal spacing between stimuli on each ring was 3.4°. On each trial, the stimulus locations were randomly shuffled until there was an approximately equal number of stimuli in each quadrant and the target was on the middle ring. That is, there were one or two stimuli per quadrant for set size 6, three stimuli for set size 12, and four or five stimuli for set size 18. The nontargets were the letter L rotated by 0, 90°, 180, or 270° (linewidth: 0.2°, side length: 0.7°). The target was the letter T rotated by 90° to the left or right (linewidth: 0.2°, side length: 0.7°). The stimuli were rendered in two colors with an equal number of stimuli per color. The possible colors were violet (xyY = 0.297, 0.159, 12, with Y in cd/m^2), orange-brown (xyY = 0.589, 0.371, 18), green (xyY = 0.271, 0.619, 14), and blue (xyY = 0.135, 0.175, 14), which correspond roughly to the mean colors in the object images. The background was light gray (xyY = 0.320, .333, 84).

Design. The stimuli in the search display were divided into two subsets sharing the same color. Each subset contained an equal number of stimuli. One subset contained the target and the color of this subset either matched the color in the memory display or it was nonmatching. The colors of the two subsets were drawn from the four possible colors. The target T had equal chances of being rotated to the left and right. The 144 combinations resulting from 2 (color match: matching, nonmatching) × 3 (set size: 6, 12, 18) × 4 (color of target subset: purple, orange-brown, green, blue) × 3 (color of nontarget subset) × 2 (rotation of T: left, right) were presented once in each trial block. Four trial blocks were run resulting in 576 trials per participant. These within-participant variables were the same for all participants. In addition, there was a between-participant variable. One group of participants performed the memory task, whereas the other group did not. Both groups performed the search task and saw a colored object at the start of the trial.

Procedure. The procedure is illustrated in Figure 1A. In the group with memory task, participants encoded the shape of an object at the start of a trial and performed a memory test at the end. In the group without memory task, participants were told to ignore the object shown at the start and the memory test display was not shown. After presentation of the memory object, all participants performed a search task where they had to locate the letter T and indicate whether it was oriented to the left or right. Participants were instructed to respond as rapidly and as accurately as possible in the search task, but to take their time and be as accurate as possible in the memory task (if applicable). A trial started with the fixation display for 500 ms, followed by the memory display for 500 ms. Then, the fixation display was shown again for 700 ms before the search display appeared. The search display remained visible until participants indicated the orientation of the letter T. Then, the memory test display appeared for the group performing the memory task and remained visible until participants localized the memorized shape by key press. Participants were encouraged to respond faster when the RT in the search task was longer than 2,200 ms, but these trials were not flagged as late. Visual feedback was given immediately after each response. A self-terminated break was given every 72 trials where performance on the search and memory tasks (if applicable) was shown. Participants performed at least 36 practice trials before the experiment started.

Results

For the analysis of RTs, we excluded trials with errors in the search or memory task. This amounted to 5% and 2% of trials in the group with and without memory task, respectively. The mean RTs for each group are shown in Figures 2A and 2B. We entered individual median RTs in a mixed 2 (memory task: yes, no) × 2 (color match: matching, nonmatching) × 3 (set size: 6, 12, 18) mixed ANOVA. The memory task was a between-participant factor, whereas color match and set size were within-participant factors. RTs were shorter when the color in the memory display matched the color of the search target, $F(1, 37) = 19.85$, $p < .001$, $\eta_p^2 = .349$, but the interaction with memory task, $F(1, 37) = 8.54$, $p = .006$, $\eta_p^2 = .188$, showed that this was only the case when the memory task was performed. RTs in the group performing the memory task were 60 ms shorter for matching than nonmatching search targets (698 vs. 758 ms), $t(19) = 4.39$, $p = .001$, Cohen's $d_z = 0.98$. RTs in the group without memory task differed in the same direction by 12 ms, but not significantly (675 vs. 687), $t(18) = 1.458$, $p = .157$, Cohen's $d_z = 0.34$. The effect of set size, $F(2, 74) = 210.68$, $p < .001$, $\eta_p^2 = .851$, showed that RTs increased with increasing set size (611, 704, 800 ms). However, the three-way interaction between memory task, color match, and set size was not significant, $F(2, 74) = 0.73$, $p = .486$, $\eta_p^2 = .019$, suggesting that although color match had an effect when the memory task was performed, the increase in set size was the same regardless of the match between target and memory color, and regardless of whether the memory task was performed. To strengthen the evidence for the null result, we conducted a separate 2 (color match: matching, nonmatching) x 3 (set size: 6, 12, 18) ANOVA on individual medians only from the group with memory task. We found main effects of color match, $F(1, 19) = 19.26$, $p < .001$, $\eta_p^2 = .503$, and set size, $F(2, 38) = 89.24$, $p < .001$, $\eta_p^2 = .824$, but no interaction, $F(2, 38) = 0.98$, $p = .386$, $\eta_p^2 = .049$. For descriptive purposes, we regressed search RTs on set size and found a search slope of 16 ms/item. Conducting the same ANOVA on choice errors in the search task found no significant effects, *p*s > .450, possibly because the percentage of choice errors was very low (2%).

Discussion

We asked whether the irrelevant content of memory would affect attentional guidance or selection in a transient or sustained manner. We observed that the match between the task-irrelevant color in memory and the color of the subset with the search target reduced search RTs by the same magnitude regardless of set size. This difference is consistent with a transient effect of memory color on attentional guidance. A sustained effect would predict increasing differences between matching and nonmatching colors as the number of scanned items increases. However, the effect size for the relevant interaction was only $\eta_p^2 = .049$, which is smaller than the effect size of $\eta_p^2 = .360$ reported by Moriya (2018, Experiment 3). Further, the experiment rules out low-level color priming because memory color had no effect in a control group without memory test, replicating previous results with similar control conditions (Soto et al., 2005; Soto & Humphreys, 2007).

Experiment 2

While we concluded that irrelevant content in working memory had a transient effect on search, this conclusion is limited to rather efficient search. The search slope in the previous experiment was 16 ms/item. Studies on interactions between working memory and search reported search slopes between 66 and 176 ms/item (Moriya, 2018; Olivers, 2009; Soto et al., 2005). That is, the search slope was 110 ms/item in Experiment 4 of Olivers (2009), 71 vs. 176 ms/item for valid vs. invalid conditions in Experiment 1 of Soto et al. (2005) and 66 vs. 113 ms/item for valid vs. invalid conditions in Experiment 3 of Moriya (2018). To make our study more like previous work, we changed the similarity between the target and the nontarget stimuli to reduce search efficiency. Possibly, sustained effects on attentional guidance or selection are only visible with less efficient search resulting in larger search slopes.

Method

Participants. There were 28 valid datasets (8 male; age: *M* = 24 years, *SD* = 7). To better meet the assumption of normality required for the ANOVA on RTs, one dataset from the original sample of 29 participants was removed. This dataset exhibited four outlier values across six experimental conditions. Outliers were defined as values falling below the first quartile minus 1.5 times the interquartile range, or above the third quartile plus 1.5 times the interquartile range. The sample size was larger than in Experiment 1 because of scheduling problems. Consequently, the minimal effect size of the critical interaction decreased slightly (η_p^2 = .057, $F(2, 38) = 3.16$) compared to Experiment 1 (η_p^2 = .080).

Stimuli and procedure. The horizontal bar in the rotated letter T was moved 0.21° vertically, randomly toward the upper or lower end of the vertical bar (see Figure 1B), which made the target more like the nontargets. Because this task was harder, participants were encouraged to respond faster after RTs longer than 3,800 ms, instead of 2,200 ms in Experiment 1.

Results

For the analysis of RTs, we excluded 5% of trials because of errors either in the search or memory task. Mean RTs are shown in Figure 2C. We entered individual median RTs in a 2 (color match: matching, nonmatching) × 3 (set size: 6, 12, 18) within-participant ANOVA. RTs were 126 ms shorter when the color of the search target matched the color in the memory display (1244 vs. 1370 ms), $F(1, 27) = 12.26$, $p < .001$, η_p^2 = .312, and RTs increased with increasing set size (992, 1309, 1621 ms), $F(2, 54) = 219.38$, $p < .001$, η_p^2 = .890. Unlike in Experiment 1, there was an interaction of color match and set size, $F(2, 52) = 3.22$, $p = .048$, η_p^2 = .107, showing that RTs increased more strongly with nonmatching than matching colors. The interaction indicated that the search slope was 55 ms/item when the target color did not match the memorized color and 45 ms/item when it did. Because a Shapiro-Wilk test indicated a violation of the assumption of normality in one condition of the full ANOVA, we calculated the mean increase from set size 6 to 12 and from 12 to 18, separately for matching and nonmatching conditions. The resulting values were then compared by non-parametric test (Wilcoxon signed-rank test). The test was significant, $p = .026$, confirming the difference in slopes. Conducting the same ANOVA on choice errors in the search task found no significant effects, *p*s > .204.

Discussion

With higher target-distractor similarity, search slopes increased from 16 ms/item to about 50 ms/item, indicating that search became less efficient. Unlike in Experiment 1, there was an interaction between color match and set size, suggesting that attentional guidance or selection was affected in a continuous manner by the color in working memory. The effect size of the critical interaction doubled from $\eta_p^2 = .049$ in the previous experiment to .107 in the current experiment. However, it is still smaller than the effect size of $\eta_p^2 = .360$ **in** Moriya (2018). Thus, less efficient search promotes sustained effects of the irrelevant feature, but the differences in slopes are small.

Experiment 3

While Experiments 1 and 2 yielded inconclusive results regarding sustained effects of the search-irrelevant color, both experiments demonstrated reliable intercept changes, strongly suggesting a transient effect. Traditionally, such effects have been linked to postattentional target identification and/or decision-making (Neisser, 1963; Sternberg, 1966). That is, maybe it was easier to decide that the target letter T was indeed the target letter when its color matched the memorized color. Or it was easier to decide that the dot was on the left or right when the colors matched. Search functions alone cannot differentiate these processes from transient attentional guidance, as both would manifest as intercept changes. In contrast, eye tracking has distinct indices for each process (e.g., Albert et al., 2024; Becker et al., 2023; Hollingworth & Bahle, 2020; Malcolm & Henderson, 2009). Attentional guidance is associated with the direction of first saccades whereas target identification is associated with dwell times on the target. Here, first saccades directed at stimuli sharing the color held in memory are consistent with effects of working memory on attention (as in Bahle et al., 2018; Soto et al., 2005), whereas shorter dwell times on targets sharing this color are consistent with effects on target identification.

To enable sufficiently precise measurements of first saccades and dwell times, we changed the stimulus displays and task (see Figure 3). The set size was reduced to 2 and 4 stimuli (compared to 6, 12, and 18) and all stimuli were presented at the same eccentricity. Further, participants searched for a T rotated to the left or right and decided whether the horizontal bar was lower or higher than the vertical midpoint. This fine discrimination required foveal vision and promoted large saccades from central fixation to the periphery. In the previous experiments, the task could be solved in peripheral vision because the difference between a left or right T was large.

Method

Participants. There were 20 valid datasets (2 male; age: *M* = 22, *SD* = 5). One dataset from the original sample size of 22 was removed because of excessive overall errors (55%) and another because it had four outlier values across four conditions in the ANOVA on search RTs, which compromised the normality of the data.

Stimuli and procedure. The stimuli appeared on an imaginary circle of 6.6° around central fixation. The stimulus configuration was randomly rotated on each trial while keeping the same separation between stimuli. With a set size of 2, stimuli were separated by 180° of rotation and with a set size of 4, the separation was 90° of rotation. As in the previous experiments, the target stimulus was the letter T randomly oriented to the left or right, but instead of judging the orientation, participants judged whether the horizontal bar in the letter was slightly higher or lower than the vertical center. Participants responded by pressing the top or bottom key on the response box. Because the vertical offset was small (0.04°), it was necessary to foveate the target stimulus. Further, the fixation cross was removed at the onset of the search display. Together, we expect these changes to promote large saccades from the center to one of the stimuli in the search display. Finally, the two images for the memory test at the end of a trial were arranged vertically so that participants could continue to use the top and bottom keys.

Apparatus. A desktop-mounted EyeLink1000 (SR Research, Ontario, Canada) was used to record eye-movements at a sampling rate of 1000 Hz. To detect saccades, we set the EyeLink1000 to the standard saccade criteria for cognitive research (i.e., velocity of 30°/s and acceleration of 8000°/sec^2).

Analysis of eye movement data. The eye movement data were converted to a format compatible with MatLab (MathWoks, Natick, MA) using the Edf2Mat Toolbox developed by Adrian Etter and Marc Biedermann at the University of Zürich (see https://github.com/uzh/edf-converter). We were interested in the first saccade and in fixations on the target stimulus just before the key was pressed. Before calculating the dependent variables, we employed the following criteria and procedures. If the first saccade was smaller than 1°, we used the second saccade instead because the first saccade was likely to be a refixation of the fixation cross. This occurred on 4.1% of trials. We considered the first saccade valid when the following criteria were met. The angle of rotation between the saccade and the stimulus was less than 20°; the saccade amplitude was larger than half the stimulus eccentricity; eye fixation was within 2° of central fixation at the start of the saccade; saccadic RT was longer than 100 ms and shorter than 300 ms. These criteria were based on histograms of the respective variables. Concerning final fixations on the target, we considered fixations to be on target when the difference between gaze direction and the center of the stimulus was less than half the stimulus eccentricity (3.3°). Only the last consecutive fixations on the target before the key press were considered because fixations on the target followed by fixations elsewhere may reflect search, rather than target identification or decision-related processes.

Results

Choice errors in the search task occurred on 5% of trials, errors in the memory task on 4% of trials, errors in the first saccade on 15% of trials, missing dwell times on the target on 2%. These errors were not mutually exclusive. On 22% of trials, there was some kind of error. For the analysis of search RTs, we excluded trials with search or memory errors (8%). Mean RTs are shown in Figure 4A. We entered individual median RTs in a 2 (color match: matching, nonmatching) × 2 (set size: 2, 4) within-participant ANOVA. RTs were 44 ms shorter when the target color matched the memory color (825 vs. 869 ms), $F(1, 19) = 35.12$, $p < .001$, $\eta_p^2 = .649$, and RTs increased by 105 ms from set size 2 to set size 4 (794 vs. 899 ms), $F(1, 19) = 133.53$, $p < .001$, $\eta_p^2 = .875$. There was no interaction of color match and set size, $F(1, 19) = 1.66$, $p = .213$, $\eta_p^2 = .081$, suggesting that the search slope was 52 ms/item regardless of whether the memory color matched the target. Running the same ANOVA on choice errors yielded a main effect of set size, $F(1, 19) = 7.90$, $p = .011$, 3, $\eta_p^2 = .294$, showing more errors with set size 2 than set size 4 (6% vs. 4%). No other effect was significant, *F*s < 0.49, *p*s > .494, $\eta_p^2 < .025$.

Next, we analyzed the first saccade occurring after onset of the search display. We were interested in the percentage of saccades directed at the search target as a function of the color match between search target and memorized object. Mean percentages are shown in Figure 4B. We entered individual percentages of saccades to the target in a 2 (color match: matching, nonmatching) × 2 (set size: 2, 4) within-participant ANOVA. There were 9% more saccades directed at the search target when it matched the color of the memory color

(48% vs. 39%), $F(1, 19) = 31.38$, $p < .001$, $\eta_p^2 = .623$. The percentage of saccades directed at the search target was also higher with set size 2 than set size 4 (55% vs. 32%), $F(1, 19) = 388.34$, $p < .001$, $\eta_p^2 = .953$, reflecting the difference in chance selection between 2 and 4 stimuli (50% vs. 25%). The interaction of color match and set size was significant, $F(1, 19) = 15.03$, $p = .001$, $\eta_p^2 = .442$, showing that the difference between matching and nonmatching targets was larger with set size 2 than set size 4 (difference of 13% vs. 6%). However, paired t-tests showed that it was significant for both set sizes [set size 2: 61 vs. 48%, $t(19) = 6.94$, $p < .001$, Cohen's $d_z = 1.55$; set size 4: 34 vs. 29%, $t(19) = 2.88$, $p = .010$, Cohen's $d_z = 0.64$]. Further, we analyzed first saccades as a function of the color of the stimulus they were directed at. For set size 2, 56% of all saccades were going to a stimulus with a matching color, which is significantly different from 50%, $t(19) = 6.94$, $p < .001$, Cohen's $d_z = 1.55$. For set size 4, this percentage was 55% and also significantly different from 50%, $t(19) = 3.20$, $p = .005$, Cohen's $d_z = 0.72$.

Further, we analyzed the RT of first saccades directed at the target. We entered individual median saccadic RTs of these saccades in a 2 (color match: matching, nonmatching) × 2 (set size: 2, 4) within-participant ANOVA. Saccadic RTs were shorter with set size 2 than set size 4 (162 vs. 170 ms), $F(1, 19) = 10.26$, $p = .005$, $\eta_p^2 = .351$. No other effect reached significance, *F*s < 0.12, *p*s > .730, $\eta_p^2 < .006$.

Finally, we analyzed the fixation durations on the target before a key press was registered (see Figure 4C). We conducted a 2 (color match: matching, nonmatching) × 2 (set size: 2, 4) ANOVA on individual median dwell times, but found no significant effects, *F*s < 0.27, *p*s > .608, $\eta_p^2 < .014$. In particular, the effect of color match was not significant, $F(1, 19) = 0.02$, $p = .881$, $\eta_p^2 = .001$. Thus, target identification or decision processes while looking at the target stimulus were not affected by the color match between the target and the object. The mean fixation duration on the target was 462 ms.

Discussion

We investigated whether increased search RTs for memory-matching, search-irrelevant colors were due to memory-based attentional guidance or later processes, such as target identification and/or decision-making. Consistent with previous studies (Bahle et al., 2018; Soto et al., 2005), we found that first saccades were more frequently directed at stimuli in the memory-matching color, suggesting that attentional guidance was biased by the memorized color. In contrast, fixation durations on the target stimulus shortly before the key press were not affected by color match, suggesting that target identification or decision-making were not involved. Further, we confirmed that search slopes did not differ between matching and nonmatching targets. The magnitude of the search slopes (50 ms/item) indicated inefficient search like in Experiment 2, but overall search times were shorter because there were fewer stimuli. The effect size of the critical interaction was $\eta_p^2 = .081$, which is close to the effect size of $\eta_p^2 = .107$ in the previous experiment. While not significant, the effect sizes suggest that a sustained effect may occur in inefficient search, but the effect is small compared to transient effects. Note that the effect size of the main effect associated with transient changes was $\eta_p^2 = .503$, .312, and .649 in Experiments 1-3, respectively. Thus, sustained effects were small and inconsistent with inefficient search in Experiments 2 and 3 and entirely absent with more efficient search in Experiment 1. In contrast, transient effects were large and robust throughout.

General Discussion

Previous research has demonstrated that the content of visual working memory may affect visual search even when it is irrelevant for the search task. In our paradigm, participants had to encode the shape of a colored object, which they later had to recognize among colorless shapes. During the retention period, participants searched for a shape, with color being irrelevant because the color of the target shape randomly matched or mismatched the memorized color. Although color was irrelevant for the memory and the search task, it nevertheless biased attentional guidance. That is, search was facilitated when the search target was in the subset of stimuli sharing the memorized color. Our research question was whether this effect reflects sustained or transient attentional guidance. To answer this question, we measured search slopes. If the memorized color had a sustained guidance effect, we expected differences in search slopes. That is, search slopes should be flatter if the target appeared in the subset of stimuli matching the memorized color compared to when it appeared in the non-matching subset. However, we found no or only small interactions between color match and set size to substantiate differences in search slopes. Rather, RTs were generally shorter when the target was in the matching subset, which is consistent with a transient effect. Transient effects were large and reliable, occurring in each experiment. In contrast, sustained effects were small and inconsistent and occurred only with very inefficient search in Experiments 2 and 3. Further, we sought to rule out that transient effects were caused by postattentional target identification and/or decision-making. To this end, we recorded eye movements in Experiment 3. We found that first saccades were more frequently directed at the stimuli matching the memorized color. In contrast, dwell times on the search target did not depend on color match. Thus, the change of intercept is related to attentional control. We suggest that attention was transiently directed at the subset of stimuli with the matching color instead of being continuously guided toward the matching color. For instance, attention may have been guided to matching stimuli at the start of the search process, but subsequent search was based on the task-relevant shape. Possibly, activation of the irrelevant feature in working memory was suppressed (e.g., Awh & Vogel, 2008) to ensure successful search completion. Or the memorized feature transiently increased the saliency of matching stimuli (Donk & van Zoest, 2008; Wilschut & Mathot, 2022), requiring suppression to prevent continued capture (Luck et al., 2021). Whatever the exact mechanism, the current results show that the temporal dynamics of guidance from relevant and irrelevant content of visual working memory are fundamentally different. Guidance from relevant content is necessarily sustained until search is complete, while guidance from irrelevant content is mostly transient to prevent search failure.

Relation to previous studies measuring search slopes

Our results are somewhat at odds with those from Soto et al. (2005) and Moriya (2018), who found effects of color match on search slopes. A possible reason for the discrepancy is that the irrelevant feature in these studies was not entirely irrelevant. Because the feature was needed in the memory task, it may not have been possible to deactivate or suppress it. However, our results are consistent with those of Olivers (2009). While participants in the mentioned studies searched for a particular shape or orientation, different methods were employed to measure effects of visual working memory on search. Like in the present study, Soto et al. (2005) and Moriya (2018) evaluated whether search RTs were shorter when the target was in the subset of items with features matching the memorized stimulus. In contrast, Olivers (2009) evaluated whether interference from a singleton distractor was larger when its color matched the memorized color. Singleton distractors are believed to attract the first shift of attention because of their saliency, even if this shift is subject to task demands (Luck et al., 2021). The stronger interference from memory-matching distractors in Olivers (2009) suggests that the initial allocation of attentional resources to the distractor was promoted when it matched the content of visual working memory. Similar facilitation was reported for simple saccades to memory-matching stimuli (Hollingworth et al., 2013). Because search slopes did not differ between conditions with matching and non-matching distractors in Olivers (2009), it appears that there was only a single shift of attention to the distractor before shape-based search resumed.

What is selected after transient guidance?

The results of the current study are like Olivers' (2009) because there was an effect of color match that was not modulated by set size. Also, we attribute the difference between matching and non-matching colors to a transient modulation of attentional guidance or selection, which may have occurred at the start of the search. However, the nature of this initial allocation of attentional resources is less clear in the current study. In Olivers (2009), color match promoted initial shifts of attention to the color singleton. The color singleton was never the target, and it was therefore likely that shape-based search resumed after the initial shift of attention to the distractor. In contrast, all colored stimuli in the current study were potentially relevant and the question is therefore how many items were attended in the initial shift of attention. Attentional selection may proceed item-by-item, or entire subsets sharing a feature may be selected (Friedman-Hill & Wolfe, 1995; Kaptein et al., 1995; Liesefeld & Müller, 2020; Treisman & Gelade, 1980). Thus, the transient modulation of attentional guidance or selection could concern a single item in a memory-matching color, several items, or an entire subset of stimuli in the memory-matching color. All options are possible because the size of the attentional window has been shown to be variable (Belopolsky et al., 2007; Biggs & Gibson, 2018; Davis, 2024; Eriksen & St James, 1986). However, not all alternatives are equally plausible. If attention was guided toward a single item in the memory-matching color, the impact of the initial selection would decrease with increasing set size. The reason is that with increasing set size, the probability of finding the search target in the selected item decreases, which would reduce the advantage of targets in the memory-matching compared to the non-matching color. This is not what we observed, suggesting that it is unlikely that the transient attentional guidance was directed at a single item. Another option is that attention was guided to several memory-matching stimuli. If the number of stimuli was fixed, the same decreasing effect of color match would be expected as with a single stimulus, which is inconsistent with our results. Possibly, the transient attentional guidance or selection was not directed at a fixed number of items, but rather at a spatial area of fixed size, for instance a quadrant. Because the density of the stimuli in the current study increased with increasing set size, more matching stimuli would be contained in this area when set size increased. As a result, the probability of finding the target among the matching stimuli in the area remains constant, which fits with the constant RT difference across set sizes. Finally, attention could be guided to an entire stimulus subset in the memory-matching color. This could be achieved through feature attention (Oxner et al., 2023; Sàenz et al., 2003; Treue & Martinez Trujillo, 1999). As the probability of finding the target in the matching subset was always p = .5, irrespective of set size, our results are also compatible with this alternative. More research is needed to determine the exact nature of the transient attentional guidance or selection, but the current study restricts the possibilities to those where either the attended space or the attended proportion of stimuli remains fixed.

Controversies in memory-based guidance

The above shows that memory-based guidance is a robust phenomenon (see also Calleja & Willoughby, 2023; Jung et al., 2018; King & Macnamara, 2020; Williams et al., 2022) and clarifies that guidance is transient if the memorized feature is entirely irrelevant. Previous research has discussed several different questions. An important question was whether the search-irrelevant items in working memory guide search only when the search target is in an "accessory" state while the search-irrelevant item is actively maintained (Olivers et al., 2011; van Moorselaar et al., 2014). This may occur when the target is fixed across trials while the memorized item is variable and requires active maintenance (Olivers, 2009; Olivers et al., 2006). However, memory-based guidance was observed for multiple search-irrelevant items in memory (Hollingworth & Beck, 2016) and with targets changing from trial to trial (Foerster & Schneider, 2018). These results are incompatible with the distinction between a single activated item driving search and ineffective "accessory" items.

Another controversy concerns the nature of the information underlying memory-based guidance. The search-irrelevant content of memory was often composed of several features, such as color and shape. Therefore, the question arose whether attention was guided to each of these features independently, or whether it was guided to the combined features that constitute an object. Again, a definitive answer is elusive. Thayer et al. (2022) observed that attention was guided to stimuli that combined features of the memorized objects, even when these combinations did not correspond to the memorized objects. On the other hand, Zhu et al. (2024) found that memory-based guidance by two features was only observed when the two features were presented in a single object, but not when they were presented on separate objects.

Conclusions

In sum, we investigated how irrelevant content in visual working memory affects visual search. We reasoned that attentional guidance or selection could be affected in a sustained fashion, which would decrease the search slopes when the search target was in the subset of items sharing the feature held in visual working memory. Alternatively, the effect could be transient, which would result in a uniform change of RTs across set sizes. Our results were consistent with a transient process, although we cannot entirely rule out sustained effects in highly inefficient search. Through eye tracking, we clarified that transient effects were not caused by target identification or decision-making. Thus, we found effects of the content of working memory on the guidance of attention to be mostly transient. Previous reports of sustained effects may have been caused by the relevance of the search-irrelevant feature for the memory task.

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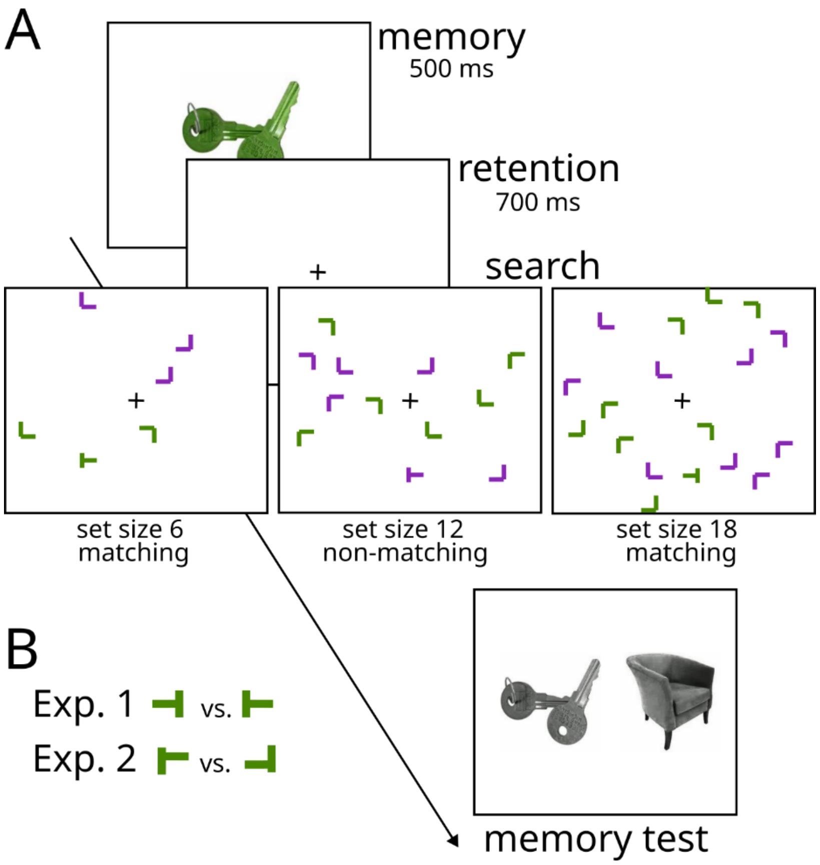
Figure 1.

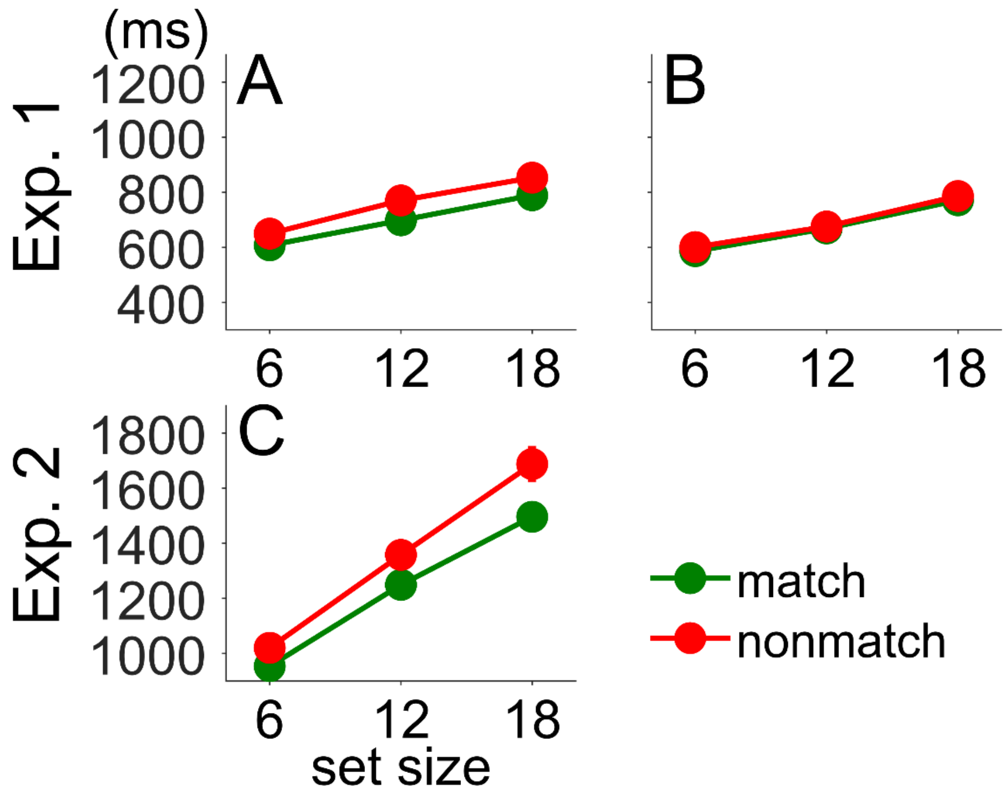
Illustration of the experimental procedure in Experiments 1 and 2.



Note. Panel A illustrates an experimental trial in Experiment 1. Participants had to memorize the object's shape and in the intervening search task, find the letter T and indicate its orientation. Panel B shows the target shapes in Experiments 1 and 2.

Figure 2.

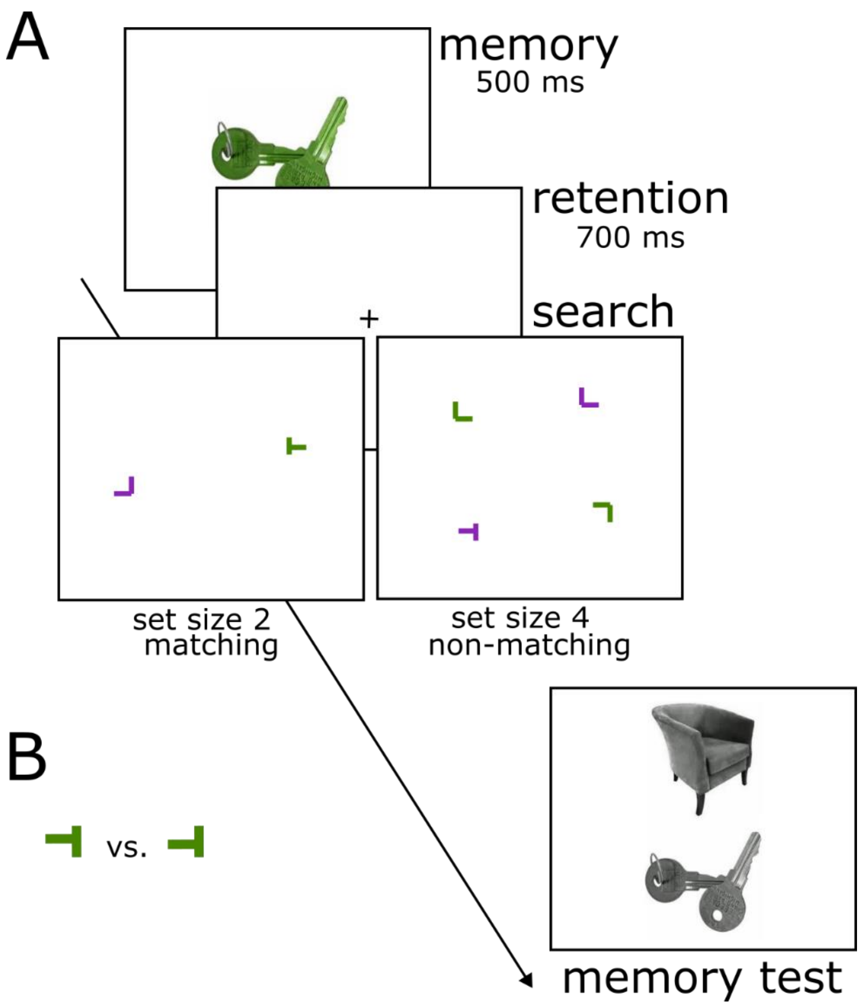
Results from Experiments 1 and 2.



Note. The graphs show mean reaction times in milliseconds (ms) as a function of color match and set size. Panels A and B show the results from Experiment 1 for the groups with and without memory task, respectively. The results from Experiment 2 are shown in panel C. Note that the y-axis starts at 300 ms in Experiment 1, but at 900 ms in Experiment 2. Error bars show the between-subject standard error but were mostly smaller than the symbols.

Figure 3.

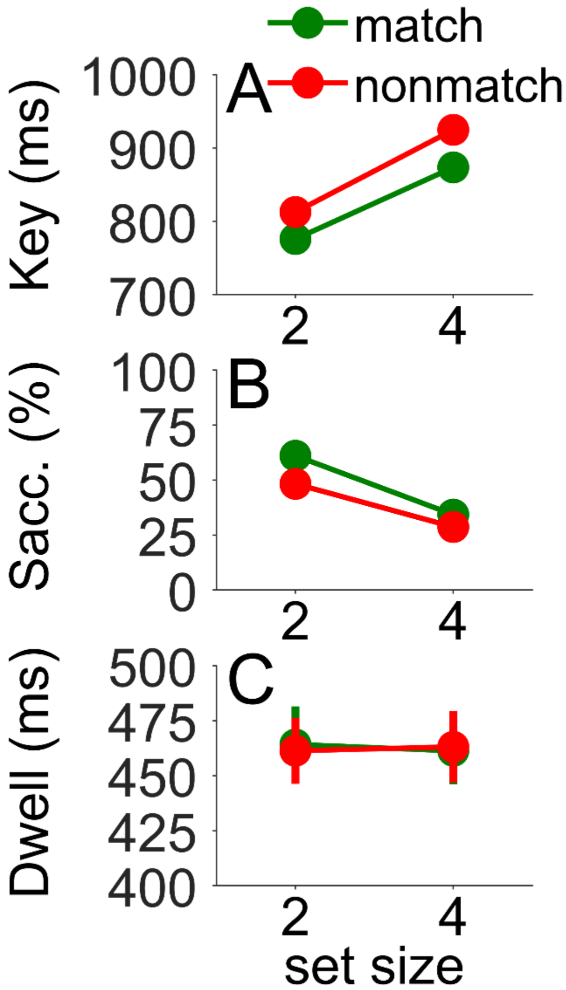
Illustration of experimental stimuli in Experiment 3.



Note. Panel A illustrates an experimental trial. The procedure was as in Experiment 1, but the fixation cross disappeared at the onset of the search display and all search items were shown on a virtual circle around fixation. Panel B illustrates the target stimulus. Participants had to decide whether the horizontal bar in the letter T was shifted up- or downward, irrespective of its orientation.

Figure 4.

Results from Experiment3.



Note. Means of different dependent variables are shown as a function of set size and color match. Panel A shows the mean RTs of key press responses in milliseconds (ms). Panel B shows the mean percentage of first saccades to the target. Panel C shows the mean ocular dwell times. Error bars show the between-subject standard error but were mostly smaller than the symbols.