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Do the Contents of Visual Working Memory Automatically Influence Attentional Selection During Visual Search?

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In many theories of cognition, researchers propose that working memory and perception operate interactively. For example, in previous studies researchers have suggested that sensory inputs matching the contents of working memory will have an automatic advantage in the competition for processing resources. The authors tested this hypothesis by requiring observers to perform a visual search task while concurrently maintaining object representations in visual working memory. The hypothesis that working memory activation produces a simple but uncontrollable bias signal leads to the prediction that items matching the contents of working memory will automatically capture attention. However, no evidence for automatic attentional capture was obtained; instead, the participants avoided attending to these items. Thus, the contents of working memory can be used in a flexible manner for facilitation or inhibition of processing.

Keywords: attention, working memory, visual search, capture

In several large-scale theories of cognition, researchers propose that individuals use working memory representations to control the operation of perceptual systems, typically by biasing the allocation of attention to objects that are relevant for current goals (e.g., Anderson, Matessa, & Lebiere, 1997; Bundesen, 1990; Logan & Gordon, 2001; Miller & Cohen, 2001). However, the nature of the current sensory input also plays a major role in determining how attention is allocated (Egeth & Yantis, 1997; Folk, Remington, & Johnston, 1992; Wolfe, 1994). Desimone and Duncan (1995) proposed an influential theory of attentional control called the *biased competition theory* that provides a framework for understanding the interaction between top-down working memory factors and bottom-up sensory factors in controlling attention. In this theory, sensory inputs compete with one another, and the winner of this competition becomes the focus of attention. Although stronger sensory inputs usually have a competitive advantage over weaker sensory inputs, working memory can bias the competition, tipping the balance in favor of weaker sensory inputs that match representations being stored in working memory. In the present study, our goal was to determine whether the influence of working memory on perception is automatic and rigid or controlled and flexible.

Single-unit recordings in monkeys and neuroimaging studies in humans have indicated that the maintenance of an object representation in working memory is accompanied by sustained increases in the firing rates of prefrontal and inferotemporal neurons (Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993; Goldman-Rakic, 1996; Miller & Desimone, 1991; Miller, Erickson, & Desimone, 1996; Pessoa, Gutierrez, Bandettini, & Ungeleider, 2002; Postle & D'Esposito, 1999). In the biased competition theory, this sustained neural activity provides an automatic competitive advantage for matching sensory inputs. For example, Chelazzi et al. (1993) recorded single-unit activity in inferotemporal cortex while monkeys performed a visual search task. The target was shown at fixation at the beginning of the trial, and then a search array was presented after a delay. Neurons that responded to the initial presentation of the target were found to maintain increased neural activity during the delay interval, which is thought to reflect the maintenance of the target in working memory. When the target array was presented, these neurons were already in a more active state than were other neurons, providing them with a competitive advantage. Consequently, when a target was present in the search array, the already-active neurons that were responsive to the target item responded vigorously, whereas the neurons that were responsive to the non-target items were suppressed. In this manner, the biased competition theory proposes that sensory inputs receive a competitive advantage when they match representations that are currently active in working memory.

A similar relationship between working memory and attention is implicit in several other theories, as well. Most comprehensive theories of attention specify that the observer uses features of the searched-for target to bias the allocation of attention to incoming

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stimuli. For example, the attentional engagement theory of Duncan and Humphreys (1989) proposes that attentional selection of perceptual representations is based on the degree to which a given perceptual representation matches a target template actively maintained in memory (see also Bundesen, 1990). Similarly, in the contingent involuntary attention capture model of Folk and colleagues (Folk, Remington, & Johnston, 1992), the observer uses task goals to create an attentional set, and inputs matching the attentional set elicit an automatic orienting of attention. In Wolfe's guided search model (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989) and recent versions of Treisman's feature integration theory (Treisman & Sato, 1990), the connections between maps of features and a master map of locations are adjusted for emphasis on the features of the target, and the order of search is determined by the distribution of activation in the master map. Thus, all of these theories propose that the attentional priority of a sensory input is automatically determined by its match to a set of target-defined properties. If these properties are stored in working memory, then these theories predict that sensory inputs matching the contents of working memory will elicit an involuntary shift of attention.

Downing (2000) used a spatial probe paradigm to directly test this hypothesis. In this study, observers were shown a face at the beginning of each trial and were instructed to remember this face for a memory test at the end of the trial. They then performed a probe discrimination task during the retention interval. Immediately before the probe was presented, two task-irrelevant faces were flashed briefly, one at each of the two possible probe locations. One of these faces was identical to the face being held in memory, and the other was different. Downing reasoned that if attention is drawn automatically to the task-irrelevant face because it matches a face being held in memory, then observers would be faster to detect the probe stimulus if it was presented at the location of the matching face. This is exactly the pattern of results that was obtained, supporting the proposal that attention is automatically deployed to items that match the current contents of working memory. However, these results may instead be explained by demand characteristics or by the strategic use of attention to aid memory performance.

The demand characteristics explanation is as follows. Although the presentation of the two faces during the retention interval was supposed to be irrelevant for the probe task, it is highly likely that observers noticed that one of these faces always matched the face being held in memory, and they may have been curious about the role of this matching face. As a result, they may have voluntarily focused attention onto the matching face on a significant proportion of trials. This explanation was addressed, albeit indirectly, by a control experiment in which the observers made an immediate discrimination of the face stimulus presented at the beginning of the trial rather than holding it in memory. This task did not lead to faster responses for probes presented at the location of the matching face even though respondents certainly must have noticed that one of the two task-irrelevant faces always matched the discrimination target that had just been presented. However, responses were significantly slowed for probes presented at the location of the mismatching face compared with that of the matching face, which suggests that demand characteristics may have been operative even though the direction of the effect was reversed.

The hypothesis that observers strategically attended the matching faces is even more compelling. Because the observers almost certainly noticed that the to-be-remembered face was always presented during the retention interval, they may have used the second presentation of this face to improve performance on the memory task. That is, the observers may have voluntarily deployed attention to the matching face so that they could refresh their memory of the face (and not suffer interference from the nonmatching face). We call this the *strategic perceptual resampling hypothesis*. Moreover, because the probe appeared at the location of the matching face just as frequently as it did at the mismatching face, this strategy was not discouraged by the experimental design.

These two explanations— demand characteristics and perceptual resampling— of the Downing (2000) results also apply to a related study by Pashler and Shiu (1999), who used a variant of the attentional blink paradigm along with an imagery task. At the beginning of each trial, observers were told to create and maintain a mental image of an object (e.g., an elephant, fish, or swimming pool). They were then shown a sequence of line drawings at a rapid rate (approximately 10 stimuli/s). This sequence also contained a digit, and the observers were required to report this digit at the end of the trial. In addition, the sequence contained a drawing that matched the object that the subjects were being asked to image. The authors reasoned that if the observers automatically allocate attention to objects similar to those held in visual working memory, then the drawing that matches the image should automatically be attended, and this should lead to an attentional blink when the digit target follows the matching image. In accord with this reasoning, they found that digit discrimination performance was impaired when the digit was the third item after the matching drawing compared with when the digit preceded the matching drawing. Note that the task did not explicitly require the observers to focus attention onto the drawing that matched the mental image, and the finding of impaired performance when the digit followed the matching drawing was, therefore, taken as evidence that the matching drawing attracted attention involuntarily.

This study has the same two shortcomings as does the Downing (2000) study. First, although the observers were not instructed to attend to the matching drawing, they probably noticed that matching drawings were presented on every trial and presumably deduced that the matching drawings were an important element of the experiment. It is, therefore, plausible that the observers intentionally focused attention onto the matching drawings in an attempt to understand the experiment, even though this led to impaired performance on the digit task (which they may not have realized). Thus, the demand characteristics of the task may have led to voluntary rather than automatic allocation of attention.

A related possibility is that the matching drawings provided stimuli that the observers could use to improve their imagery. That is, the observers may have found that focusing attention onto the matching drawings aided them in their task of creating and maintaining a mental image of that object. Consequently, the observers may have engaged in strategic perceptual resampling to facilitate their imagery performance.

Recent research seems to support our alternative interpretation of the previous evidence for automatic biasing of attention toward working memory-matching items. Downing and Dodds (2004) conducted a study in which deploying attention to items that matched the contents of visual working memory could potentially interfere with the visual search task being performed. Specifically, at the beginning of each trial, observers were simultaneously shown two shapes. One shape was the search target for that trial, and the other shape was an item that they needed to remember for a possible subsequent memory test. Two seconds later, they were shown an array of three, six, or nine shapes, and they were required to report whether the target was present. On half the trials, regardless of target presence, one of the two distractors matched the memory item. In this case, the results suggested that attention was not automatically deployed to the item that matched the memory representation because search reaction times (RTs) were similar whether or not the memory-matching distractor was present in the array. Given these new findings, Downing and Dodds proposed that a portion of the contents of visual working memory can be switched off or the representations not relevant for the current task can be maintained in a separate working memory store so as to not influence attentional selection during visual search. Such flexible use of the contents of visual working memory would greatly constrain models that account for top-down effects by proposing that working memory representations bias selection.

In summary, the studies in which researchers tested whether working memory representations bias the deployment of attention have reported a diversity of findings. In some cases, observers may have been motivated to allocate attention to items that matched the contents of visual working memory for strategic reasons or because of the demand characteristics of the tasks. This interpretation is consistent with the Downing and Dodds (2004) study and suggests that the interactions between perceptual attention and working memory are complex and do not consist simply of a change in attentional bias caused by a simple increase in the baseline firing rates of the cells that code the features of objects being held in working memory. To determine whether holding a representation in visual working memory automatically leads to the selection of similar items (e.g., Soto, Heinke, Humphreys, & Blanco, 2005), it is critical that researchers eliminate any possible motivation for attending to the stimulus.

To achieve this goal, in the present study we used an approach that was based on previous studies designed to establish whether peripheral precues automatically attract attention (e.g., Folk et al., 1992; Jonides, 1981). Specifically, the participants were provided with an incentive for not attending to items that match information being stored in working memory: The matching items were never targets in the search task. If attention is automatically captured by items that match the current contents of working memory, then these items should capture attention even if they are never targets. In contrast, if attention is strategically allocated to matching items, then matching items should not capture attention when the matching item is never the target.

Experiment 1

On each trial, participants were first presented with a single colored square to store in visual working memory, followed by a search array that required a speeded response to a target defined by its shape, and finally by a single colored square that served as a memory test and that required an unspeeded same/different judgment (see Figure 1). Color was not relevant to the search task, but

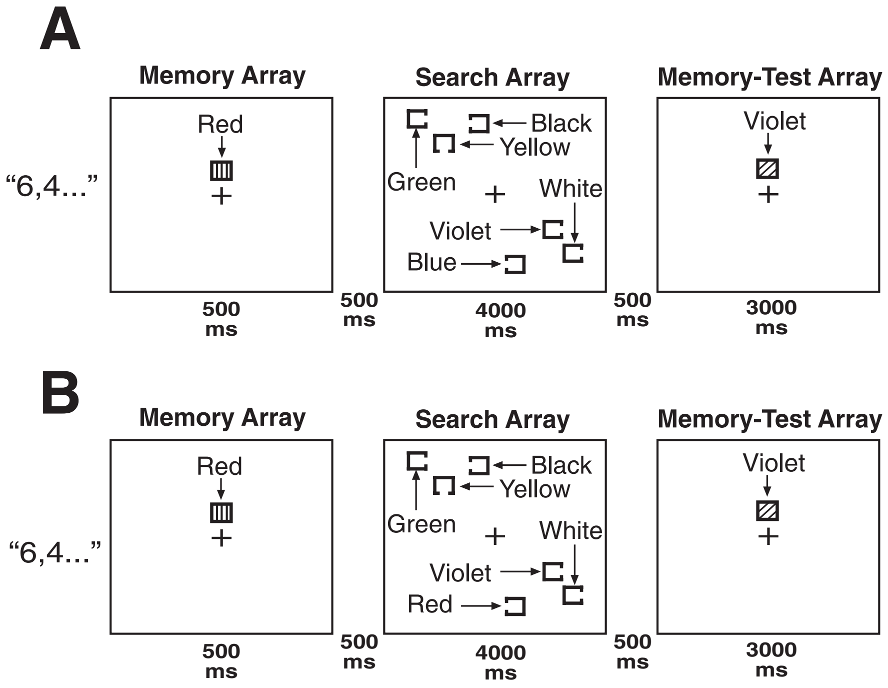

Figure 1. Examples of the stimuli used in Experiment 1. A: Example of a stimulus sequence during a trial of the mismatching-distractor condition. B: Example of a stimulus sequence during a trial of the matching-distractor condition; note the matching distractor in the lower hemifield.

the items in the search array also varied in color. If attention is automatically biased toward items that match the contents of visual working memory, then when a distractor item in the search array is the same color as the item stored in working memory (which we call a *matching distractor*), it should automatically attract attention. This will yield slower responses to the target because attention would be drawn toward the distractor and away from the actual target item.

Several aspects of the experimental design should be noted. First, the memory task required the storage of only one simple object in visual working memory, which avoids stressing working memory capacity (see, e.g., Irwin, 1993; Lee & Chun, 2001; Luck & Vogel, 1997; Palmer, 1990; Rensink, 2000; Vogel, Woodman, & Luck, 2001; Woodman, Vogel, & Luck, 2001) and leads to very straightforward predictions. Second, the target objects in the visual search arrays were defined by the relative location of a gap in an outlined square. In previous studies, researchers have demonstrated that the search for target objects defined by spatial relations is very inefficient (e.g., Logan, 1994), and we have shown that the search for these particular Landolt-C-like targets is serial (Woodman & Luck, 1999, 2003). This demanding search task should create high levels of competition for resources, maximizing the opportunity to observe any biasing effects of the contents of working memory. Unlike the study of Downing and Dodds (2004), in which the memory and search stimuli were matched on the basis of complex shape features that might be difficult to store accurately in visual working memory, we tested whether color might be a more potent feature in attracting attention to memory-matching items. Finally, the participants in this experiment were required to perform an articulatory suppression task—repeating two digits aloud—throughout each trial. This task served to minimize contributions from verbal working memory, ensuring that visual working memory would be used. In previous studies, researchers have shown that this procedure is highly effective in preventing the recoding of visual stimuli into a verbal form (Baddeley, 1986; Besner, Davies, & Daniels, 1981).

Method

Participants. Ten undergraduates from the University of Iowa participated for course credit. All participants reported having normal or corrected-to-normal visual acuity and normal color vision. Informed consent was obtained at the beginning of the session.

Stimuli. Stimuli were viewed from a distance of 70 cm on a video monitor with a gray background (9.9 cd/m^2). Stimulus luminance and chromaticity were measured with a Tektronix J17 LumaColor chromaticity meter using the 1931 Commission International d'Eclairage coordinate system.

The memory array consisted of a single colored square that subtended 0.45° × 0.45° of visual angle, centered 0.68° above the center of the screen. The color of the square was randomly selected on each trial from a set of seven possible colors: white (92.46 cd/m^2); black ($<$0.01 cd/m^2); red (x= .642, y = .327; 22.62 cd/m^2); blue (x = .152, y = .067; 9.66 cd/m^2); green (x = .318, y = .569; 64.99 cd/m^2); yellow (x = .478, y = .452; 65.23 cd/m^2); and violet (x = .304, y = .149; 7.04 cd/m^2). The objects that composed each search array were outlined squares (0.45° × 0.45°, 0.08° line thickness), with a 0.12° gap on the top, bottom, left side, or right side. Each search array contained five distractor objects and one target object. The search items were randomly positioned within a 6.1° × 6.1° region centered on the monitor; each item was at least 0.72° from the center of the monitor and at least 0.59° from its nearest neighbor (measured center to center). The target had a gap on the top or the bottom, and the distractors had gaps on the left or the right. Each square in the search array was drawn in a different color, which was randomly selected (without replacement) from the same set of seven colors described previously (with constraints described in the next section).

Procedure. The main body of each trial began with of a 500-ms presentation of the memory object. This presentation was followed, after a 500-ms delay, by the presentation of a visual search array that remained visible for 4 s. The participants were required to make a speeded response to the search array that indicated which of the two possible target objects was present (i.e., a square with a top gap or with a bottom gap). The offset of the visual search array was followed by a 500-ms delay, and a working memory test object was then presented for 3 s at the same location as the preceding memory item. On 50% of trials, the memory test object was the same color as that of the original memory object, and on the other 50% of trials, it changed to a different randomly selected color. Participants made an unspeeded response to indicate whether the object had changed. Each participant used the index and middle finger of his or her dominant hand to make the button-press responses, indicating top-gap or bottom-gap targets in the visual search task, respectively. Each participant used the index and middle finger of his or her other hand to indicate no change or a change in the memory task, respectively.

On mismatching-distractor trials, the colors of all the squares in the visual search array were different from the color of the memory object. On the matching-distractor trials, one of the distractor objects was drawn in the same color as that of the memory object. Mismatching-distractor trials and matching-distractor trials were equally probable and were randomly intermixed within an experimental block of 96 trials (48 of each type). Each participant was given approximately 10 practice trials before the experimental block.

Participants were required to perform an articulatory suppression task on every trial. This task consisted of repeating two digits at a rate of approximately 3–4 digits per second from the beginning of the trial until both responses had been made. On each trial, two digits were randomly selected without replacement from the integers 2–9 and were presented centered 0.65° to the left and right of the middle of the monitor. Each digit subtended approximately 1.70° × 0.85° and was presented in white (92.46 cd/m^2). Each pair of digits was shown for 500 ms, beginning 1,500 ms before the presentation of the visual working memory stimulus for that trial. Trials on which a participant failed to continuously repeat the two digits were excluded from further analysis. These trials accounted for less than 1% of all trials across all the participants and accounted for no more than 2% for a single participant.

Data analysis. In all experiments reported in this article, the data were analyzed in three separate analyses of variance (ANOVAs), one for search RT, one for search accuracy, and one for memory accuracy. Each ANOVA had a single within-subjects factor that represented the number of items in the search array that matched the item being held in memory.

Results and Discussion

Figure 2 shows mean RTs and accuracy for the search task and mean accuracy for the memory task. Visual search RTs were slightly faster for the matching-distractor trials (M = 1,475 ms) than for the mismatching-distractor trials (M = 1,505 ms). This small difference was not significant, $F(1, 9) = 0.64$, $p > .40$, and was opposite in direction to the pattern predicted by the biased competition theory. The error rate for the search task showed the same pattern, with a slightly but nonsignificantly greater error rate for mismatching-distractor trials (M = 98.9%) than for matching-distractor trials (M = 99.4%), $F(1, 9) = 0.99$, $p > .35$. Accuracy

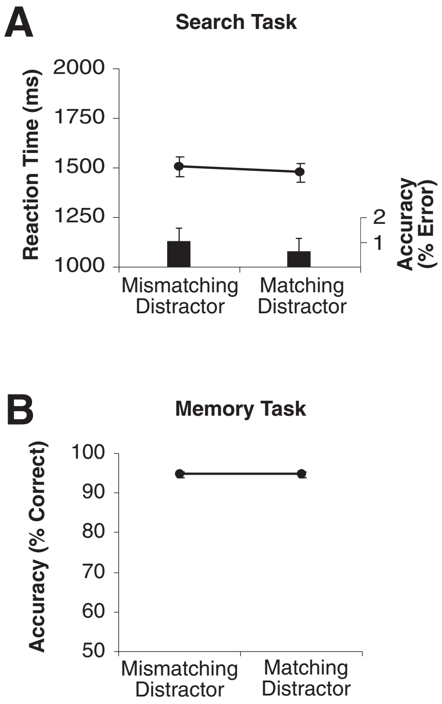

Figure 2. Search performance and change-detection accuracy from Experiment 1. A: Data from the visual search task performed during the retention interval of the change-detection task; search set size was always 6. B: Data from the change-detection task with a set size of 1. Error bars represent the 95% within-subjects confidence intervals, as described by Loftus and Loftus (1988).

in the memory task was identical for both types of trials (M = 94.6% for mismatching-distractor trials and M = 94.6% for matching-distractor trials). Thus, we found no evidence that attention was automatically captured by the visual search item that matched the color of the object being held in working memory.

These results are inconsistent with the proposal that attention is automatically captured by objects that match the current contents of visual working memory. However, these conclusions are tempered by at least two limitations of the present experiment. First, these conclusions are based on a lack of a significant difference between the matching-distractor trials and mismatching-distractor trials, but this null effect simply may reflect a lack of sensitivity and power. Second, the memory object in Experiment 1 shared only one feature with the matching distractor, and this commonality may have been insufficient to cause attentional capture by the matching distractor. The following experiments were designed to address these limitations.

Experiment 2

To provide a stronger test of the hypothesis that attention is automatically captured by objects that match the contents of working memory, we ensured that the memory object and the matching distractor were identical to one another in Experiment 2. Specifically, the memory object was a colored square with a gap on one side, and this exactly matched one of the distractors on matching-distractor trials.

Method

The method was identical to that of Experiment 1, with the following exceptions. A new group of 10 observers from the same pool volunteered for this experiment. During the sample and test presentations of the visual working memory task, a colored square with a gap on the left or right side was shown centered 0.68° above the center of the monitor. Participants were instructed to remember both the color and the gap position of this object, because either might change across the retention interval. The memory and test objects were identical on 50% of trials; they differed in color on 25% of trials and in gap position on 25% of trials. When gap position changed, it was always from left to right or from right to left. Participants indicated whether the memory test was the same or different from that held in memory and were not required to indicate which feature changed. The visual search task was the same as that used in Experiment 1.

Results and Discussion

As illustrated in Figure 3A, visual search RTs were virtually identical for the mismatching-distractor trials (M = 1,458 ms) and the matching-distractor trials (M = 1,455 ms). As in Experiment 1, search responses were slightly faster and slightly more accurate in the matching-distractor condition, but these differences did not approach significance, $F(1, 9) = 0.01$, $p > .90$ for RT and F(1,

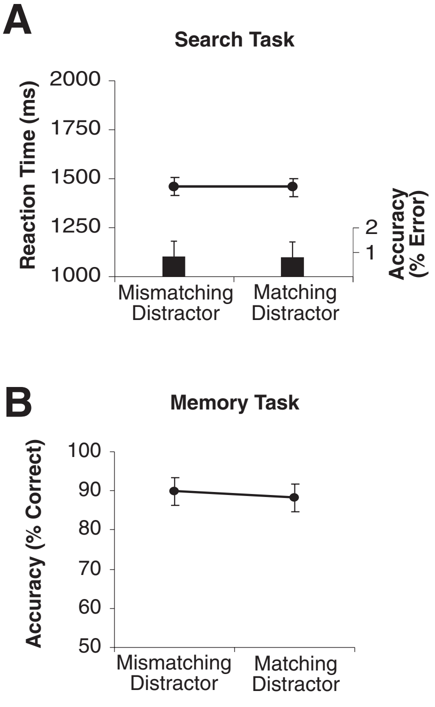

Figure 3. The results of Experiment 2. A: The visual search reaction times and accuracy at set size 6. B: The data from the change-detection task in Experiment 2. The working memory set size on each trial was one colored Landolt-C-like square. Error bars represent the 95% within-subjects confidence intervals, as described by Loftus and Loftus (1988).

9) = 0.01, $p > .95$ for accuracy. Figure 3B summarizes the mean accuracy from the visual working memory task. Accuracy was 90.0% for the mismatching-distractor trials and 88.3% for the matching-distractor trials, a nonsignificant difference, $F(1, 9) = 0.38$, $p > .50$.

Thus, even when the matching distractor exactly matched the memory object, we found no evidence that the matching distractor captured attention. This is a null result, but it replicates the null result found in Experiment 1, and the statistical power was fairly high (see the error bars in Figures 2 and 3, which show 95% confidence intervals).

Although we can never conclusively prove that this experimental manipulation had no effect, it is possible to show that any effect was quite small. To accomplish this task, we computed the difference in RT between the matching-distractor and mismatching-distractor conditions for each participant and then computed the 95% confidence interval of this difference. We found that the difference was –3.3 ± 5.9 ms. Consequently, we can be 95% confident that if automatic capture of attention by the matching distractor led to a slowing of responses, the effect was no more than 2.6 ms. In contrast, the time required to shift attention from one item to the next for these stimuli is 100–150 ms (Woodman & Luck, 1999, 2003). Thus, although we cannot conclude that matching-distractor trials and mismatching-distractor trials yielded equivalent RTs, we can conclude that if the matching distractor did capture attention, this effect was extremely small.

Experiment 3

The goal of Experiment 3 was to further generalize the results of Experiments 1 and 2 by increasing the number of objects being held in working memory. In addition, we carried out this manipulation to determine whether the results from Experiments 1 and 2 are only obtained when visual working memory is not heavily taxed—that is, in Experiments 1 and 2, the observers' visual working memory stores were not filled to capacity, and it is possible that this free capacity was used to overrepresent the search target in visual working memory. This overrepresentation may have prevented the memory item from causing attention to be captured by the matching distractor. The procedure of Experiment 3 was identical to that of Experiment 2, except that the participants were required to maintain three squares in memory. On matching-distractor trials, one of the distractors in the search array matched one of the memory items in both color and gap position. On mismatching-distractor trials, none of the items in the search array matched the color of any of the memory items.

Method

The method was identical to that of Experiment 2 except that a new group of 10 observers from the same pool participated in this experiment. During the sample and test presentations of the visual working memory task, a group of three colored squares with gaps on their left or right sides was presented. The three memory items were arranged in a triangular formation, with one centered 0.68° above the fixation point, one centered 0.68° to the left of the fixation point, and one centered 0.68° to the right of the fixation point. Participants were informed that they were to detect changes of color or shape (i.e., whether the gap changed from the left to the right side) in any of the three objects across the retention intervals of each trial. On half of all trials, the test objects were identical to the sample objects; on another 25% of trials, the color of one of the objects changed; and on the final 25% of trials, the gap position of one of the memory objects changed (i.e., from left to right or vice versa). On mismatching-distractor trials, none of the search distractors matched any of the memory items in color; on matching-distractor trials, one of the distractors was identical to one of the memory items.

Results and Discussion

The results are shown in Figure 4. Visual search RT was slower for the mismatching-distractor trials ($M = 1{,}394$ ms) than for the matching-distractor trials ($M = 1{,}327$ ms), just as in Experiments 1 and 2. This difference of 67 ms was statistically significant, $F(1, 9) = 14.47$, $p < .01$. Search error rates were slightly lower on matching-distractor trials ($M = 0.2\%$) than on mismatching-distractor trials ($M = 1.5\%$), a difference that approached significance, $F(1, 9) = 4.89$, $p < .06$. In the working memory task, responses were approximately 3% less accurate on mismatching-distractor trials ($M = 68\%$) than on matching-distractor trials ($M = 71\%$), but this difference did not approach significance, $F(1, 9) = 1.06$, $p > .30$.

These results provide further evidence that attention is not automatically drawn to items that are similar to the current contents of working memory. In Experiments 1 and 2, we found a trend toward faster RTs on matching distractor trials than on mismatching-distractor trials, and this effect was significant in

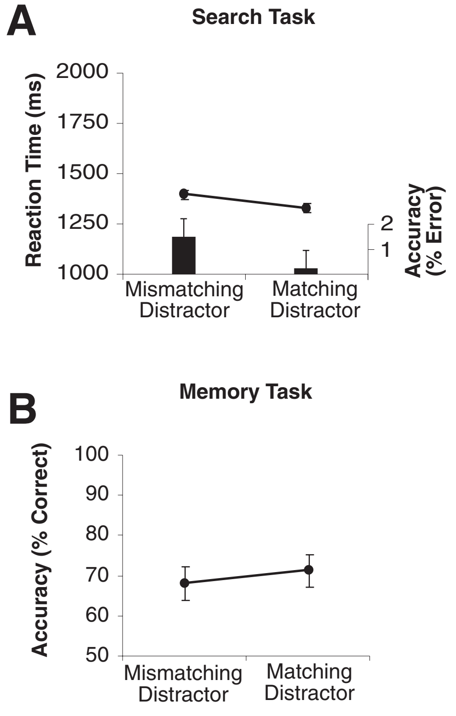

Figure 4. Results of Experiment 3. A: Visual search reaction times and search accuracy at set size 6. B: Data from the change-detection task in Experiment 3. The working memory set size on each trial was three colored Landolt-C-like squares. Error bars represent the 95% within-subjects confidence intervals, as described by Loftus and Loftus (1988).

Experiment 3. This pattern of results is the opposite of the predictions of the biased competition theory and the findings of Downing (2000) and Pashler and Shiu (1999).

The finding of faster RTs on matching-distractor trials suggests that the participants took advantage of the fact that the target never matched the items in working memory and actively avoided searching matching items (at least for some subjects on some proportion of trials). This conclusion suggests that participants can use the contents of visual working memory in a flexible manner to guide the allocation of attention either toward or away from matching items. In other words, the contents of working memory can be used as either a template for selection or a template for rejection, depending on the nature of the task.

We also observed better performance on the memory task when a matching distractor was present in the search array. Although this effect did not approach significance, it is consistent with the strategic perceptual resampling hypothesis—that is, participants may have taken advantage of the presence of a matching item to refresh their working memory representations, leading to improved memory performance when the search array contained a matching distractor. Moreover, this could have been accomplished after the search task was completed to avoid interfering with the search task.

Experiment 4

Experiment 3 indicated not only that attention is not automatically drawn to items that match the contents of working memory but also that observers can strategically avoid searching items that match the contents of working memory. That is, Experiment 3 suggests that the contents of visual working memory can be used as a template for rejection. Experiment 4 provided a further test of this hypothesis and also provided an additional test of the strategic perceptual resampling hypothesis. If the visual system can reject search items on the basis of their similarity to representations stored in visual working memory, then the processing of the search array should become more efficient as the number of matching distractors is increased. Moreover, increasing the number of visual search distractors that are similar to a representation that is being maintained in visual working memory should increase the likelihood that perceptual resampling can be used to increase the fidelity of similar working memory representations. Imagine, for example, that 8 of 10 objects in a search array matched an item being stored in working memory; thus, it would be trivial for an observer to find a matching item and use it to refresh the working memory representation after the search task has been completed. If, in contrast, only 1of the 10 search items matched the working memory object, it would be more difficult for an observer to find the matching item and engage in perceptual resampling. Moreover, if the contents of working memory can be used as a template for rejection, then the search process should be completed faster when many search items match the memory object, leaving more time for the observer to engage in perceptual resampling.

Experiment 4 was designed so that the heterogeneity of the items that made up the search arrays did not vary when the number of items that matched the memory item was manipulated because the heterogeneity of a group of search distractors has been shown to influence how efficiently a search can be performed (Duncan & Humphreys, 1989). Specifically, each search array contained two items drawn in one color, four items drawn in a second color, and six items drawn in a third color (see Figure 5). The color of one of these three groups of items was the same as the color of the memory object (i.e., memory-matching items), and the target was always drawn in a color other than that of the item held in memory. In this way, we were able to manipulate the number of items that were similar to the item held in working memory while controlling the degree of heterogeneity that existed among the items in the search arrays. To avoid confounding the effects of the number of memory-matching items with the number of elements that matched the color of the target, we compared search and memory performance when the number of elements that matched the target was held constant and when the number of memory-matching items was varied (e.g., one item matching the color of the target and four items matching the memory object vs. one item matching the target and 6 items matching the memory object).

The main factor manipulated in Experiment 4 was the number of memory-matching distractors in each search array. We predicted that search RTs would decrease as the number of memory-matching distractors increased, indicating that the memory object was being used as a template for rejection. We also predicted that memory performance would increase as the number of memory-matching distractors increased, indicating that the participants engaged in strategic perceptual resampling.

Method

The method was identical to that of Experiment 2 with the following exceptions. A new group of 10 volunteers from the same pool participated. Each visual search array contained 11 distractors (i.e., colored squares with left or right gaps) and one target with a top gap or bottom gap. Each item was drawn in one of three colors on a given trial. As the example in Figure 5 shows, two items were drawn in one color, four items were drawn in a second color, and the remaining six items were drawn in a third color. The three colors in a given array were selected at random, without replacement, from the same set of seven colors used in the previous experiments. The target item was never the same color as the item that was being held in memory on that trial. One of the other two colors in a given search array did match the color being held in memory, but gap position (left or right) varied randomly and independently across the items in the search array. Thus, the color of the item being held in memory always matched two, four, or six of the items in the search array but never matched the color of the target item. All of these factors varied unpredictably within trial blocks.

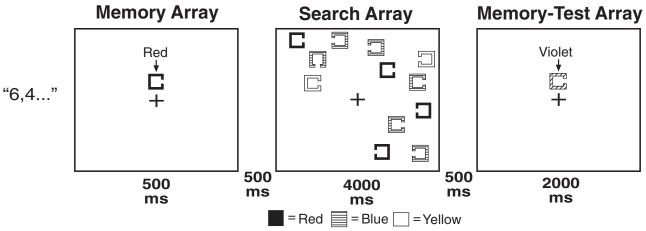

Figure 5. Example of the stimuli used in Experiment 4. In this example, the correct response to the working memory task is different, and the target is a blue square with a gap down. This example represents a possible stimulus configuration for a trial in which four distractors were similar to the memory item.

Results and Discussion

The results are summarized in Figure 6. Visual search RT decreased as the number of matching distractors increased. RT was faster when more distractors were similar to the memory item, regardless of how many items were similar to the target. To quantify the effect of the number of memory-matching items while removing the influence of variation in the number of search elements that were similar to the target, we computed the difference between performance for the two trial types with the same number of distractors that were similar to the target. When one distractor was the same color as the target, the observer's RT was 98.3 ms faster with six memory-matching items than with four memory-matching items, and this difference was significantly greater than zero, $F(1, 9) = 7.39$, $p < .05$. When three distractors matched, the target RT was 185.2 ms faster when six memory-matching items were present versus when two memory-matching items were present, $F(1, 9) = 7.95$, $p < .05$. Finally, when five items matched the target, responses were 105.8 ms faster when four memory-matching items were present compared with when two memory-matching items were present, $F(1, 9) = 1.48$, $p > .25$. Although this final difference was not significant, the effect was in the same direction as in the other comparisons. The effect of increasing memory-matching items was approximately linear across all trial types, as would be expected if participants simply avoided searching these items. Search error rates were low and were not significantly influenced by the number of memory-matching distractors in any of the comparisons (see Table 1; $F\text{s} < 1.0$).

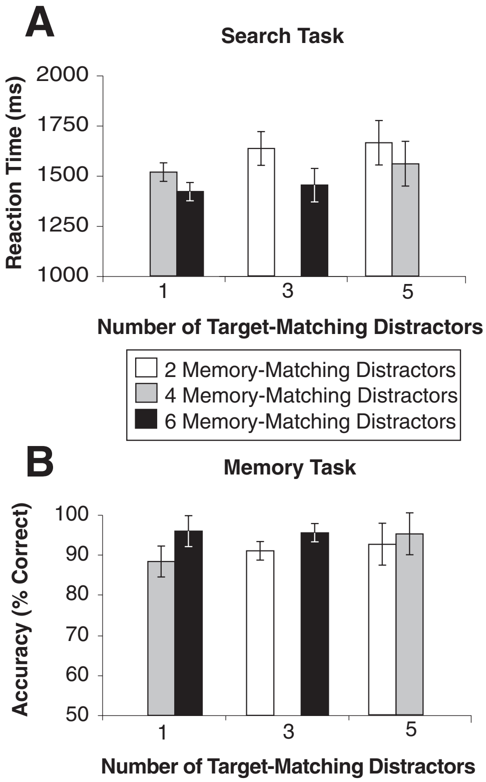

Figure 6. Results of Experiment 4. A: Visual search reaction times as a function of the number of memory-matching and target-matching distractors. B: Data from the change-detection task; the numbers on the *x*-axis indicate how many of the visual search items, of the 12 present, were similar to the target item, and the three types of bars indicate how many items matched the memory item. The working memory set size on each trial was one colored Landolt-C-like square. The error bars represent the 95% within-subjects confidence intervals from each statistical comparison performed, as described by Loftus and Loftus (1988).

In the working memory task, participants were more accurate at detecting changes when more of the distractors matched the color of the memory item (see Figure 6B). When one distractor was the same color as the target, change-detection accuracy was 7.6% higher on trials in which six memory-matching items were present than when four such distractors were present, a difference that is significantly greater than zero, $F(1, 9) = 6.56$, $p < .05$. When three of the distractors were the same color as the target, change detection was 4.5% more accurate with six memory-matching distractors than with two memory-matching distractors, $F(1, 9) = 5.96$, $p < .05$. On the trials in which five items were the same color as the target, accuracy was 2.6% higher when four memory-matching items were present compared with when 2 memory-matching items were present, $p > .25$. Thus, increasing the number of matching distractors leads to faster search RTs and more accurate performance of the memory task, consistent with observers' strategic use of attention to avoid searching the matching items and also consistent with observers' use of strategic perceptual resampling of the matching items to aid working memory performance. Thus, the results suggest that the participants avoided searching the matching items until after they found the search target, and then they oriented attention to the matching items to engage in perceptual resampling.

In summary, Experiments 1 through 4 demonstrate that observers' responses are not slowed by the presence of distractors that match items stored in visual working memory. Moreover, participants' responses were significantly faster when more distractors could be rejected as a possible target on the basis of their similarity to an item held in visual working memory. From these findings, we conclude that attention is not automatically deployed to distractors simply because they match an object representation in visual working memory. In previous reports of experiments that suggest attention was drawn to items that matched representations in visual working memory, participants had no reason not to deploy attention to the matching items. As discussed above, the previous findings are consistent with observers adopting a strategy of attending to the matching items either to aid performance on the memory task or because of demand characteristics. However, in those previous studies, researchers used qualitatively different tasks than those we used in the present study. It is possible that even when subjects do not have a reason to avoid processing matching items during visual search, they still do so in this paradigm. Thus, in Experiment 5, we wanted to test our explanation of previous findings using essentially the same dual-task paradigm that we did in Experiments 1–4 with the exception that the item in memory occasionally matched the critical features of the visual search target.

Table 1
Mean Visual Search Error Rates From Experiment 4

	Two match memory		Four match memory		Six match memory	
Trial type	% error	±*SEM*	% error	±*SEM*	% error	±*SEM*
One match target			1.67	0.92	2.92	1.25
Three match target	3.75	1.15			3.33	1.21
Five match target	2.08	2.0	1.25	1.9		

Note. *SEM* = standard error of the mean.

Experiment 5

We propose that in Experiments 1–4, observers were biased to deploy attention away from the items in the search array that matched the memory object because they knew that these items would never be the search targets. However, we have yet to explicitly test the hypothesis that if the contents of visual working memory do occasionally match the searched-for target, then this bias for rejecting such items would be eliminated. In Experiment 5B, we did just that. As illustrated in Figure 7, participants searched for squares with a gap either up or down while maintaining a colored square with two gaps in visual working memory. The shapes of the memory stimuli were slightly different from those in the previous experiments; thus, the shape features of these stimuli overlapped with the target shapes. In contrast with the previous experimental designs, the target item and the memory item occasionally matched one another (with the exception of an additional line segment on the top or bottom of the target). Specifically, the color of the memory item matched the searched-for target and two of the distractors on one sixth of all trials (target-matching trials); on a different one sixth of the trials, the memory item matched half the distractors in the array but not the target (distractor-matching trials); and on the other two thirds of trials, the colors of the items in the search array did not match those of the memory item (neutral trials). Because six possible stimulus colors were used, the probability that the target matched the color of the memory item was no greater than would be expected by chance.

This experiment allowed us to determine whether it is possible to obtain effects similar to those reported by Downing (2000) and Pashler and Shiu (1999) using our dual-task paradigm. According to our explanation of these previous studies, we expected that observers would deploy attention to the memory-matching items because (a) there was no motivation not to do so, (b) this would

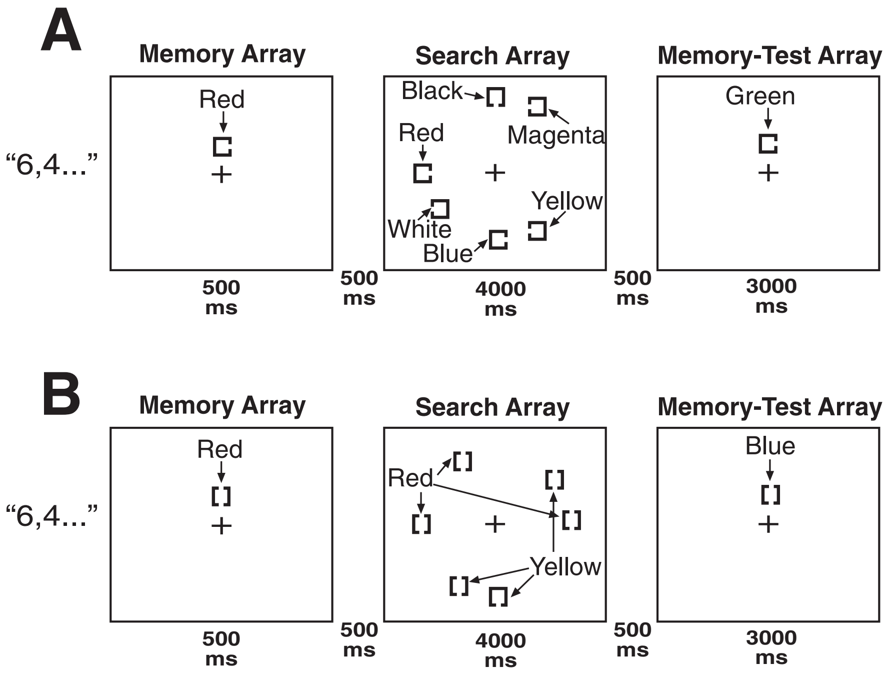

Figure 7. Example of the stimuli used in Experiment 5A and 5B. A: An example of the stimuli shown on a trial in Experiment 5A. B: Example of the stimuli presented during a distractor-matching trial in Experiment 5B. In both of these examples, the correct response to the working memory task is different, and the correct visual search response is that the target has a gap down.

lead to a benefit when the memory-matching item happened to be the target, (c) the demand characteristics of the experiment may have made observers curious about the memory-matching items, and (d) doing so may have allowed observers to better maintain their representation of the memory item.

Experiment 5B was conducted through the use of different hardware, software, and search stimulus configurations than those used in Experiments 1–4, and the participants were drawn from a different pool. Because of these differences, Experiment 5A was a replication of Experiment 2: We used the same general methods and participant pool as that of Experiment 5B. Specifically, we required observers to search arrays of elements in a circular array of possible locations. As in Experiment 2, the distractors were colored squares with left or right gaps, and the targets were colored squares with top or bottom gaps. The memory item was a randomly colored square with a left or right gap. The search target was never the same color as the memory item, but a distractor matched the memory item in color and shape on the other 50% of trials. We expected to observe the same pattern of results as those observed in Experiment 2.

Method

Participants. Different groups of 10 volunteers from Vanderbilt University participated in Experiment 5A and 5B. All participants reported having normal or corrected-to-normal visual acuity and normal color vision. Informed consent was obtained before the experiment began.

Stimuli and procedure. Stimuli were viewed from a distance of approximately 57 cm on a gray background (48.5 cd/m^2). Stimulus luminance and chromaticity were measured with a Minolta CA-100 chromaticity meter using the 1931 Commission International d'Eclairage coordinate system.

The stimuli and procedure used in Experiment 5A were based on those of Experiment 2. Specifically, we required participants to perform articulatory suppression while concurrently performing a visual working memory task and visual search. The articulatory suppression stimuli were two white numbers (0.7° × 0.4°, 92.6 cd/m^2, drawn from the set 2–9) centered 1.8° above the black fixation point (0.3° × 0.3°, < 0.01 cd/m^2), with one number centered 0.3° to the left of fixation and one number centered the same distance to the right. The memory and memory–test arrays consisted of one colored square (0.7° × 0.7°, 0.15° line thickness) with a gap (0.1°) on the left or right side in Experiment 5A and a gap on the top and bottom of the square in Experiment 5B. This memory item was centered approximately 0.9° above the black fixation point. The color of the memory stimulus was randomly drawn from a set that was qualitatively similar to that used in the previous experiments (i.e., red: $x = .627$, $y = .327$; blue: $x = .142$, $y = .065$; violet: $x = .279$, $y = .139$; green: $x = .280$, $y = .589$; yellow: $x = .397$, $y = .500$; black: < 0.01 cd/m^2; and white: 92.6 cd/m^2).

In Experiment 5A, the visual search arrays were composed of five distractors with gaps left and right (randomly selected) and one target with a gap up or down (randomly selected). All items were randomly colored with the exception that on half the trials, one of the distractors exactly matched the memory item. In Experiment 5B, the search arrays were composed of five distractors with gaps on both the top and bottom of the squares and one target object with a gap on either its top or bottom. Three distractors were drawn in one randomly selected color, and the other two distractors and the target were drawn in a different randomly selected color with the constraint that on one sixth of trials, three distractors matched the color of the memory item; on another one sixth of trials, two distractors and the target matched the color of the memory-item; and on the rest of the trials, none of the items in the search array matched the color of the memory item. In both Experiments 5A and 5B, observers were required to report the identity of the search target (gap up or gap down) by making a speeded button-press response on a keyboard. They indicated that the target had a gap up by pressing the '*1*' key on the number pad with the index finger of their right hand, and they pressed the '*2*' key with their middle finger to indicate that the target had a gap down. The objects in the search array were centered approximately 3.3° from the fixation point on an imaginary circle. The object locations were randomly selected from a set of 12 possible locations that were evenly spaced on this circle with the center-to-center distance between objects being at least 1.7° of visual angle. Participants made an unspeeded '*X*' keypress response on the keyboard with their left index finger to indicate that the test item was identical or a '*Z*' keypress with their left middle finger to indicate that the test item differed from the memory sample item. In Experiment 5A, the memory item and memory-test item were either identical (50% of trials) or they differed in color (25% of trials) or side of gap (25% of trials). In Experiment 5B, the shapes of the memory items were all the same, and only color changes were possible (50% of trials).

In Experiment 5A and 5B, each trial began with the presentation of a pair of digits for 500 ms, beginning 1,500 ms before the presentation of the visual working memory stimulus for that trial. The memory item was then shown for 500 ms followed by a 500-ms interstimulus interval before the search array was presented for 4 s. Following another 500-ms interstimulus interval, the memory test item was shown for 3 s.

Each experimental session began with 12 practice trials. In Experiment 5A, the experimental session was divided into two 36-trial blocks with a break between the blocks. This yielded 36 memory-matching trials and 36 memory-mismatching trials. In Experiment 5B, the session was divided into seven 36-trial blocks; participants were allowed to rest between blocks. As a result, each participant performed 42 target-matching trials, 42 distractor-matching trials, and 168 neutral trials.

Results and Discussion

The results of Experiment 5A are shown in Table 2. Mean search RTs were 46.8 ms faster when a memory-matching distractor was present, but this effect was not statistically significant, $p > .30$. In addition, there were 1.6% fewer search errors when a memory-matching distractor was present, and this effect was significant, $F(1, 9) = 11.98$, $p < .01$. Memory accuracy was 4% higher when the search array contained a distractor that matched the memory item than when it did not, and this effect was significant, $F(1, 9) = 4.89$, $p = .05$. These results indicate that the findings of Experiment 2 generalize across the variations in the stimulus arrays used in Experiment 5 when the target never matches the item held in visual working memory, as in Experiments 1–4.

Table 2
Mean Visual Search and Memory Task Performance From Experiment 5A

	Mismatching distractor		Memory-matching distractor	
Trial type	*M*	±95% CI	*M*	±95% CI
Visual search RT	1,371.3	58.6	1,324.5	58.6
Visual search error	2.45	0.60	0.86	0.60
Memory accuracy	91.5	2.29	95.5	2.29

Note. RT = reaction time. CI = confidence interval.

The results from Experiment 5B are shown in Figure 8. Visual search RT was fastest on target-matching trials (1,373.5 ms), slower on neutral trials (1,446.4 ms), and slowest on distractor-matching trials (1,571.4 ms), $F(2, 18) = 11.45$, $p < .001$. Planned comparisons revealed that each of these mean RTs differed significantly from the others, $ps < .05$. Visual search responses were highly accurate on target-matching trials, distractor-matching trials, and neutral trials (97.6%, 97.7%, and 98.3% correct, respectively), $p > .60$. These findings indicate that when the target occasionally matches the item held in visual working memory, observers adopt a strategy of deploying attention first to the matching items in the search array. This conclusion was evidenced not only by faster RT on target-matching trials than on neutral trials but also by slower RT on distractor-matching trials relative to the neutral baseline.

The neutral trials from Experiment 5B are comparable to the mismatching trials from Experiment 5A, and distractor-matching trials were present in both experiments. Thus, a statistical comparison is possible between the two experiments by excluding the target-matching trials from Experiment 5B. We performed this between-experiments comparison on the RT data using a between-subjects factor of experiment and a within-subjects factor of matching. We found a significant Experiment × Matching interaction, $F(1, 18) = 9.38$, $p < .001$, indicating that the presence versus absence of occasional trials in which the target matched the item being held in memory led observers to adopt different search strategies.

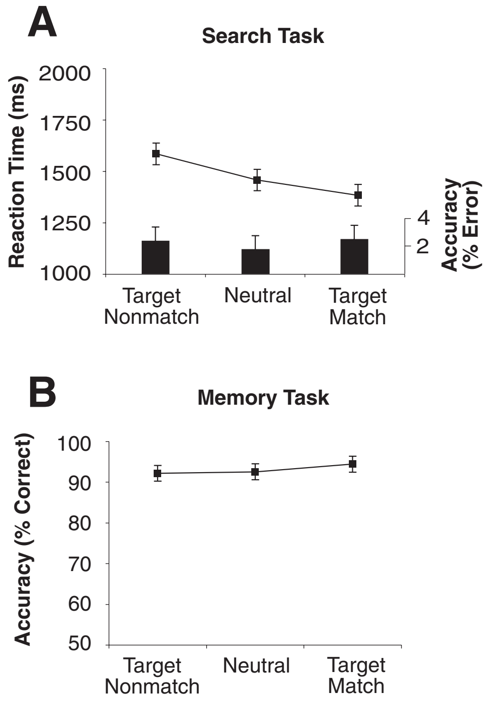

Figure 8. Graphs of the results from Experiment 5B. A: Visual search RT and percent error during the three types of trials. B: Accuracy of change detection as a function of the type of visual search trial performed during the retention interval. Error bars represent the 95% within-subjects confidence intervals, as described by Loftus and Loftus (1988).

Change-detection performance in the memory task was above 90% across all trials. However, participants were slightly more accurate on the target-matching trials (94.4%) than on distractor-matching trials (92.1%) or neutral trials (92.5%). Although this difference was not statistically significant, $F(2, 18) = 1.16$, $p > .30$, the finding of slightly higher change-detection accuracy on target-matching trials is consistent with the observer's strategic allocation of attention to the matching item to refresh the working memory representation.

The findings of Experiment 5 allowed us to refine the conclusions that we drew from this study in two ways. First, the results of Experiment 1–5 illustrate that just having a representation in working memory is not sufficient for attention to be biased so that observers select similar items during visual search. Instead, participants need another reason to deploy attention to the matching item(s). Experiment 5B demonstrates that a task context in which observers sometimes can speed the search by first shifting attention to the memory-matching items is sufficient for observers to adopt the strategy of deploying attention first to the memory-matching items and then to the other elements in the search array. Second, Experiment 5 establishes that observers use the template for rejection strategy when the features of the memory item consistently map to nontargets. However, if the search target can match an item held in visual working memory, observers then deploy attention to the memory-matching items, an act which also improves retention of the memory representation. It seems logical that observers are motivated to engage in strategic perceptual resampling while performing the search task because the costs of deploying attention to memory-matching items when the target is not one of them is compensated for by benefits when the target does match the memory item. This conclusion is analogous to what Downing (2000) found in his study except that he used a paradigm in which probe discrimination was the primary task.

General Discussion

In these experiments, we tested a fundamental hypothesis of many theories of attention regarding the role of visual working memory in visual search, namely that holding a representation in visual working memory automatically biases the visual system to selectively process objects that match that representation. As described in the introductory paragraphs, in several prominent theories of attention, researchers have proposed that observers achieve attentional selectivity by maintaining a target representation in working memory. An implicit assumption of this proposal is that observers automatically bias attention to select incoming information that is similar to that stored in visual working memory. We directly tested this assumption by requiring participants to perform a visual search task during the retention interval of a change-detection task. The findings of this series of experiments indicate that attention did not cause observers to automatically select items in visual search arrays that were similar to the items maintained in service of the change-detection task. Indeed, when they knew that the target would never match the item being held in memory, observers could strategically avoid items that matched the working memory representation. This pattern of findings indicates that the relationship between what is represented in visual working memory and what is selected by perceptual attention mechanisms is more complex than that which is outlined by the biased competition theory and related theories of attention.

Before accepting the conclusion that attention is not automatically drawn to items matching the contents of working memory, we must consider an alternative explanation of these results[1]. Specifically, because the observers knew that the memory-matching item was never the target in Experiments 1–4, it is possible that attention was attracted to this item but then was shifted away extremely rapidly. Thus, even though attention was automatically attracted to the nonmatching item in the search array, it was moved away so rapidly that this shift of attention produced no measurable effect on RT. Although this explanation cannot be ruled out, it seems very unlikely. First, it would require extremely rapid shifts of attention. However, previous electrophysiological experiments in which researchers used the same search stimuli indicate that attention shifts between these objects required at least 100 ms, and behavioral evidence suggests that it is unlikely that attention can actually shift in less than 100 ms (RT slopes in most visual search experiments probably underestimate the actual dwell time of attention; see Ward, Duncan, & Shapiro, 1996; Woodman & Luck, 2003). Second, it would require that subjects can rapidly change the dwell time of attention, dwelling only briefly for the memory-match items but dwelling longer for other items. There is no evidence that the dwell time of attention can be rapidly adjusted on the basis of complex information such as the presence of a match with working memory. Moreover, the adjustment of dwell time would need to be essentially instantaneous to explain the present results; otherwise, RTs would have been slowed by the presence of a memory-matching item. The available evidence indicates that reconfiguring the parameters that control visual attention requires significant time (Logan & Gordon, 2001). Thus, it is extremely unlikely that subjects briefly shifted attention to the memory-matching items in Experiments 1–4.

The results of this study indicate that theories of attention must specify how observers can avoid attending to items that possess a given set of features. For example, the guided search theory specifies how attention can be directed toward items containing a given set of target features, but it does not specify how attention can be directed away from items that contain a given set of nontarget features (Wolfe, 1994). Feature integration theory, in contrast, explicitly specifies that individual features can be inhibited (Treisman & Sato, 1990).

Because it is so flexible, Bundesen's (1990) theory of visual attention (TVA) could easily account for the results of this study. Specifically, TVA proposes that observers use a target template in working memory to bias perceptual selection to process similar items by increasing the attentional weights for the template's features. However, it is possible for observers to use the contents of visual working memory to set attentional weights for the features of an item in working memory to zero (or to a very small value) and therefore prevent similar items from receiving the benefit of attention. In this way, TVA could account for the observation that participants are faster to find a target when the search array contains a distractor that is similar to an item retained in working memory and that is known never to be similar to the searched-for target.

Our finding that visual search is faster when the search array contains an item that cannot be the target because of its relationship to a memory representation may be related to recent research on visual marking during search. Watson and Humphreys (1997) demonstrated that search is more efficient when the distractor objects are presented in two spatially intermixed groups with the target always appearing in the second group of items than when all of the distractors are presented simultaneously with the target. Watson and Humphreys called this effect *visual marking* to suggest that the first group is somehow marked for inhibition and, therefore, is not searched. However, debate continues as to whether the facilitation of search in the visual marking paradigm is caused by top-down inhibition of the first group of distractors, as originally proposed, or whether it is due to a bottom-up attentional prioritization of the second group of items (Donk & Theeuwes, 2003) perhaps via known perceptual grouping cues (Jiang, Chun, & Marks, 2002). The interpretation of visual marking in terms of top-down guidance away from known distractors is similar to our explanation of the present findings.

Several specific findings from studies of visual marking are particularly relevant here. First, Olivers and Humphreys (2002, 2003) showed that when items in the second group of potential targets share features with the nontargets in the first group, these targets are discriminated more slowly than are targets that differ in color or orientation from the old array. In addition, the capture of attention by a singleton in the new arrays of search items is modulated by whether or not that singleton shares features with the distractors from the old array. These findings indicate that the bias to avoid deploying attention to old items spreads to potential targets that have the same visual features and suggests that the inhibition of the nontarget features in the old array carries over to similar items in the new array. More recently, Braithwaite, Humphreys, and Hulleman (2005) provided converging evidence for inhibition spreading across items grouped by color using a probe detection task. In these studies, the researchers suggest that the features of a set of previously inhibited distractor objects may affect attentional deployment during visual search such that perceptual selection favors features that have not recently been inhibited. Conceptually, these findings from studies of visual marking are similar to those observed in the present study, in which perceptual similarity to an item represented in working memory seems to bias selection away from such items.

Although the present findings and those from previous studies of visual marking may be related in that attention is directed away from certain items, in the present study we address a qualitatively different issue: We focus on whether an active memory representation of a distractor object biases attention and causes the observer to select similar objects encountered at other points in time and space. Unlike the findings from studies of visual marking in which feature-based inhibition of the old items carries over to similar items later in time, our findings specifically demonstrate the complexity of the dynamic interactions between what object representations are maintained in visual working memory and what is selected via visual–spatial selection mechanisms. For example, the findings that attention initially is biased away from memory-matching items during search but then toward such items after search is completed suggests that the role of the working memory

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[1] We thank Chip Folk for pointing out this possibility.

representation in biasing attention is rapidly changing as the search array is viewed. In addition, the specific cognitive resources underlying the effects we examined and those of visual marking appear to be different. Recent research suggests that visual marking is not based on a representation of the first group in working memory but is instead based on a representation of the new possible target items (Jiang & Wang, 2004).

The findings of this study complement and extend a recent study by Downing and Dodds (2004) that was conducted in parallel with the present study. Using a paradigm similar to ours, they found that the presence of a distractor that matched an item held in memory did not significantly impair search performance, just as we found. Rather than taking this as evidence against the biased competition model, however, they proposed that observers can somehow switch off or ignore working memory representations that are irrelevant for a given task so that these representations do not influence the allocation of attention.

Experiments 3 and 4 of the present study provide data that challenge such a proposal, because the presence of matching distractors actually led to faster RTs. If the working memory representations were switched off or stored elsewhere such that they did not influence attentional deployment during search, as proposed by Downing and Dodds (2004), these representations could not have led to a speeding of RTs. And if they were switched on, they should have led to the automatic allocation of attention to the matching distractors, impairing rather than improving performance. Instead, we have shown that observers can use working memory representations to orient attention away from matching items when doing so is beneficial for the task. Moreover, Downing and Dodds (2004) found a similar effect on target present trials in their Experiment 2 but not in their Experiment 1, although they did not focus on this aspect of the data in their general account of the findings. To be reconciled with these results, the account of Downing and Dodds (2004) would need to be modified such that the representations in working memory are not turned off or sequestered in a separate working memory store but instead actively guide perceptual selection away from the memory-matching items while search is performed. This would be a major departure from the spirit of the original Downing (2000) and Downing and Dodds (2004) accounts, in which the activation of working memory leads directly and inexorably to a competitive advantage for memory-matching items, an advantage that can be avoided only by switching off or buffering the memory representations in a separate store. The present results are instead consistent with a more flexible conceptualization of the role of working memory, in which executive systems consult working memory representations when setting attentional control parameters to match the demands of the task.

In contrast to the similarity of the findings of the present study and those of Downing and Dodds (2004), researchers in another recent study concluded that attention is automatically biased to items that match a visual working memory representation. Specifically, Soto et al. (2005) used a paradigm in which a memory stimulus was rapidly flashed three times immediately before a visual search array was presented. The target feature could appear embedded in an object that either did or did not match the object that participants were supposed to remember. The researchers found that observers were faster to discriminate target features embedded in objects that matched the memory item in color but not in shape. In addition, observers were more likely to make their first saccade to the memory-matching items even when they knew that it would not be the target. The cause of the discrepancy it not immediately clear, but the tasks and stimuli used in present study and that of Soto et al. differ in a number of ways. In particular, Soto and colleagues presented the to-be-remembered stimuli three times in rapid succession very shortly before the search array (i.e., a 188-ms interstimulus interval), whereas in the present study, the memory stimuli were presented for longer exposure durations with a longer interval between the memory stimulus and the search array. It is possible that the cognitive control settings needed to use a visual working memory representation as a template for rejection take some time to implement, as proposed in the visual marking literature discussed previously. Thus, it is possible that the short retention interval between the presentation of the memory stimuli and the search array in the study conducted by Soto et al. was not long enough for the observers to reconfigure their cognitive control settings. Similarly, the effects observed by Soto et al. may have been based on a short-lived memory representation that was not still active by the time of the search array in the present study. Further research is needed for determination of the boundary conditions in which these strikingly different patterns of effects are found.

In addition to demonstrating that observers can strategically avoid attending to items that match working memory representations while they are performing visual search, in the present study we also suggest that after the search task is completed, observers may strategically focus attention onto matching items so that they can refresh working memory representations. This perceptual resampling of objects appears to be an object-based analog to what Awh and colleagues (e.g., Awh, Jonides, & Reuter-Lorenz, 1998) have suggested observers carry out when trying to maintain locations during spatial working memory tasks. The strategic perceptual resampling hypothesis was supported by two of our findings. First, memory accuracy increased as the number of matching items increased. Second, in Experiment 5, in which the contents of memory could match the critical features of the visual search target, we found that participants not only were faster to discriminate targets that matched the memory item but they could also more accurately remember that item. Finally, this strategic resampling hypothesis may explain why researchers in previous studies found that attention was directed to items that matched the contents of working memory (e.g., Downing, 2000; Pashler & Shiu, 1999). Future studies in which researchers use techniques that can more directly measure what information is overtly or covertly attended during visual search are needed for clarification of the role of perceptual resampling in memory-intensive dual-task paradigms.

In summary, in this study we provide evidence that attention can be biased away from memory-matching distractors during visual search and then become biased toward such items to perform perceptual resampling after the search target has been found. This finding suggests that dynamic changes in the control of visual attention may occur within a few hundred milliseconds. Thus, we suggest that it is possible to reconfigure attentional control settings in the middle of a trial, which is analogous to between-trial changes that are hypothesized to occur in task-switching procedures (Logan & Gordon, 2001; Mayr & Kliegl, 2000; Rogers & Monsell, 1995). For example, as we stated previously, TVA could explain our template-for-rejection effects by proposing that attentional weights for memory-matching items initially be set to near zero in anticipation of the visual search array. However, once visual search has been completed, the attentional weights for memory-matching items could be reset to a value near 1.0, making it possible for the observer to engage in perceptual resampling. In this way, visual attention switches between avoiding memory-matching items and being guided to them in service of two different tasks (i.e., visual search and memory maintenance).

This proposal is a conceptual cousin of the explanation provided by Downing and Dodds (2004), in which memory representations are rapidly turned on and off, except that observers use the same representation to guide attention toward or away from matching items at different points during the trial. This idea is very similar to the switching of TVA parameters that Logan and Gordon (2001) proposed in the context of dual-task experiments. A second way to account for the present pattern of effects within the conceptual framework of TVA is to posit that the attentional weights for memory-matching features initially are not set to zero but are set to some value slightly below the value for the visual-search target. Once the target is attended and discriminated, the attentional weights for target-like features would be set to zero, and the memory-matching items would then have the highest weights and become selected. Additional research is necessary for determination of whether the present results reflect an explicit change in attentional control parameters or a more simple prioritization scheme.

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