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Attentional Guidance by Working Memory Overrides Salience Cues in Visual Search

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Many factors influence visual search, including how much targets stand out (i.e., their visual salience) and whether they are currently relevant (i.e., Are they in working memory?). Although these are two known influences on search performance, it is unclear how they interact to guide attention. The present study explored this interplay by having participants hold an item in memory for a subsequent test while simultaneously conducting a multiple-target visual search. Importantly, the memory item could match one or neither of two targets from the search. In Experiment 1, when the memory item did not match either target, participants found a high-salience target first, demonstrating a baseline salience effect. This effect was exaggerated when a high-salience target was in working memory and completely reversed when a low-salience target was in memory, demonstrating a powerful influence of working memory guidance. Experiment 2 amplified the salience effect by including very high-salience, "pop-out"-like targets. Yet this salience effect was still attenuated when the memory item matched a less salient target. Experiment 3 confirmed these were memory-based effects and not priming. Collectively, these findings illustrate the influential role of working memory in guiding visual attention, even in the face of competing bottom-up salience cues.

Keywords: visual attention, working memory, attentional guidance, salience

At any given moment, the human visual system receives more input than it can process, necessitating attentional mechanisms that filter and select a subset of information for further processing. An important question to consider is what determines the filtering and selection such that certain items are processed more so than others. In general, attentional selection is thought to be influenced by "bottom-up" cues (e.g., when attention is captured by an item's physical distinctiveness) and "top-down" cues (e.g., when attention is directed toward a task-relevant location). Several theoretical models (e.g., Treisman, 1986; Wolfe, 1994) embrace the idea that visual attention is guided by a reciprocal interaction between both bottom-up and top-down factors (see Folk, Remington, & Johnston, 1992; Theeuwes, 2010, regarding the temporal dynamics of bottom-up and top-down influences on visual selection). Although there has been substantial research investigating bottom-up or top-down influences on attention, less work has focused on bottom-up *and* top-down influences, specifically exploring the interactions between the two (e.g., Awh, Belopolsky, & Theeuwes, 2012; McMains & Kastner, 2011; Soto, Humphreys, & Heinke, 2006). To better understand the interplay between these two factors, and to inform the nature of attentional guidance, the current study simultaneously examined two specific factors: bottom-up visual salience and top-down working memory representations.

In terms of bottom-up attentional selection, visual salience is often defined as differences in visual cues (e.g., luminance, color, motion, orientation, depth) between an item and the rest of the visual field (e.g., Nothdurft, 2002; Theeuwes, 2010). Neurophysiological studies in monkeys have demonstrated that salience is represented neurally by retinal ganglion cells that emphasize discontinuities (Treue, 2003) and cortical V4 cells that respond preferentially to the highest contrast within their receptive fields (Reynolds & Desimone, 2003). In humans, behavioral evidence has also shown that local contrast in at least one feature dimension, such as color, form, or luminance, in the visual field can capture attention (Nothdurft, 1993, 2002; Turatto & Galfano, 2000). Furthermore, several computational models of visual attention have successfully implemented maps of visual salience values in guiding bottom-up control of attention (e.g., Harel, Koch, & Perona, 2007; Itti & Koch, 2000; Parkhurst, Law, & Niebur, 2002).

Previous research has also established a top-down role for working memory in guiding attention (see Olivers, Peters, Houtkamp, & Roelfsema, 2011; Soto, Hodsoll, Rotshtein, & Humphreys, 2008, for recent reviews). One theory of task-relevant attentional guidance posits that active maintenance of a search template in working memory biases attention toward items in the visual field that match the template (Desimone & Duncan, 1995). To test this hypothesis, several studies have used a dual-task

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paradigm in which participants are asked to remember an item (e.g., a colored shape) while performing an intervening visual search task (e.g., Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005; Woodman & Luck, 2007). Critically, the memory item might reappear in the search display as a search target or as an irrelevant distractor. Compared to a neutral condition, in which the memory item does not match any item in the array, search times are faster when the memory item matches the target and slower when the memory item matches a distractor (Downing, 2000; Olivers et al., 2006; Soto et al., 2005). These results have been replicated with eye-tracking, with participants making more first saccades to the location matching the memory item (Olivers et al., 2006; Soto et al., 2005).

An important consideration in the attentional guidance literature is whether attentional effects are driven by working memory or by bottom-up priming, such that mere exposure to the "memory" item, without a memory requirement, would be sufficient to bias the deployment of attention. Previous studies (e.g., Downing, 2000, Experiment 3; Soto et al., 2005, Experiment 3) have addressed this possibility by including a control condition in which participants are presented with an item before a search but know they will not be tested in a subsequent memory task; neither study found attentional guidance effects when there was no requirement to hold the item in working memory. In another study, the order of tasks was changed such that the memory test was administered *prior* to the search task, effectively "priming" the item representation twice (once during the memory item presentation and once during the memory item test; Olivers et al., 2006, Experiment 5). Even so, no attentional effects were found, suggesting that, after the memory test was completed, the memory item was released from working memory and thus lost its effect on guiding visual attention (Olivers et al., 2006). These previous studies strongly suggest that attentional guidance effects are driven by working memory and not by simply priming low-level features in the search array, and the current study extended and confirmed this conclusion.

Current Goals

A critical issue is whether there is an interaction between bottom-up salience and top-down working memory. Soto et al. (2006) approached this question by measuring working memory guidance of attention in search tasks that contain a more or less salient target. Search times were faster when the memory cue matched the target and slower when the memory cue matched a distractor, but performance benefits and costs were amplified for higher salience targets compared to lower salience targets. Furthermore, when search arrays included a "pop-out" target (i.e., a target with a flat search slope over increasing set sizes; Treisman, 1986), already efficient search times were still faster when the memory cue matched the target. Thus, top-down working memory cues are able to enhance visual salience cues, resulting in more efficient attentional guidance.

The above argues for working memory contents being able to guide search, but just how strong is this working memory guidance? Previous research has showed that working memory contents can additively enhance the effects of visual salience, but can working memory cues in fact override the attentional priority of visual salience? Such results would argue for an important top-down role for working memory representations in guiding attention.

The current study examined bottom-up visual salience and top-down working memory cues as competing forces, specifically looking at how working memory guidance might enhance detection of a less salient target. Three experiments investigated whether working memory can modulate the detection of more salient and less salient targets within the same search array. In Experiments 1A and 1B, we used a dual-task procedure similar to that of Soto et al. (2005), combining a working memory task with an intervening search task. However, to align our findings with previous visual search literature, our search task used larger search arrays (i.e., 25–35 items) with less discriminable search stimuli (e.g., Wolfe, 1998; Wolfe & DiMase, 2003). Critically, we adopted a multiple-target search paradigm, which can provide a different perspective on search dynamics (e.g., Fleck, Samei, & Mitroff, 2010; Horowitz & Wolfe, 2001). Our search arrays could contain up to two targets, one more salient and one less salient, such that the influence of working memory could be directly pitted against effects of visual salience. Experiment 2 amplified visual salience effects to gauge the limits of working memory cues on attentional guidance. Experiment 3 tested whether search effects were attributable to working memory or to bottom-up priming alone. To preview the results, top-down working memory biases were strong enough to override bottom-up salience cues and enhance the detection of a less salient target. These findings indicate that the deployment of attention in visual search can be modulated by a competitive balance between visual salience effects and relatively strong working memory cues, indicating an influential role of working memory on guiding visual attention.

General Method

All three experiments in this study used a similar paradigm, detailed here. Any differences from this paradigm are noted for each experiment.

Apparatus

All experiments were conducted on a Dell Dimension E510/520 computer, running Windows XP, and were programmed in Matlab using Psychophysics Toolbox, Version 3.0 (Brainard, 1997). Participants viewed the experimental displays on a ViewSonic G90f CRT monitor with a refresh rate of 75 Hz at an approximate distance of 60 cm.

Stimuli

Based on previous studies (e.g., Cain, Dunsmoor, LaBar, & Mitroff, 2011; Cain & Mitroff, 2012; Fleck et al., 2010), the stimuli used here were Ts and pseudo-Ls. Each stimulus item consisted of two perpendicular lines slightly separated from one other (stroke width = 0.3°, subtending 1.0° × 1.0° total), with target Ts having a crossbar aligned directly in the middle and with distractor Ls having the crossbar slid at variable distances away from the center (see Figure 1).

All stimuli were presented with varying luminance (i.e., shades of gray) on a white background. For the purposes of these experiments, visual salience is operationally defined as the contrast in

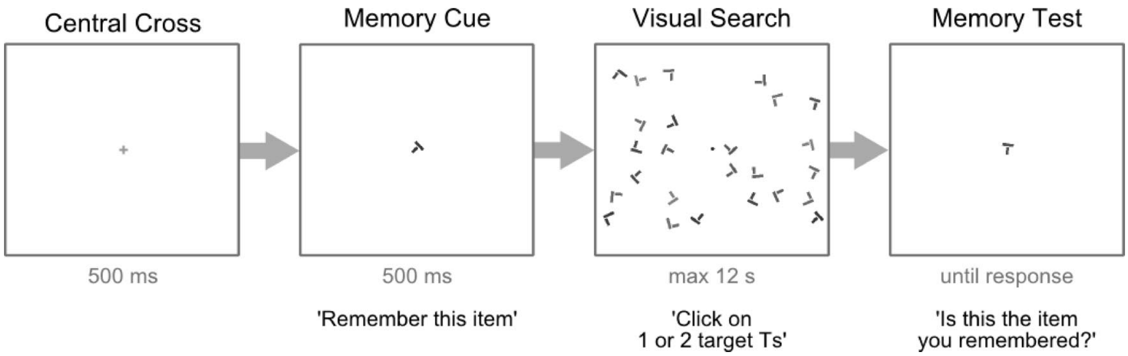

Figure 1. Example trial sequence of Experiment 1A showing a memory task with an intervening search task. In this example, the search task includes two targets, a high-salience target and a low-salience target. This trial depicts a valid, high-match trial because the memory cue matches the high-salience target in both luminance and orientation. The memory probe differs from the memory cue in this example.

luminance between an item and the rest of the array. Target Ts were presented at one or both of two visibility levels: high salience (range: 65–75% black) or low salience (range: 30–40% black). Distractor Ls were presented at varying shades of gray, which ranged between the low- and high-salience shades for each trial. For example, if on a given trial, the high-salience T was 73% black and the low-salience T was 36% black, then distractors were all less than 73% black but greater than 36% black. If a trial had only one target, for example, only the 73% black high-salience T, then distractors were all less than 73% black but greater than 30% black. This setup made high-salience Ts relatively easy to detect and low-salience Ts more difficult to detect. All stimuli were also presented at varying orientations (range: 6–356° in steps of 10°). Each stimulus was placed with a slight spatial jitter within randomly selected cells of an invisible 8 × 7 grid subtending 19.4° × 14.8°. Items did not overlap.

Procedure

Each trial began with the presentation of a central cross (stroke width = 0.2°, subtending 0.8° × 0.8°) for 500 ms (see Figure 1). The cross was followed by a blank screen for 300 ms, then by the memory item, a single T of random luminance (range: 30–75% black) and orientation (range: 6–356° in steps of 10°), which was presented at the center of the screen for 500 ms. Participants were instructed to remember both the color and the orientation of the memory item.

The memory item was followed by a blank screen for 300 ms, and then by the search array, which consisted of 25 items. There were one or two target Ts to find within each display. Participants used the mouse to click on each detected target item, regardless of luminance or orientation, then pressed the space bar to complete the search. Each search had a time limit of 15 s, after which no further clicks were accepted and a message was displayed encouraging participants to try to finish searching and to press the space bar before time elapsed on subsequent trials. Responses made prior to the time limit were recorded and analyzed even if the space bar was not pressed.

The search array was followed by a blank screen for 300 ms, then by a probe item that appeared in the center of the screen until response. The probe item was a single T that was either identical to the memory item in both dimensions of luminance and orientation, or different on one or both dimensions. Participants reported via key press (“s” or “d,” respectively) whether the probe item was exactly the same as the previously seen memory item or different on either or both features. Feedback tones were used to indicate whether the memory probe response was correct (i.e., a short, high tone) or incorrect (i.e., a long, low tone), and were meant to encourage participants to remember the memory item.

Trial Conditions

Trials were classified across two factors: validity (i.e., valid or neutral) and search type (i.e., single-target low-salience, single-target high-salience, or dual-target low- and high-salience). The two validity conditions were defined by the relationship of the search items to the working memory cue. In valid trials, the memory item matched a target within the search display; if there was a match, the target was identical to the memory item on both dimensions of luminance and orientation. In neutral trials, the memory item matched neither a target nor any of the distractors on luminance or orientation. There was never an invalid condition, in which the memory item matched a distractor. There were three search types, each defined by the number and salience of the target Ts presented within the array of distractor Ls. The search array could include a single target, either a high-salience or a low-salience, or two targets, both a high-salience and a low-salience. For valid, dual-target trials, the memory item could match either the high-salience target (high match) or the low-salience target (low match). In total, there were seven different trial type combinations (see Table 1).

Each experiment began with a practice phase of 12 trials that was matched to the trial-type frequency of the rest of the experiment. During practice, immediate search feedback was provided on any false-positive identification or missed targets, in addition to memory feedback tones. The experimental phase consisted of 240 trials, which were counterbalanced by trial types according to validity, number of targets, and salience of targets (see Table 1). Neutral trials were equally as frequent as valid trials. No search feedback was provided during the experimental trials.

Table 1
Trial Types by Number of Search Targets, Salience of Search Targets, and Memory-to-Search Target Relationship

Number of targets in visual search	Salience of search targets	Memory-to-search target relationship	Memory-to-search target match condition
Single	High	Valid	High match (20)
		Neutral	Neutral (20)
	Low	Valid	Low match (20)
		Neutral	Neutral (20)
Dual	High and low	Valid	High match (40)
		Valid	Low match (40)
		Neutral	Neutral (80)

Note. Memory-to-search target validity condition refers to whether the memory cue matched a search target, and memory-to-search target match condition refers to which target the memory cue matched. Trial counts are presented in parentheses.

Data Analysis

Our primary measure of interest was search accuracy, because it offers a more compatible measure with previous studies (e.g., Soto et al., 2005) than response times in the current design. The current dual-task memory and search paradigm differs from others in that participants respond with mouse clicks on targets, as opposed to forced-choice responses, and the search size arrays employed are much larger, with as many as 35 items in the current tasks compared to a maximum of eight items in Soto et al. (2005). Nevertheless, the response time data are consistent with the accuracy results and are presented in Table 2 and in the Appendix.

In all experiments reported here, a one-way analysis of variance (ANOVA) was conducted to compare first-hit percentages of the high-salience target across the three memory-to-search target-match conditions (i.e., high match, low match, or neutral).[1] Paired *t* tests were also conducted, comparing first-hit percentages of the high-salience target to first-hit percentages of the low-salience target within each of the three match conditions. To analyze search response times, a two-way ANOVA was conducted across factors of memory-to-search target relationship (i.e., neutral or valid) and target salience. All statistics are reported in Table 2.

Experiment 1A

A dual-task paradigm for working memory and visual search was tested to directly contrast the effects of bottom-up visual salience versus the effects of top-down working memory on the deployment of visual attention. Twelve Duke University students (six men, age range: 18–21 years) participated in the study, and all signed informed consent in accordance with Duke University's Institutional Review Board. Data from two participants were excluded from analysis, one for having a false-alarm rate more than 2.5 *SD* from the mean across all participants, and one for being more than 2.5 *SD* from the mean across all participants for search accuracy in the neutral condition.

Results

Memory task. Performance on the memory task was above chance ($M = 69.4\%$, $SD = 7.7$), $t(9) = 8.00$, $p < .001$, and was significantly better for valid trials ($M = 71.3\%$, $SD = 9.2$) than for neutral trials ($M = 67.6\%$, $SD = 6.4$), $t(9) = 2.88$, $p = .018$. Validity benefits likely resulted from an updating of the memory representation due to the reprocessing of the memory item if the valid target item was found.

Visual search task. Analyses for the search task were focused on accuracy performance for dual-target search trials; see Table 2 for dual-target response time data and the Appendix for single-target search trial data. False alarms (defined as mouse clicks that were not on target items; i.e., on distractor items or on empty space) accounted for 2.0% of all clicks, and those trials are excluded from all subsequent analyses. Participants exceeded the search time limit on 0.9% of trials. The critical measure was "first hits," or which of the two targets was found first. Previous research using a dual-target search task found that, given a more salient and a less salient target, the more salient target is not only more likely to be found, but also more likely to be found first (Fleck et al., 2010; Cain & Mitroff, 2012). The percentage of high-salience targets found first was compared to the percentage of low-salience targets found first, separately for the neutral and valid conditions (see Table 2).

The critical comparison was whether the pattern of first-hit performance between conditions was affected by the contents of working memory. Even in the presence of a baseline salience effect from the neutral condition, in which high-salience targets were more likely to be found first, $t(9) = 3.14$, $p = .012$, there was a significant effect of memory-to-search target-match condition (i.e., whether the memory item matched the high-salience, low-salience, or neither target) on first-hit percentages for high-salience targets, $F(2, 27) = 39.86$, $p < .001$. That is, attention was guided to the target that matched the item being held in working memory (see Figure 2). Guidance by working memory either enhanced the effects of salience (for the high-salience match) or overrode them (for the low-salience match). Search time analyses also revealed that validity had a significant effect on how quickly participants found the first target, $F(1, 36) = 11.57$, $p = .002$ (see Table 2).

Discussion

In this dual-task paradigm, working memory cues were strong enough not only to enhance but also to override attentional priority of salience cues. Dual-target search performances for each memory-to-target match condition highlight different attentional guidance effects. In the neutral condition, without guidance from the contents of working memory, participants were more likely to find the high-salience target first. This demonstrated a baseline effect of visual salience, in which attention was biased toward the target with greatest local contrast. In the high-match condition, holding a matching high-salience item in working memory enhanced the likelihood of finding the high-salience target first, replicating the main result of Soto et al. (2006). However, in the low-match condition, holding a matching low-salience item in

[1] A two-way analysis of variance with the main factors of memory-to-search target-match condition and salience was not administered because the first-hit percentage values within each condition were dependent. Because the first hit was either high salience *or* low salience (or neither was found at all), such an analysis over condition would sample the same data twice.

Table 2
Overall Accuracy and Search Times to Find a Target First in Dual-Target Searches

	Proportion of first hits			Average time in seconds to first hit		
Experiment	High salience	Low salience	Statistical tests	High salience	Low salience	Statistical tests
Experiment 1A ($n = 10$)						
Neutral	.555 (.06)	.445 (.06)	$t(9) = 3.14$ $p = .012$	4.15 (1.05)	4.20 (1.01)	$t(9) = 0.85$ $p = .849$
High match	.741 (.11)	.259 (.11)	$t(9) = 6.95$ $p < .001$	3.37 (0.79)	4.40 (1.05)	$t(9) = 2.76$ $p = .022$
Low match	.282 (.16)	.718 (.16)	$t(9) = 4.35$ $p = .002$ $F(2, 27) = 39.86$ $p < .001$	4.12 (1.05)	3.09 (0.57)	$t(9) = 3.27$ $p = .010$ $F(1, 36) = 11.57$ $p = .002$
Experiment 1B ($n = 12$)						
Neutral	.568 (.09)	.432 (.09)	$t(11) = 2.69$ $p = .021$	5.24 (0.92)	5.27 (1.4)	$t(11) = 0.09$ $p = .927$
High match	.766 (.15)	.224 (.15)	$t(11) = 6.33$ $p < .001$	4.09 (1.10)	5.80 (2.14)	$t(11) = 2.54$ $p = .028$
Low match	.363 (.20)	.637 (.20)	$t(11) = 2.40$ $p = .035$ $F(2, 33) = 21.63$ $p < .001$	5.61 (1.61)	4.36 (1.17)	$t(11) = 2.63$ $p = .023$ $F(1, 44) = 9.47$ $p = .004$
Experiment 2 ($n = 10$)						
Neutral	.919 (.07)	.081 (.07)	$t(9) = 18.41$ $p < .001$	2.13 (0.55)	3.72 (0.87)	$t(9) = 6.61$ $p < .001$
High match	.985 (.03)	.015 (.03)	$t(9) = 57.07$ $p < .001$	1.72 (0.38)	5.02 (6.75)*	$t(9) = 1.09$ $p = .302$
Low match	.720 (.16)	.280 (.16)	$t(9) = 4.41$ $p = .002$ $F(2, 27) = 12.78$ $p < .001$	2.70 (0.95)	3.68 (0.71)	$t(9) = 2.75$ $p = .022$ $F(1, 36) = 1.164$ $p = .288$
Experiment 3 ($n = 10$)						
Neutral	.651 (.10)	.349 (.10)	$t(9) = 4.97$ $p < .001$	5.38 (0.77)	5.28 (0.71)	$t(9) = .36$ $p = .726$
High match	.712 (.12)	.288 (.12)	$t(9) = 5.82$ $p < .001$	4.82 (0.71)	4.84 (0.90)	$t(9) = -.11$ $p = .915$
Low match	.613 (.10)	.387 (.10)	$t(9) = 3.73$ $p = .005$ $F(2, 27) = 2.37$ $p = .113$	5.31 (0.87)	4.69 (0.94)	$t(9) = 1.66$ $p = .131$ $F(1, 36) = 3.33$ $p = .027$

Note. Standard deviations are presented in parentheses. Test statistics represent paired *t* tests for first hits and search times between high-salience and low-salience targets within each match condition, and analysis of variance test statistics for the main effect of match condition across first hits, and the main effect of validity across search times.
* Seven of ten participants never found the low-salience target first in the high-match condition.

working memory guided attention toward the less salient target, reversing the predicted pattern of bias by visual salience. This result supports the idea that visual attention can be guided by a competitive balance between bottom-up influences of visual salience and top-down influences of working memory.

Experiment 1B

In Experiment 1A, holding a less visually salient item in working memory enhanced the detection of that particular item, overriding attentional priority of a more visually salient item. The strength of this guidance by the contents of working memory is somewhat surprising, so Experiment 1B was intended to replicate the effect with a more complex search task. Specifically, this experiment was identical to Experiment 1A except with the search array size increased to 35 stimuli. Seventeen Duke University students (seven men, age range: 18–24 years) participated in the study. Data from five participants were excluded from analysis for having a false-alarm rate more than 2.5 *SD* from the mean across all participants.

Results

Memory task. Performance on the memory task was above chance ($M = 76.2\%$, $SD = 8.2$), $t(11) = 11.04$, $p < .001$, and was significantly better for valid trials ($M = 79.0\%$, $SD = 7.1$) than for neutral trials ($M = 73.3\%$, $SD = 9.6$), $t(11) = 3.70$, $p = .003$.

Visual search task. Table 2 summarizes first-hit performance of the 12 participants in terms of accuracy and search times for dual-target search trials. False alarms accounted for 2.5% of all clicks, and participants exceeded the search time limit on 4.5% of trials. As in Experiment 1A, the critical measure of performance was first hits. Experiment 1B replicated the two key effects: a baseline effect of visual salience in the neutral condition, $t(11) = 2.69$, $p = .021$, and an overall effect of memory guidance, $F(2, 33) = 21.63$, $p < .001$, in which attention was guided to the target

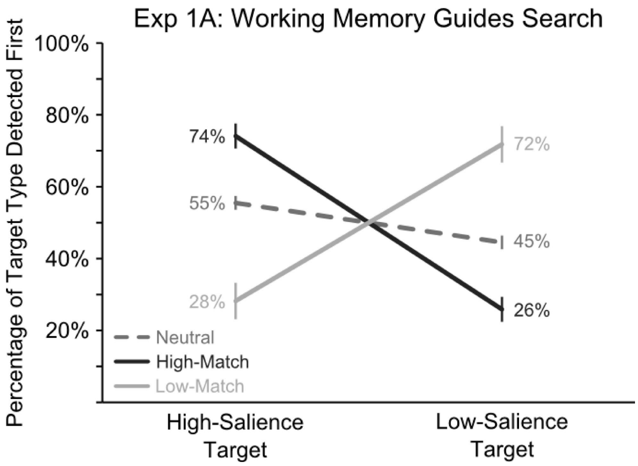

Figure 2. Data from Experiment 1A. Average rates of which target was correctly found first ("first hits"), as a function of match condition. Error bars represent standard errors.

that matched the item being held in working memory, regardless of visual salience (see Figure 3). Search time analyses also supported this result: participants were significantly faster to find the target that matched the contents of working memory, $F(1, 44) = 9.47$, $p = .004$. Response times were overall longer than in Experiment 1A, which represents the added complexity introduced by increasing the set size from 25 to 35 items.

Discussion

Experiment 1B replicated the findings of Experiment 1A, showing that, even in a more complex search task, performance in dual-target search is influenced by an interaction between effects of visual salience and working memory guidance. In the neutral condition, participants were more likely to find the high-salience target first, revealing a baseline effect of visual salience. However, when the memory cue matched a search target, participants were more likely to find that particular item first, regardless of salience. This indicates that working memory cues are able to override attentional priority of a more salient target and to guide attention to a less salient target first.

Experiment 2

The results of Experiments 1A and 1B demonstrate that working memory cues are sufficiently strong to enhance or even to override attentional guidance toward targets of high salience. But what happens when the local contrast of the high-salience target is increased even more, effectively strengthening the prioritizing effect of visual salience? To further examine the strength of top-down working memory cues in guiding attention, stimulus salience was manipulated in Experiment 2 such that the high-salience target was extremely easy to detect. The stimuli array size and procedure were identical to those in Experiment 1B. Eleven Duke University students (seven men, age range: 18–21 years) participated in the study. Data from one participant was excluded for having a false-alarm rate more than 2.5 *SD* from the mean across all participants.

Verification of "Pop-Out"-Like Search

Stimulus salience was manipulated such that the high-salience, darker Ts were much easier to detect. As in Experiments 1A and 1B, target Ts were presented at one or both of two visibility levels: high salience (range: 65–75% black) or low salience (range: 30–40% black). However, distractor Ls were presented at varying shades of gray in a muted range (30–52% black) closer to the low-salience range. Thus, high-salience Ts were so distinctive as to seemingly "pop-out" from the search array.

The pop-out-like character of the high-salience T in this search array was verified by comparing simple search performance across varying set sizes. An independent group of 10 additional participants (seven men, age range: 18–30 years) was recruited for this verification task. Participants were instructed to judge whether a single target T was present or absent in intermixed search arrays of 8, 12, 24, and 36 stimuli. A single target T was present on 50% of the trials, and was either high salience or low salience in a field of muted distractors (all salience values match those used in Experiment 2). Search slopes were calculated as the slope of the linear regression line that best fit search times across set sizes. When the target T was high salience, a nearly flat search slope was generated ($M = 9.5$ ms/item, $SD = 1.2$); in contrast, when the target T was low salience, the search slope was highly positive ($M = 100.1$ ms/item, $SD = 71.2$). The search slopes between the two target types differed significantly, $t(9) = 3.72$, $p = .005$, confirming that the high-salience, pop-out-like target did produce highly efficient search (see Figure 4).

Results

Memory task. Performance on the memory task was above chance ($M = 78.7\%$, $SD = 4.9$), $t(9) = 18.36$, $p < .001$, and was significantly better for valid trials ($M = 81.3\%$, $SD = 5.2$) than for neutral trials ($M = 76.0\%$, $SD = 6.0$), $t(9) = 3.25$, $p = .010$.

Visual search task. Table 2 summarizes first-hit performance of the 10 participants in terms of accuracy and search times for

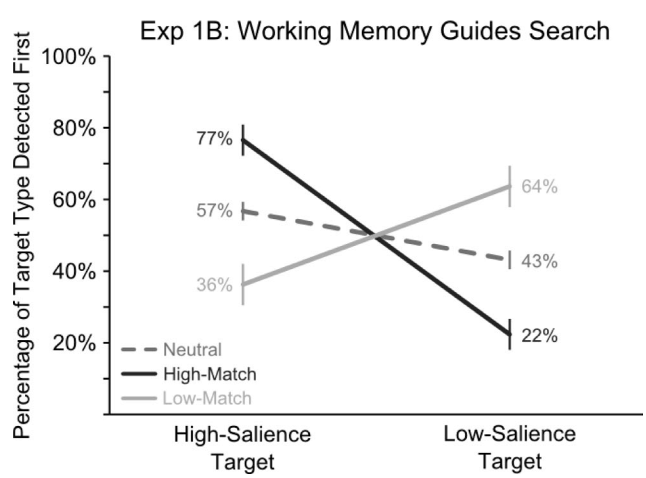

Figure 3. Data from Experiment 1B. Average rates of which target was correctly found first ("first hits"), as a function of match condition. Error bars represent standard errors. Note the values may not total to 100% due to rounding.

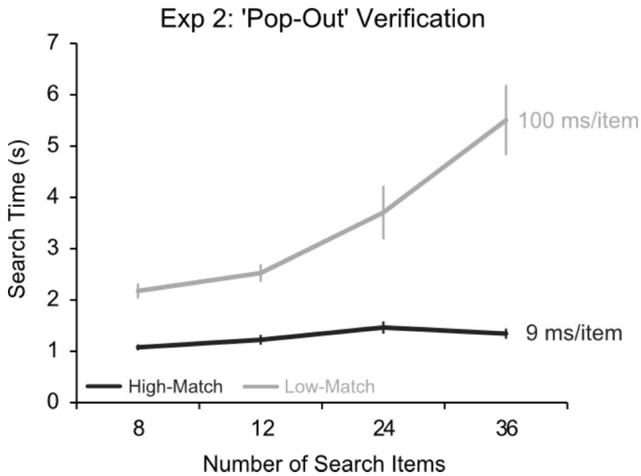

Figure 4. Data from Experiment 2 "pop-out" verification task. Search times as a function of set size when searching for low-salience versus high-salience targets among distractors, with slope values provided. Error bars represent standard errors.

dual-target search trials. False alarms accounted for 0.9% of all clicks, and participants exceeded the search time limit on 0.3% of trials. As in Experiments 1A and 1B, the critical measure of performance was proportion of first hits. A one-way ANOVA revealed a significant effect of memory-to-target match condition, $F(2, 27) = 12.78$, $p < .001$. In the neutral condition, participants were significantly more likely to find the high-salience target first than the low-salience target first, $t(9) = 18.41$, $p < .001$. The salience effect was extremely strong, with an advantage of 83.74% for finding the high-salience target first compared to finding the low-salience target first, due to the pop-out-like nature of the high-salience target. Nevertheless, this salience effect was significantly enhanced by working memory guidance in the high-match condition, $t(9) = 2.93$, $p = .017$, with participants finding the high-salience target first almost every trial, $t(9) = 57.07$, $p < .001$. Furthermore, a one-way ANOVA of search times revealed that the high-salience target was found significantly faster in the high-match condition than in neutral or low-match conditions, $F(2, 27) = 5.46$, $p = .010$. Crucially, in the low-match condition, although participants were still more likely to find the high-salience target first, $t(9) = 4.41$, $p = .002$, working memory guidance toward the low-salience target significantly attenuated the proportion of finding the high-salience target first, $t(9) = 4.79$, $p < .001$ (see Figure 5).

Discussion

In an already efficient search for a high-salience, pop-out-like target, memory guidance can still enhance search performance, replicating the effect by Soto et al. (2006). Furthermore, although memory guidance does not reverse the pattern of attentional priority of a pop-out-like target, working memory cues can still significantly attenuate the effect of visual salience. When the low-salience item was held in working memory, the matching low-salience target was more likely to be detected first than when it was not held in memory. This indicates that top-down working memory guidance is strong enough to counteract even a highly robust bottom-up salience effect.

Experiment 3

The aim of Experiment 3 was to test whether the attentional guidance effects observed in Experiments 1A, 1B, and 2 were driven by working memory or by bottom-up priming. Previous research (e.g., Downing, 2000; Olivers et al., 2006; Soto et al., 2005) has suggested that priming cannot account for attentional guidance such as that observed in the current study, but it is nevertheless important to demonstrate here that merely presenting the "memory" cue would not be sufficient to guide attention. This experiment is identical to Experiment 1B, except that it did not include the memory test. Specifically, participants were no longer required to hold the initial cue in working memory for later comparison to the probe item. Fourteen Duke University students (four male, age range: 18–22 years) participated in the study. Data from four participants were excluded from analysis for reporting that they explicitly used the "memory" cue to guide their search.

Results

Visual search task. Table 2 summarizes first-hit performance of the 10 participants in terms of accuracy and search times for dual-target search trials. False alarms accounted for 2.7% of all clicks, and participants exceeded the search time limit on 4.7% of trials. As in Experiments 1A, 1B, and 2, the critical measure of performance was first hits. Experiment 3 replicated the baseline effect of visual salience in the neutral condition, $t(9) = 4.969$, $p < .001$. However, contrary to a visual priming account, there was no overall effect of memory guidance, $F(2, 27) = 2.365$, $p = .113$, such that attention was not significantly guided to the target that matched the cued item (see Figure 6). In fact, there was a significant effect of visual salience within each match condition, such that the high-salience target was found first more than the low-salience target in every condition (see Table 2).

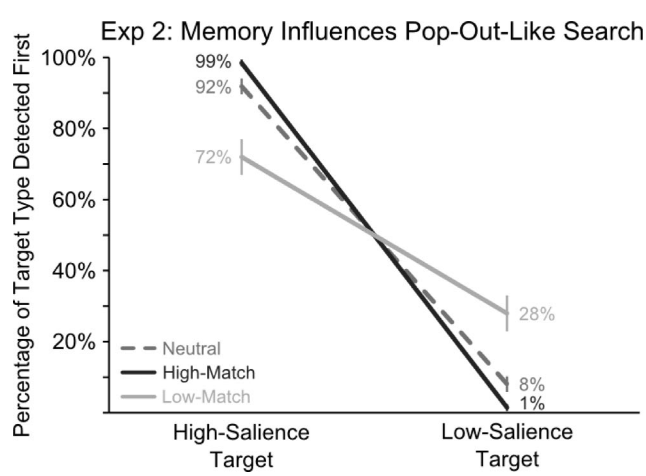

Figure 5. Data from Experiment 2. Average rates of which target was correctly found first ("first hits"), as a function of match condition. Error bars represent standard errors.

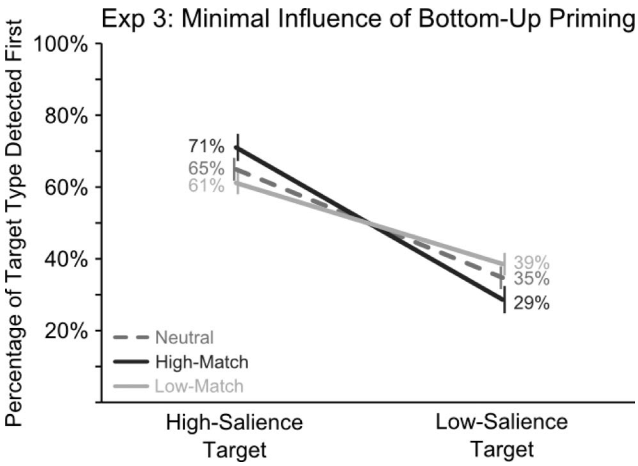

Figure 6. Data from Experiment 3. Average rates of which target was correctly found first ("first hits"), as a function of match condition. Error bars represent standard errors.

Discussion

The results of Experiment 3 rule out a bottom-up priming account of attentional guidance. Simply presenting the "memory" cue before the visual search array, without any requirement to hold the cue in working memory, failed to produce the attentional guidance effects found in Experiments 1A, 1B, and 2. These results support previous studies (e.g., Downing, 2000; Olivers et al., 2006; Soto et al., 2005), which also found that visual priming alone cannot explain attentional guidance effects. All together, these studies are strong indications that the currently observed attentional guidance effects are driven by working memory and not by simply priming low-level features in the search array.

General Discussion

The present study demonstrates that the deployment of attention in visual search is modulated by a competitive balance between bottom-up visual salience and top-down working memory cues. A previous study found that working memory cues can enhance search performance for more salient items (Soto et al., 2006), and the current study specifically investigated the *strength* of working memory guidance when contrasted with salience effects. Top-down memory guidance was found not only to be able to enhance, but also to override, attentional priority of bottom-up visual salience. Experiments 1A and 1B confirmed that holding an item in working memory significantly biased participants to find that specific item first, regardless of its salience. Experiment 2 further explored the relationship between working memory and salience effects on attentional guidance. Even in a pop-out-like search with a highly salient target, working memory cues still enhanced the detection of a less salient target. Experiment 3 showed that these effects were not found when participants were asked only to observe the cue prior to search and not required to hold the item in working memory. In line with previous studies, these results support a guiding role for working memory in the deployment of visual attention (Downing, 2000; Olivers et al., 2006; Soto et al., 2005). The observed pattern of search performance in the current study supports models of visual attention in which visual attention is guided by a reciprocal interaction between stimulus properties and the contents of working memory (e.g., Awh et al., 2012; Treisman, 1986; Wolfe, 1994).

The present study introduces a novel dual-task paradigm that provides a number of elements not present in similar tasks. First, the current task employs a greater number of stimuli, with as many as 35 items compared to a maximum of eight items in Soto et al. (2005). Second, the T and L stimuli used are also less discriminable than colored shapes or lines (Wolfe & DiMase, 2003), which makes the memory task and the visual search task more complicated. Third, the current search task features multiple targets, which increases the attentional, memory, and decision-making demands (Cain & Mitroff, 2012). Importantly, these changes in the basic paradigm did not affect the base effects of working memory guidance on search, while allowing for novel questions to be addressed. Specifically, by adopting a search task with multiple targets, these experiments were able to simultaneously present targets of unequal salience. This allowed for an evaluation of the relative strength of working memory as a top-down factor, revealing that working memory has a powerful influence over the guidance of visual attention. Furthermore, the current results demonstrate that the contents of working memory can guide attention, even in an effortful and relatively time-consuming search task. This paradigm could be applied in future studies to explore the potential distinction between a fast capture of attention by bottom-up salience and a longer-lived guidance of attention by top-down working memory.

The multiple-target nature of the current design offers a potentially powerful methodological tool. Multiple-target searches with targets of unequal salience are common in real-world searches, such as when radiologists search for medical abnormalities in radiological scans or when airport baggage screeners search for safety concerns. This paradigm could be used to explore the effects of working memory guidance on real-world objects, as well as with regard to other definitions of salience, such as emotional salience. For example, in baggage x-rays, a water bottle might be more visually salient but less emotionally salient than a handgun. Future research using real-world objects or affective stimuli could simultaneously inform on the interaction between memory and attention in both cognitive psychology and real-world applications.

Working Memory Guidance or Strategy?

An ongoing debate in the field of visual attention involves the automaticity of working memory guidance. In tasks that require participants to hold an object representation in working memory while performing visual search, some studies have shown that items matching the contents of working memory attract attention automatically (e.g., Olivers et al., 2006; Soto et al., 2005), while others have not (e.g., Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Woodman & Luck, 2007). These studies included a critical condition in which the working memory cue reappeared only as an invalid distractor, such that it was more beneficial to avoid the matching item. In some studies, working memory effects were still found, even at a cost to performance (Olivers et al., 2006; Soto et al., 2005), supporting the theory that working memory guidance of attention is automatic (see Soto et al., 2008). However, in contrast, one experiment found that when the memory cue could only reappear as an invalid distractor, there were no significant costs to search times, demonstrating the participants' ability to strategically avoid memory-matching distractors and supporting the flexible and voluntary nature of working memory guidance (Woodman & Luck, 2007). Although some researchers have attempted to reconcile the automatic and strategic influences of working memory on visual attention (e.g., Carlisle & Woodman, 2011; Olivers et al., 2011), others have attributed discrepancies in the results to methodological details, such as the time between the memory display and the search array or the difficulty of the search task (Han & Kim, 2009).

Akin to the above alternative hypotheses, the current data could fit one of two interpretations: the observed search performance differences could be explained either by a claim that attention is guided by working memory cues or by a claim that participants used an overt strategy to complete the search task. That is, participants are quicker to find the target that matches the memory cue because they were guided by the contents of their working memory or because they were explicitly, strategically searching for the memory cue. It is not possible to definitively rule out either alternative,[2] but additional data from the current study and from previous studies support an attentional guidance by working memory interpretation.

From the current study, it is possible to inform which interpretation (memory guidance vs. explicit strategy) best explains the current data by considering how each theory predicts performance change after a target is found in search. A memory guidance hypothesis predicts that by holding a particular item in working memory and then finding that matching target first, the memory representation would be strengthened by additional spatial location information (Woodman & Luck, 2007) and through a refreshing of the memory (Kiyonaga, Egner, & Soto, 2012). A strengthening of the memory representation will lead to it effectively using a greater proportion of memory resources (Bays & Husain, 2008). This more robust representation would thus interfere with finding the second, nonmatching target (Cain & Mitroff, 2012). In terms of the current study, a memory guidance account would predict that participants should be *slower* to find a nonmatching target after finding the matching target, compared to a neutral baseline. In contrast, an explicit strategy hypothesis posits that the participant would maintain an overt goal of finding the exact match of the memory cue. In neutral conditions in which the cue does not appear in the search array, participants would be hindered by this overt goal, because they would continue searching for the memory cue even after finding other targets. In high-match or low-match conditions, participants would find the matching cue and then know to discard that goal target (i.e., a template for rejection; Arita, Carlisle, & Woodman, 2012), allowing them to be relatively faster to find the second, nonmatching target. In terms of the current study, an explicit strategy account would predict that participants should be *faster* to find a nonmatching target after the matching target, compared to a neutral baseline. The data suggest a trend in which participants are slower to find a nonmatching target after finding the matching target, compared to a neutral baseline, $t(63) = 1.94$, $p = .057$. These data are not conclusive, but support a memory guidance interpretation more than an explicit strategy hypothesis.

Previous research has shown that strategies can influence the guidance of attention by working memory (Carlisle & Woodman, 2011; Kiyonaga et al., 2012). However, even for trials in which participants know to strategically avoid the item matching the memory cue, performance costs due to working memory guidance are still present (Carlisle & Woodman, 2011; Kiyonaga et al., 2012). In other words, even though the use of strategy can modulate attentional guidance by working memory, strategy alone does not account for all deployments of visual attention. This finding, taken in conjunction with the additional data above from the current study, suggests that participants were not detecting matching targets first and faster simply due to an overt strategy.

Conclusion

The primary goal of the present study was to explore the interaction between attentional guidance by bottom-up visual salience and by top-down working memory representations. By demonstrating that the contents of working memory can powerfully guide attention, even in the face of conflicting visual salience effects, this study illustrates the influential role of working memory as a top-down factor for guiding visual attention. Furthermore, this study also offers a novel paradigm that can be used to study specific interactions between bottom-up and top-down influences on visual attention.

[2] The dual-target nature of the current paradigm provides a novel manner to explore interactions between memory and attention, but also eliminates the possibility of including a condition of strategic avoidance, in which the memory cue matches only invalid locations (e.g., Arita et al., 2012; Soto et al., 2005; Woodman & Luck, 2007).

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(*Appendix follows*)

Appendix

Overall Accuracy and Search Times to Find a Target in Single-Target Searches

Experiment	Accuracy		Average time in seconds to find target	
	High salience	Low salience	High salience	Low salience
Experiment 1A ($n = 10$)				
Neutral	.920 (.08)	.875 (.13)	5.37 (0.92)	5.90 (1.53)
High match	.945 (.06)	—	4.08 (0.61)	—
Low match	—	.915 (.09)	—	4.37 (0.82)
Experiment 1B ($n = 12$)				
Neutral	.833 (.11)	.788 (.14)	6.23 (1.07)	6.92 (1.27)
High match	.946 (.05)	—	5.32 (1.48)	—
Low match	—	.842 (.15)	—	5.30 (1.65)
Experiment 2 ($n = 10$)				
Neutral	.990 (.02)	.750 (.17)	2.47 (0.87)	7.11 (1.47)
High match	1.00 (0)	—	1.79 (0.62)	—
Low match	—	.810 (.17)	—	5.69 (1.04)
Experiment 3 ($n = 10$)				
Neutral	.785 (.15)	.825 (.12)	5.65 (1.21)	5.85 (1.64)
High match	.825 (.09)	—	4.98 (0.75)	—
Low match	—	.795 (.12)	—	4.79 (0.93)

Note. Standard deviations are presented in parentheses.

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