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The presence of a distractor matching the content of working memory induces delayed quitting in visual search

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Abstract

Previous research has shown that the presence of a distractor object matching the current content of working memory interacts with visual search. Because finding a target and quitting a search without finding a target may be implemented by qualitatively different processes, it is possible that the effects of a memory-matching distractor on target-present trials and on target-absent trials reveal different mechanisms by which the memory-matching distractor interacts with visual search. Although previous studies have well established the effect of attentional capture by a memory-matching distractor when the target object is found in the search display, there remains an open question about whether the presence of a memory-matching distractor can affect the process of search termination when no target is found. In the present study, we showed that search termination times on target-absent trials were delayed by the presence of a distractor matching the content of visual working memory. This delayed quitting effect cannot be conceived of as a more general influence of visual short-term memory, because the presence of a distractor matching the content of passive visual short-term memory (i.e., visual priming) did not influence quitting behavior in visual search. These findings offer a novel perspective that distractors matching the information maintained in visual working memory can cause observers to delay search termination when no target has been found.

Keywords Working memory · Visual search · Attentional capture · Search termination

Introduction

Many theories of visual search posit an important role for working memory in the process of visual search (e.g., Bundesen, 1990; Desimone & Duncan, 1995; Duncan & Humphreys, 1989; Wolfe, 2021). For example, during visual search, a mental representation of the search target, known as the attentional template, is often assumed to be maintained in working memory to guide the deployment of visual attention until the target is found or the search process is terminated. According to the biased competition model of selective attention (Desimone & Duncan, 1995), active maintenance of an attentional template in working memory serves to bias attention in a top-town manner toward objects with template-matching features in the search array, providing a competitive advantage for these objects to be selected for further processing. Once selected, these objects can then be identified as targets or distractors by comparing them with the attentional template in the temporary workspace of working memory (Bundesen, 1990; Duncan & Humphreys, 1989; Treisman & Gelade, 1980; though see also Li et al., 2019; Woodman et al., 2001). Consistent with this assumption, there has been convergent evidence demonstrating that an attentional template for the search target may indeed be maintained in working memory (e.g., Carlisle et al., 2011; Gunseli et al., 2014; Woodman & Arita, 2011).

Previous studies have also investigated the role of working memory in visual search by examining the influence of target-unrelated memory representations on search performance (e.g., Bahle et al., 2018; Han & Kim, 2009; Hollingworth & Beck, 2016; Olivers, 2009; Olivers et al., 2006; Olivers & Eimer, 2011; Soto et al., 2005; Soto & Humphreys, 2007; van Moorselaar et al., 2014; Woodman & Luck, 2007; Zhang et al., 2011; Zhang et al., 2018). In a typical experiment of these studies, participants are asked to search for a visual target among distracting stimuli while holding a target-unrelated item in working memory. They have to identify a feature of the target object, which is present in the search display on every trial. The critical experimental manipulation is that one of the distractors in the search display could match

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the current content of working memory. The typical results show that relative to trials on which there is no match between working memory content and search stimuli, search performance is slower on trials wherein a memory-matching distractor is present in the search array. The longer search times for matching-distractor trials than for no-match trials reflect that a distractor matching the content of working memory captures attention during the early stage of visual search. This is further demonstrated by evidence showing more first saccades toward a distractor's location and less first saccades toward the target's location on matching-distractor trials compared with no-match trials (e.g., Bahle et al., 2018; Foerster & Schneider, 2018; Hollingworth et al., 2013; Schneegans et al., 2014; Soto et al., 2005; Zhang et al., 2018). That is, when the target is present in the search array, a memory-matching distractor can capture attention and make the initial shift of attention away from the target, thereby increasing the amount of time required to find the target. This effect of memory-driven attentional capture in visual search has been reported by a large body of previous studies, though it may be subject to some boundary constraints (for comprehensive reviews, see Olivers et al., 2011; Soto et al., 2008).

It is noteworthy, however, that most of previous studies on the effect of the presence of a distractor matching the target-unrelated content of working memory in visual search used search arrays always containing a to-be-identified target (e.g., Bahle et al., 2018; Han & Kim, 2009; Hollingworth & Beck, 2016; Olivers, 2009; Olivers et al., 2006; Olivers & Eimer, 2011; Soto et al., 2005; Soto & Humphreys, 2007; van Moorselaar et al., 2014; Zhang et al., 2011). In these studies, participants had to discriminate a feature of the search target, which was present in the search array on every trial. For example, the search task was to find a tilted line among vertical lines and report the orientation of the target line. To the best of our knowledge, in the literature regarding the effect of a distractor matching the content of working memory in visual search, there has been only three published studies that used search tasks in which a prespecified target could be either present or absent on a given trial, and participants had to detect the presence of the target rather than discriminate the target's feature (Balani et al., 2010; Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006). There is an important aspect of the search process in such target-detection search tasks (Moher, 2020)—that is, when is it time to terminate search if no target has been found? This problem of search termination, however, has been completely neglected in previous studies regarding the relationship between working memory and visual search. Motivated by this observation, the present study is concerned with how the presence of a distractor matching the content of working memory affects quitting behavior in visual search. Our study would have implications for understanding the role of working memory representations in search termination, about which very little to date has been known.

In models of visual search, it is assumed that observers set a quitting threshold when performing a target-detection search task (e.g., Chun & Wolfe, 1996; Wolfe, 2021; Wolfe & Van Wert, 2010). According to these models, if a target is not found in the search display, then search will terminate when an accumulating quitting signal reaches that threshold. Thus, the quitting threshold determines how much time observers are willing to spend on searching before they abandon the search and report that no target is present. The quitting threshold is supposed to be set adaptively during visual search. Feedback about prior search performance can change the quitting threshold for subsequent searches (e.g., Chun & Wolfe, 1996; Wolfe, 2021). The threshold will be lowered after a correct rejection, advancing subsequent search terminations. In contrast, the threshold will be raised after a miss error, delaying subsequent search terminations. This adaptive process of setting the quitting threshold can also be influenced by target prevalence—that is, the prior probability of target presence (e.g., Fleck & Mitroff, 2007; Ishibashi et al., 2012; Wolfe et al., 2005; Wolfe et al., 2007), in that the quitting threshold would be decreased if target prevalence is low. Moreover, recent research by Moher (2020) shows that the presence of a physically salient distractor in the search array can reduce the quitting threshold, leading to faster search times on target-absent trials and more miss errors on target-present trials. The importance of Moher's (2020) study is that it provides the first evidence suggesting that in addition to initial effects of attentional capture, distracting objects can also exert long-lasting effects on search performance by changing the threshold for when to terminate search.

In the present study, we sought to extend the previous research by examining whether the presence of a distractor matching the target-unrelated content of working memory influences the process of search termination. In order to determine the effect of a memory-matching distractor on search termination, it is critical to include a target-detection search task during working memory maintenance. As noted above, there has already been three published studies using such a task paradigm to assess the effect of a memory-matching distractor in visual search (Balani et al., 2010; Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006). However, all of these studies concerned only the effect of attentional capture by a memory-matching distractor, and none of them even mentioned the plausible distractor effects on search termination. In fact, some of these studies found slower search times for matching-distractor trials than for no-match trials in the target-absent condition, but they erroneously considered this finding to reflect the effect of attentional capture by a memory-matching distractor (Balani et al., 2010; Houtkamp & Roelfsema, 2006). Note that the slowing of search times on matching-distractor trials can be routinely considered a reflection of attentional capture in the target-present condition but not in the target-absent condition. Specifically, in a serial search process, attention can initially shift to the target on some trials when the target is present in the search array. If the presence of a memory-matching distractor captures attention, this would make the initial shift of attention away from the target and hence increase the amount of time required to find the target. However, when the target is absent, all stimuli in the search array are nontargets, and hence there is no possibility of selecting the target with the initial shift of attention regardless of the presence of a memory-matching distractor. Accordingly, the previously reported delay effect of a memory-matching distractor on search times in the target-absent condition (Balani et al., 2010; Houtkamp & Roelfsema, 2006) cannot be considered to reflect the initial capture of attention by a memory-matching distractor. Instead, given the separation between finding a target and terminating a search without finding a target (Wolfe & Van Wert, 2010), the previously reported effect of a memory-matching distractor on search times for target-absent trials may actually reflect the influence of a distractor matching the content of working memory on search termination when no target has been found. The present study therefore sought to provide direct demonstrations for this idea. Our findings would offer a novel perspective on how the presence of a distractor object matching the content of working memory interacts with visual search.

Experiment 1

The aim of this experiment was to establish the effect of a distractor matching the target-unrelated content of visual working memory on search termination times. Participants were required to maintain a sample color in visual working memory, followed by a visual search task in which they had to detect the presence of a target among distractors. The sample color would never be related to the search target. Critically, one of the distractors in the search array could match the sample color held in working memory. Based on the findings of previous studies (Balani et al., 2010; Houtkamp & Roelfsema, 2006), we predicted that the presence of a distractor matching the current content of working memory would capture attention on target-present trials and delay search termination on target-absent trials, leading to longer response times (RTs) when one of the distractors in the search array matched the memory sample on both target-present and target-absent trials.

Method

Participants

A total of 20 adult students (16 females; 19–25 years of age) from Hangzhou Normal University participated in this experiment for monetary compensation. We calculated the sample size required to detect the significant search RT difference between matching-distractor trials and no-match trials in the target-absent condition ($\eta_p^2 = 0.563$) reported in Houtkamp and Roelfsema's (2006) Experiment 2B in which visual working memory for color stimuli was used. We conducted this power analysis using MorePower (Campbell & Thompson, 2012), with 95% power, at an alpha level of 0.05. We found the minimum of sample size required to be 14 participants. In this and the following experiments, all participants were right-handed and reported having normal or corrected-to-normal vision. Informed consent was obtained from each participant prior to the experiments, which were conducted in accordance with the tenets of the Declaration of Helsinki and local ethics regulations.

Apparatus and stimuli

The experiment was controlled by E-Prime software. Responses were made by pressing keys on a standard keyboard. Stimuli were presented on a 19-in. LCD monitor with a resolution of 1,440 × 900 pixels and a 60-Hz refresh rate. All stimuli were presented on a black background at a viewing distance of approximately 60 cm. The memory sample was a colored square (1.5° × 1.5°), whose color category was selected at random from a set of five (red, green, blue, yellow, and purple) on each trial. Within a selected color category, the specific color value was randomly chosen from a pool of five similar colors, each of which was produced by RGB coordinates. The memory-test display contained two squares: one in the color of the memory sample (correct alternative) and the other in a color selected randomly from the remaining four colors within the same category (false alternative). The two colored squares were presented 6° to the left and right of the central fixation, with the positions of the two alternatives determined randomly. This within-category discrimination task served to minimize verbal encoding of the memory sample, ensuring that visual working memory would be used (cf. Hollingworth et al., 2013; Pan & Zhang, 2020).

The search display contained four colored outlined squares (each 1.5° × 1.5°, 0.2° line thickness), each of which had a gap (0.9°) on one of its four sides. The color category of each Landolt-C-like square in the search array was randomly selected without replacement from the same set of five color categories described previously. In each search display, one Landolt-C-like square was defined as the target that had a gap on the right or the left, and the remaining three Landolt-C-like squares were defined as the distractors that had gaps on the top or the bottom. The search items were presented at the four corners of an imaginary square centered on fixation, with an

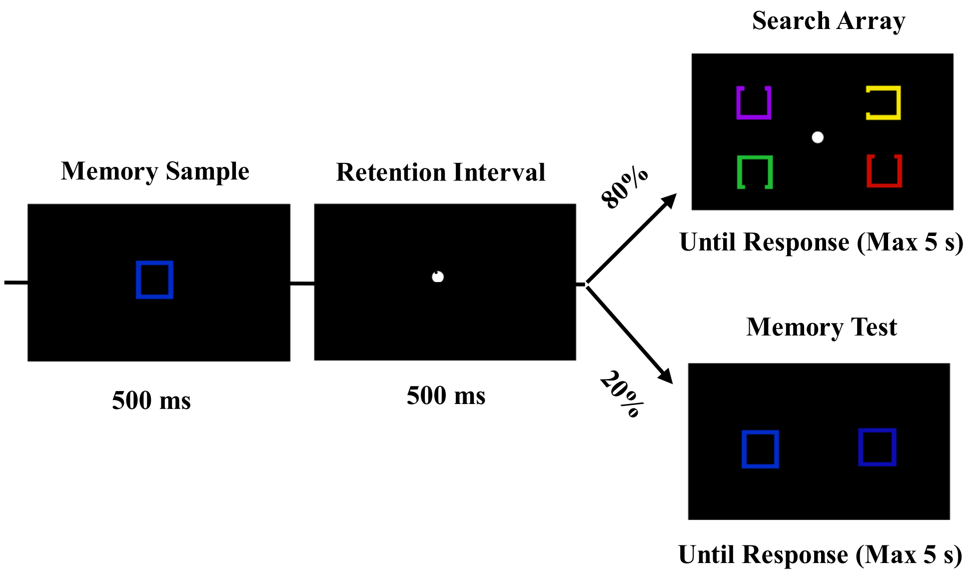

Fig. 1 Schematic illustration of the trial sequence and example stimuli in Experiment 1. The memory sample could be followed by a search array on 80% of the trials or by a memory test on the remaining 20% of the trials

eccentricity of 6° of visual angle. The target, when it was present, appeared equally often at four possible locations.

Procedure and design

Participants initiated each trial by pressing the space bar. As shown in Fig. 1, each trial began with a 500-ms presentation of the memory sample. Here, participants were instructed to memorize the color of the sample and to keep it in mind throughout the entire trial. The memory sample was followed by a 500-ms interval during which only a central fixation dot was displayed. Then, a visual search array that contained four colored Landolt-C-like squares was presented. The target could be either present or absent in the search array. The target-present and target-absent conditions occurred equally often and varied randomly across trials. Participants were required to press with their left hand the "A" key if the target was present and the "S" key if the target was absent. The search display remained in view until response was made or until 5,000 ms had passed. Critically, there were two types of trials, each defined by the matching between the search array and the memory sample. On the matching-distractor trials, one of the distractor stimuli in the search array was drawn in the same color as that of the memory sample. On the mismatching-distractor trials, the colors of all the search stimuli were different from the color of the memory sample. These two types of trials occurred equally often and in randomized order for both the target-present and target-absent conditions. Note that when the target was present in the search array, it would never match the color of memory sample.

In the experimental session, on 20% of all trials, instead of the visual search display, a memory-test display was presented to ensure that the memory sample was maintained in working memory. On these memory catch trials, participants were asked to make an unspeeded judgment regarding which of the two squares in the memory-test display had the same color as the memory sample. They pressed with their right hand the "K" key if the left square shared its color with the memory sample, and the "L" key if the right square shared its color with the memory sample. Participants were encouraged to perform both the visual search task and working memory task as accurately as possible, and response time on the search task was also emphasized. Each participant completed 20 practice trials, followed by 400 experimental trials.

Note that participants should actively maintain the sample color until the onset of the search display, as they cannot anticipate whether the search task or the memory test would be required on a given trial. However, we suggest that when the search array was displayed, the irrelevant color may not be removed immediately or completely from working memory, because the removal process is slow and gradual (Lewis-Peacock et al., 2018). The procedure that separates the search task and memory test across trials has also been used in previous studies examining the effects of working memory representations on visual search (e.g., Downing & Dodds, 2004; Kiyonaga et al., 2012). And the results of these study suggest that the irrelevant information is still maintained in working memory during visual search, exerting impacts on search performance. More importantly, because memory would not be probed after the visual search task, the use of this procedure ensures that there should be no strategic incentive for participants to voluntarily shift attention toward a memory-matching distractor in the search display so that they could refresh their memory representation of the sample color to help complete the memory test.

Data analysis

In all of the experiments reported here, a repeated-measures analysis of variance (ANOVA) with target (present vs. absent) and distractor (matching vs. mismatching) as within-subject factors was conducted separately on accuracy rates (percentages of correct responses) and RTs for correct responses in the visual search task. This omnibus analysis was then followed by two separate planned contrasts between matching-distractor and mismatching-distractor trials for the target-present and target-absent data, using paired-samples *t* tests. All *t* tests over search accuracy rates without a priori directional hypotheses were two-sided; all *t* tests over search RTs were one-sided, because a priori directional hypotheses (i.e., slower search times on matching-distractor trials than on mismatching-distractor trials) were made for search RTs results.

Results and discussion

Overall, accuracy on the memory test was 75.3% correct on average, which was similar to that reported in previous studies using a within-category discrimination task for the memory test (e.g., Bahle et al., 2018; Hollingworth et al., 2013; Pan & Zhang, 2020). Mean accuracy on the visual search task was high (98.7% correct). The search accuracy rates across different conditions are shown in Table 1. A two-way ANOVA over the search accuracy data showed that there was a significant main effect of target, $F(1, 19) = 16.170$, $p = .001$, $\eta_p^2 = .460$, in that accuracy rates were lower overall when the target was present ($M = 98.1\%$) than when the target was absent ($M = 99.3\%$), consistent with the findings of previous research (e.g., Chun & Wolfe, 1996; Lawrence & Pratt, 2022; Moher, 2020; Treisman & Gelade, 1980). The main effect of distractor was just significant, $F(1, 19) = 5.381$, $p = .032$, $\eta_p^2 = .221$, with lower accuracy rates on matching-distractor trials ($M = 98.4\%$) than on mismatching-distractor trials ($M = 98.9\%$). There was no interaction effect between the two factors, $F < 0.001$. However, the planned contrasts revealed that while the effect of a memory-matching distractor in the target-absent condition reached statistical significance, $t(19) = 2.179$, $p = .042$, Cohen's $d = .487$, the effect of a memory-matching distractor in the target-present condition did not approach significance, $t(19) = 1.322$, $p = .202$, Cohen's $d = .296$. We suggest that the effect of the presence of a memory-matching distractor on search accuracy was trivial and could be ignored, especially considering that the magnitude of the effect (0.5%) was minimal.

The outcome of a two-way ANOVA over search RTs showed that the main effect of target was significant, $F(1, 19) = 8.297$, $p = .010$, $\eta_p^2 = .304$. Visual search RTs were significantly faster when the target was present ($M = 976$ ms) than when the target was absent ($M = 1{,}065$ ms). This is the typical finding for a visual search task with the target prevalence of 50% and is consistent with the pattern of results reported previously in the literature (e.g., Balani et al., 2010; Houtkamp & Roelfsema, 2006; Moher, 2020; Wolfe et al., 2005). The main effect of distractor was also significant, $F(1, 19) = 10.567$, $p = .004$, $\eta_p^2 = .357$, in that visual search RTs were slower on matching-distractor trials ($M = 1{,}036$ ms) than on mismatching-distractor trials ($M = 1{,}005$ ms). There was no significant interaction between the two factors, $F(1, 19) = 0.422$, $p = .524$, $\eta_p^2 = .022$. The planned contrasts further confirmed the significant effect of a memory-matching distractor on search times both in the target-absent condition, $t(19) = 3.088$, $p = .003$, Cohen's $d = .691$, and in the target-present condition, $t(19) = 1.833$, $p = .041$, Cohen's $d = .410$. This pattern of RTs results is depicted in Fig. 2.

The serial search process begins at the onset of a visual search array composed of Landolt-C-like squares (Woodman & Luck, 1999, 2003). These data suggest that when the target is present in the search array, the presence of a memory-matching distractor can capture attention and make the initial shift of attention away from the target, thereby increasing the overall time required to find the target. However, given that there is no possibility of selecting the target with the initial shift of attention when the target is absent because all stimuli in the search array are nontargets, the slower search RTs for matching-distractor trials than for mismatching-distractor

Table 1 Mean percentages of correct responses in the visual search task for Experiments 1-3

	Target absent		Target present	
	Mismatching distractor	Matching distractor	Mismatching distractor	Matching distractor
Experiment 1	99.6% (0.7%)	99.1% (1.1%)	98.3% (1.6%)	97.8% (1.8%)
Experiment 2	99.4% (1.0%)	99.2% (1.0%)	96.3% (4.1%)	96.8% (3.6%)
Experiment 3	99.7% (0.7%)	99.6% (0.7%)	95.3% (7.1%)	94.8% (9.1%)

Note. Standard deviations are included in parentheses trials in the target-absent condition cannot be considered the effect of attentional capture by a memory-matching distractor. Rather, the results indicate that when no target has been found, search termination tends to occur later on matching-distractor trials than on mismatching-distractor trials. In other words, the slowing of search times for matching-distractor trials when the target is absent suggests that the presence of a memory-matching distractor causes participants to raise their quitting threshold in visual search, spending more overall time searching the display before deciding that no target is present.

Experiment 2

The aim of this experiment was to examine whether the effects of a memory-matching distractor are specific to active maintenance of the sample color in visual working memory. It is possible that a more passive visual short-term memory (i.e., visual priming) of the sample color might also lead the matching distractor to capture attention and delay quitting in visual search. Experiment 2 was designed to test this possibility. Here, we asked participants to identify the sample color but did not make any explicit demands on working memory. If the attentional capture and delayed quitting effects observed in Experiment 1 reflect the more general influences of visual short-term memory and are not exclusively generated by visual working memory, then the effects should generalize to visual priming wherein the sample color is merely identified without working memory requirements. However, the absence of an effect of the matching distractor under the condition of visual priming would mean that the sample color has to be encoded and maintained in visual working memory to produce the effect.

Method

This was similar to that used in Experiment 1 with the following exceptions. A new group of 20 students (four males; 18–25 years of age) from the same pool participated in this experiment for monetary compensation. These participants were asked to attend the color of the sample, but they received no

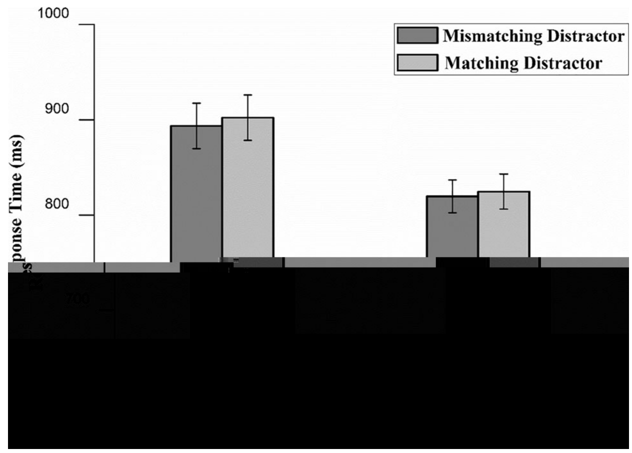

Fig. 3 Mean correct search times for Experiment 2, as a function of target and distractor. Error bars represent within-subject 95% confidence intervals (Loftus & Masson, 1994)

attention or delay quitting in visual search. This therefore rules out the possibility that the effects of a matching distractor observed in Experiment 1 are due just to the mechanism of visual priming. We suggest that the attentional capture and delayed quitting effects of a matching distractor in visual search are specifically attributed to visual working memory.

Experiment 3

The preceding two experiments were conducted with a high target prevalence of 50% in visual search. This final experiment sought to replicate the delayed quitting effect of a memory-matching distractor with a change in target prevalence for the visual search task. Previous research has shown that target prevalence affects quitting behavior in visual search, with search RTs becoming faster on target-absent trials when target prevalence is lower than 50% (e.g., Moher, 2020; Wolfe et al., 2005; Wolfe & Van Wert, 2010). This suggests a lowering of the quitting threshold at low target prevalence, so that observers spend less overall time on visual search before deciding that no target is present. In Experiment 3, the target was present on only 20% of the trials in which the visual search task had to be completed following the memory sample. We tested whether the presence of a memory-matching distractor might still delay search termination times when target prevalence was relatively low.

Method

This was virtually identical to the method of Experiment 1, except that the target appeared on only 20% of the search trials. A new group of 31 university students (eight males; 18–25 years of age) from the same pool participated in this experiment for monetary compensation. Each participant complete 20 practice trials, followed by a total of 500 experimental trials in which 400 search trials and 100 memory-test trials were intermixed randomly.

Results and discussion

Performance on memory-test trials was 80.8% correct on average. Mean accuracy on the visual search task was high (97.4% correct). The search accuracy rates across different conditions are shown in Table 1. The outcome of a two-way ANOVA over the search accuracy data showed that the main effect of target was significant, $F(1, 30) = 11.067$, $p = .002$, $\eta_p^2 = .269$, with less accurate search performance when the target was present ($M = 95.1\%$) than when the target was absent ($M = 99.6\%$). Neither the main effect of distractor, $F(1, 30) = 0.555$, $p = .462$, $\eta_p^2 = .018$, nor the interaction effect, $F(1, 30) = 0.125$, $p = .727$, $\eta_p^2 = .004$, reached statistical significance. The planned contrasts further confirmed that there was no effect of a memory-matching distractor on search accuracy either in the target-present condition, $t(30) = 0.551$, $p = .586$, Cohen's $d = .099$, or in the target-absent condition, $t(30) = 1.114$, $p = .274$, Cohen's $d = .200$.

A two-way ANOVA over search RTs showed that the difference between the RTs on target-present trials ($M = 934$ ms) and on target-absent trials ($M = 920$ ms) did not approach significance, $F(1, 30) = 0.494$, $p = .488$, $\eta_p^2 = .016$. This finding was consistent with data reported in previous studies (e.g., Moher, 2020; Wolfe et al., 2005), suggesting that the typical target-presence effect on search times (i.e., faster search RTs on target-present trials than on target-absent trials when target prevalence is 50%) can be absent or even reversed at low target prevalence. This occurs probably because while target-absent RTs decrease as the target prevalence declines, target-present RTs are minimally affected by the target prevalence (e.g., Ishibashi et al., 2012; Wolfe & Van Wert, 2010). The main effect of distractor approached statistical significance, $F(1, 30) = 3.602$, $p = .067$, $\eta_p^2 = .107$, with slower search RTs on matching-distractor trials ($M = 935$ ms) than on mismatching-distractor trials ($M = 918$ ms). The interaction effect between the two factors did not approach significance, $F(1, 30) = 0.076$, $p = .785$, $\eta_p^2 = .003$. However, when we analyzed the target-present and target-absent data separately, it revealed that while the effect of a memory-matching distractor on search times was reliable in the target-absent condition, $t(30) = 2.353$, $p = .013$, Cohen's $d = .423$, it was not reliable in the target-present condition, $t(30) = 0.959$, $p = .173$, Cohen's $d = .172$. This pattern of RTs results is depicted in Fig. 4.

The results showed the slowing of search termination times by a memory-matching distractor on target-absent trials, suggesting that the presence of a memory-matching distractor can still raise the quitting threshold in visual search with relatively low target prevalence. This finding replicated and extended the delayed quitting effect of a memory-matching distractor

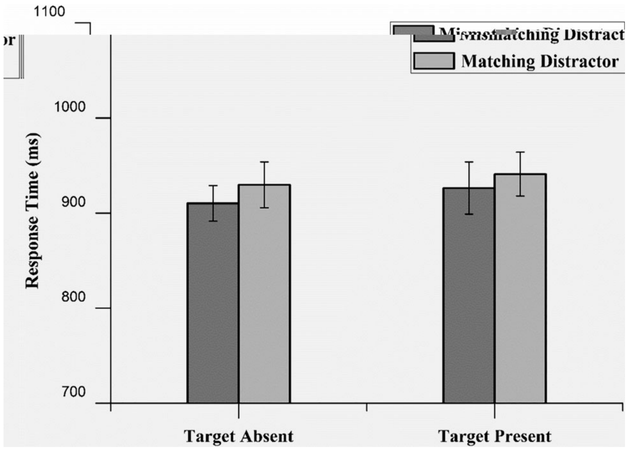

Fig. 4 Mean correct search times for Experiment 3, as a function of target and distractor. Error bars represent within-subject 95% confidence intervals (Loftus & Masson, 1994)

observed in the first experiment to a search condition in which the target appeared infrequently. Thus, the presence of a memory-matching distractor can raise quitting thresholds under both high (i.e., 50%) and low (i.e., 20%) target-prevalence search conditions. This was further confirmed by a comparison of the RT data on target-absent trials between Experiments 1 and 3. The outcome of a mixed ANOVA over target-absent RTs with distractor and experiment as factors showed that the main effect of experiment was significant, $F(1, 49) = 6.057$, $p = .017$, $\eta_p^2 = .110$, suggesting that search termination times on target-absent trials decrease as the target prevalence declines. Crucially, the main effect of distractor was reliable, $F(1, 49) = 16.034$, $p < .001$, $\eta_p^2 = .247$, and it did not differ significantly between experiments, $F(1, 49) = 1.520$, $p = .224$, $\eta_p^2 = .030$. Thus, the magnitude of the delayed quitting effect of a memory-matching distractor at 20% target prevalence seems to be comparable to that at 50% target prevalence. Of course, given that we did not examine distractor effects on search termination times in a greater range of target prevalence, it remains unclear whether the effect of the presence of a memory-matching distractor on search termination times can be modulated by target prevalence. This issue will need to be addressed in future research.

Note that here we did not obtain reliable evidence for the memory-driven attentional capture effect when the search target was present. The absence of an effect of a memory-matching distractor on search times for target-present trials may reflect the fact that under some circumstances manual RTs are not sensitive enough to measure attentional capture effects occurring early during visual search. Indeed, previous studies have shown that the attentional capture effect of a memory-matching distractor can be reliably reflected in oculomotor but not in manual measures (e.g., Bahle et al., 2018; Zhang et al., 2018). That is to say, although we failed to find clear evidence for the capture effect with the measure of overall search time at 20% prevalence, it does not necessarily exclude the possibility that the memory-matching distractors could have captured attention on target-present trials in Experiment 3. This possibility is likely if one considers that the distractor effect on search times did not significantly vary according to whether the target was present, as indicated by the lack of an interaction between the two factors of distractor and target.

General discussion

The process of search termination can be constrained by several factors, such as feedback about past search performance, target prevalence, and even the intrinsic value of the search target (Wolfe, 2012, 2021). Moreover, recent research by Moher (2020) shows that the presence of a physically salient distractor induces early quitting in visual search, highlighting a critical role of a particular distractor in constraining search termination. The present study extends this previous work by examining whether the presence of a distractor matching the information kept in working memory can affect search termination times. The results showed that the presence of a distractor matching the content of visual working memory influenced quitting behavior in visual search, with longer search termination times when the memory-matching distractor was present compared with when it was absent. This pattern of results was observed when target prevalence was either high or low. The results suggest that the presence of a memory-matching distractor raises the quitting threshold, leading to delayed quitting in visual search. Importantly, this distractor effect on search termination cannot be considered a more general influence of visual short-term memory, because visual priming (i.e., a form of passive visual short-term memory) of the memory sample did not lead the matching distractor to influence quitting behavior in visual search. It is therefore conceivable that the currently observed distractor effect on search termination is exclusively generated through active maintenance of information in visual working memory. The present results extend previous work, which has established that the presence of a physically salient distractor causes search termination to occur earlier (Moher, 2020; but see Lawrence & Pratt, 2022). Here, we further corroborate distractor effects on quitting behavior in visual search by demonstrating that the presence of a distractor matching the content of visual working memory causes search termination to occur later.

Therefore, combining the findings of Moher's (2020) study and ours provides evidence that physically salient distractors and memory-matching distractors change the quitting threshold in opposite directions. Specifically, physically salient distractors induce early quitting in visual search, whereas distractors that match the content of working memory elicit late quitting in visual search. Thus, although both of these two forms of distractors can capture attention and interfere with the process of finding a target (e.g., Jung et al., 2020), they nevertheless exert opposite effects on search termination times when no target is found. While the exact mechanisms by which these distractor-induced effects on search termination are functionally implemented are unclear, we speculate that the difference between bottom-up and top-down influences on a saliency map of the search display (e.g., Itti & Koch, 2000) may be responsible for the different effects of physically salient distractors and memory-matching distractors on quitting behavior in visual search. This seems highly likely in light of the competitive guided search model (Moran et al., 2013), which posits that quitting decisions in visual search are tightly linked to the overall activity on a saliency map.

One might argue that the delay effect of a memory-matching distractor on search times in the target-absent condition could be attributed to delayed disengagement of attention from the memory-matching distractor. However, this seems unlikely if one considers evidence that when the eyes are captured, they do not dwell on the memory-matching distractor for longer than on the memory-mismatching distractor (e.g., Houtkamp & Roelfsema, 2006; Olivers et al., 2006). That said, given the lack of eye-tracking data in the present study, the possibility of delayed disengagement contribution to the slowing of search times on matching-distractor trials cannot be excluded completely. But even in this possibility, it would still be consistent with our claim that observers spend more overall time on searching when a distractor that matches the content of working memory is present before they quit the search and report that no target is present.

The present finding that the presence of a distractor matching the content of working memory delays search termination times is consistent with the results of previous studies showing the effects of a memory-matching distractor on search performance on target-absent trials (Balani et al., 2010; Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006). Specifically, it has previously been reported that search times on target-absent trials were lengthened by the presence of a memory-matching distractor (Balani et al., 2010; Houtkamp & Roelfsema, 2006) and that search performance on target-present trials was more accurate when a memory-matching distractor was present (Downing & Dodds, 2004, Experiments 1 and 2). Nevertheless, these previous findings were either wrongly conceived to reflect the capture of attention by the memory-matching distractor (Balani et al., 2010; Houtkamp & Roelfsema, 2006) or completely neglected in the interpretation of the observed data (Downing & Dodds, 2004). We suggest that this line of previously reported data might otherwise be considered to reflect the modulation of search termination by the presence of a distractor that matches the content of working memory.

Note that although Downing and Dodds (2004) failed to obtain any significant effects of a memory-matching distractor on search times for target-absent trials, their finding that search accuracy on target-present trials was higher when the memory-matching distractor was also present suggests that the presence of a memory-matching distractor could have affected the process of search termination in their study. This claim is grounded on the notion that changes in the quitting threshold could influence miss errors on target-present trials due to a speed-accuracy trade-off, in that later search quitting is typically accompanied by less miss errors (e.g., Fleck & Mitroff, 2007; Moher, 2020; Wolfe et al., 2005). Accordingly, it is possible that in Downing and Dodds's (2004) study the presence of a memory-matching distractor may lead observers to raise their quitting thresholds and to terminate their searches later, through which miss errors decreased and search accuracy improved on target-present trials when the memory-matching distractor was also present. Altogether, the previously reported data showing effects of a memory-matching distractor on search accuracy for target-present trials (Downing & Dodds, 2004) and on search time for target-absent trials (Balani et al., 2010; Houtkamp & Roelfsema, 2006) are consistent with the claim that the presence of a distractor matching the content of working memory delays search termination.

It should also be noted that the present study did not observe any effects of a memory-matching distractor on miss errors for target-present trials. The only distractor effect on search accuracy that we observed was a minimal increase in false alarms for target-absent trials in Experiment 1. If search termination times can influence miss errors through the mechanism of a speed–accuracy trade-off as suggested by some previous studies (e.g., Fleck & Mitroff, 2007; Moher, 2020; Wolfe et al., 2005), why did the presence of a memory-matching distractor delay search termination times without a decrease in miss errors in the present study? We suggest that changes in miss errors could be only partly driven by the mechanism of a speed–accuracy trade-off in visual search. A change in miss errors (and also in false alarms) may be mainly caused by a shift in the decision criterion that governs the series of perceptual decisions as to whether each attended item is the target during search (e.g., Ishibashi et al., 2012; Wolfe et al., 2007; Wolfe & Van Wert, 2010). Given that this decision criterion is dissociable from the quitting threshold that governs the timing of target-absent responses (Wolfe & Van Wert, 2010), it is plausible that the presence of a memory-matching distractor could affect search termination times without any effects on miss errors by changing the quitting threshold but not the decision criterion.

Importantly, the present work goes beyond previous studies that have emphasized the interference effect of attentional capture by a memory-matching distractor when the target is present in visual search (e.g., Bahle et al., 2018; Hollingworth

& Beck, 2016; Olivers et al., 2006; Olivers & Eimer, 2011; Soto et al., 2005; Soto & Humphreys, 2007). The current study addresses a qualitatively different issue than previous studies: We focus on the question of whether the presence of a distractor object that matches the current content of working memory affects quitting decisions in visual search. Our findings offer a novel perspective that the presence of a memory-matching distractor can interact with visual search by delaying search termination when no target has been found. Altogether, we conclude from the existing evidence that a distractor object that matches the content of working memory can interact with visual search through two different mechanisms—namely, that the memory-matching distractor captures attention with an interference with target selection and delays search termination without finding a target.

Data availability The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Conflicts of interest The authors declare that they have no conflicts of interest with respect to the authorship or the publication of this article.

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