

Research Article

INTERACTIONS BETWEEN VISUAL WORKING MEMORY AND SELECTIVE ATTENTION

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Abstract—*The relationship between working memory and selective attention has traditionally been discussed as operating in one direction: Attention filters incoming information, allowing only relevant information into short-term processing stores. This study tested the prediction that the contents of visual working memory also influence the guidance of selective attention. Participants held a sample object in working memory on each trial. Two objects, one matching the sample and the other novel, were then presented simultaneously. As measured by a probe task, attention shifted to the object matching the sample. This effect generalized across object type, attentional-probe task, and working memory task. In contrast, a matched task with no memory requirement showed the opposite pattern, demonstrating that this effect is not simply due to exposure to the sample. These results confirm a specific prediction about the influence of working memory contents on the guidance of attention.*

Selective attention reduces the load on limited-capacity cognitive systems by filtering irrelevant information from the stimulus stream. Working memory refers to the active maintenance of a representation after the stimulus that produced it is no longer present. Many researchers have commented on the basic link between these two cognitive systems, the classical view being that attention gates, or controls, what sensory information is allowed into short-term memory stores. Recent work by Desimone and Duncan (1995; Desimone, 1996; Duncan, 1998) has suggested an important link operating in the opposite direction: The contents of working memory will influence the allocation of selective attention. According to this account, both functions depend on a top-down biasing mechanism that enhances the activation of object representations stored in long-term memory.

The application of this proposal to working memory for objects is fairly straightforward. An object is held in working memory by top-down modulation, perhaps from prefrontal cortex (Miller, Erickson, & Desimone, 1996), that maintains the activation of cortical representations of the object after it is no longer present. This activation can then be used to guide response to the remembered object, for example, in a delayed-match-to-sample task.

A similar mechanism has been proposed to underlie target selection in visual search tasks. In a typical scene filled with many objects, the amount of information present exceeds the capacity of object representation systems. As a result, the objects can be described as “competing” for attention. The strongest competitors will tend to become the focus of selective attention, gaining privileged access to awareness and guidance of action. Duncan and Humphreys (1989) suggested that in the search situation, maintenance of the “search template” activates the representation of that object in long-term storage. This, in turn, provides a competitive advantage for the target

object, leading to its eventual selection and the effective suppression of other irrelevant objects.

Single-cell recording studies provide key evidence on the relationship between attention and working memory. Chelazzi and his colleagues (Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993) examined the activity of macaque inferior temporal (IT) neurons during a simple visual search task. In each trial, monkeys were presented with a single target image, which was followed after a delay by a search array. The search array contained two or more objects, one of which matched the target. The monkeys’ task was to saccade to the target. The target item was selected to be either an effective or an ineffective stimulus for the neuron being tested, and the entire search array fell within the cell’s receptive field. The findings were consistent with previous research (e.g., Miller & Desimone, 1994): Some neurons continued to show some stimulus selectivity during the delay period. That is, even after the sample was removed, they responded more if the sample had been effective for that cell than if it had not.

The initial neural response to the search array itself did not show stimulus selectivity. However, after approximately 175 ms, neurons responded well if the target was effective for that cell, and poorly if it was not. By generalizing this result across individual neurons, we can characterize the behavior of the population of object-selective neurons. Initially, the network responds nonselectively to the entire array, but over time, the network becomes tuned to respond as though only the target were present. This change in response can be characterized as a narrowing of attention to include only the target object. Desimone and Duncan (1995) suggested that this process reflects the resolution of a competition between object representations, biased by the active maintenance of the target during the delay.

EXPERIMENT 1

The purpose of the studies reported here was to test, in humans, a key prediction that follows from the biased-competition model. Maintaining an object in working memory should bias the competition among the objects in a scene, even if there is no explicit search goal.

Participants performed two tasks in each trial. A trial began with the presentation of a picture of a face (the sample). While the sample was held in memory, a pair of faces was presented simultaneously. One of these faces matched the one held in memory, and the other was novel. Participants performed a discrimination task on a small bracket appearing at the location of one of the two faces. The logic of many previous studies of selective attention (e.g., Kim & Cave, 1995; Posner, 1980) suggests that increased attention to one of the faces would facilitate the processing of other information at the same location. The discrimination judgment was unrelated to the memory task, and thus provided an unbiased measure of which of the two competing items received more attention. Finally, at the end of the trial, a single face was presented, and subjects reported whether or not it matched the one

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held in memory. It was predicted that attention would shift to the location of the face matching the one held in working memory, so that processing of probes at the location of the matching face would be faster than processing of probes at the location of the nonmatching face.

Participants

Ten undergraduates at the Massachusetts Institute of Technology participated for cash compensation.

Materials

The stimuli were 160 gray-scale, digitized photographs of Harvard undergraduates. Half of the photos were of males and half were of females. The images were approximately 5 cm wide by 9 cm tall. Each image was used in only one trial of the experiment. This and all following studies were conducted on a Macintosh computer using Matlab 5.2 (the MathWorks, Inc.) and the Psychophysics Toolbox package (Brainard, 1997).

Procedure

The trial sequence is illustrated in Figure 1. Participants initiated each trial by pressing the space bar. A fixation point appeared for 1 s, followed by a single face (the sample), presented at the center of the screen for 1 s. A fixation point was then presented for 1,506 ms, and next two faces were presented side by side, flanking a central fixation point, for 187 ms. The faces were separated by approximately 10 cm from center to center. After a 40-ms delay, a small bracket was presented for 106 ms at the center of the location previously occupied by one of the two faces. The bracket was oriented either up (⌊) or down (⌋), and was approximately 0.5 cm in size. Finally, after a delay of 1,506 ms, a single face (the memory-test item) appeared at the center of the screen, remaining until the participant responded.

Participants were instructed to keep the sample in mind until the end of the trial. They were also told to respond immediately to the orientation of the bracket, pressing one key for "up" and another for "down." Finally, at the end of the trial, participants pressed one key if the test face matched the sample and another if it did not. Participants were told that response times for the orientation judgment would be measured, but accuracy on both tasks was emphasized.

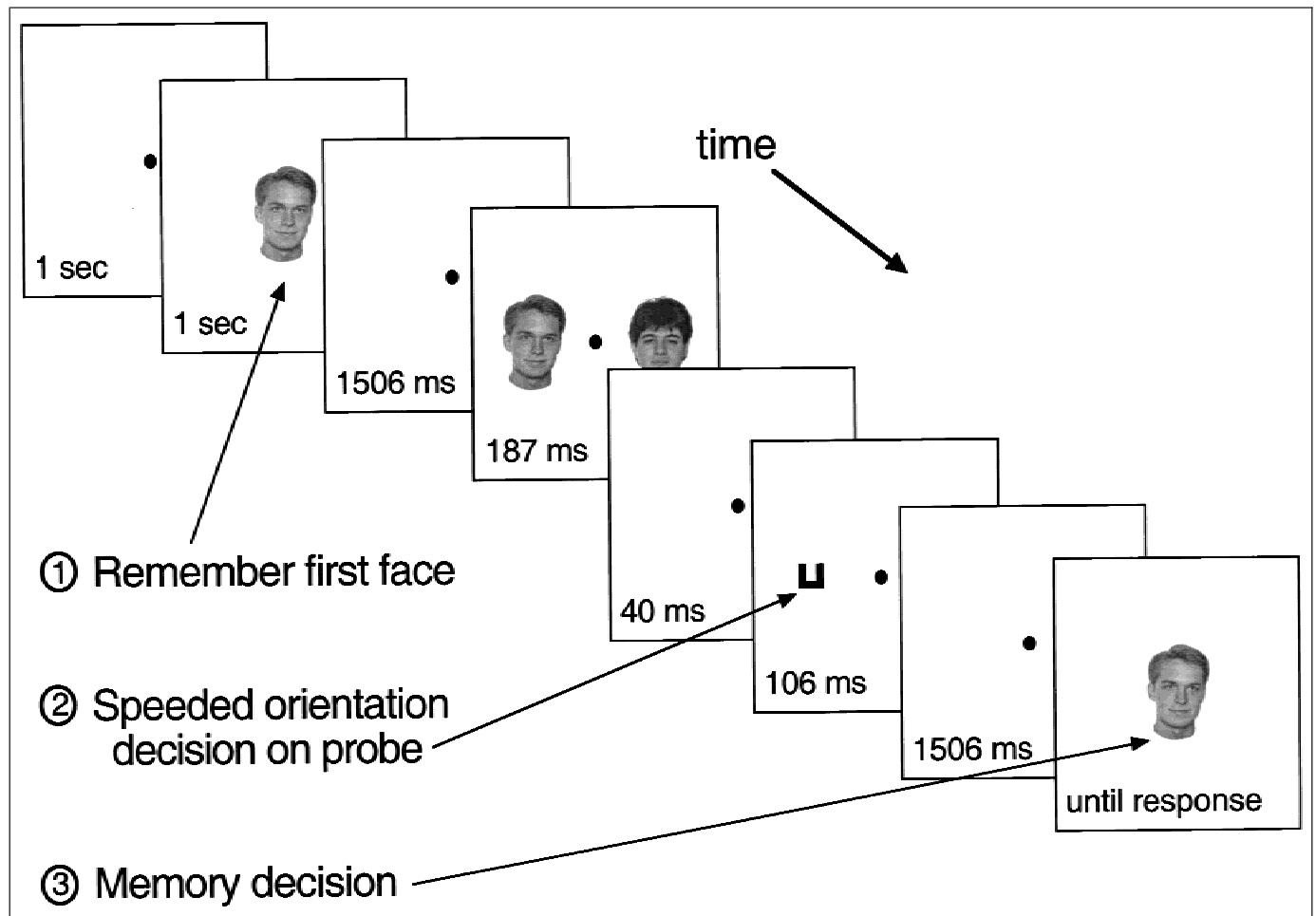


Fig. 1. Schematic illustration of the experimental paradigm used in Experiment 1.

Design

One of the two faces presented during the delay interval matched the sample (the memory-match item), and the other was novel (the nonmatch item). The memory-match face appeared equally often on the left and on the right. The bracket appeared at the location of the memory-match face in exactly half of the trials. The bracket was oriented up in half of the trials and down in the other half. Finally, the test face matched the sample in half of the trials and was a novel face in the other half. These four factors were block-randomized so that all possible combinations of them occurred every 16 trials. Thus, nothing about the design of the experiment allowed subjects to predict which item would be probed or which item would appear in the memory test. Sixteen practice trials were followed by 64 test trials.

Results

In all of the experiments reported here, only data from trials in which both responses were correct were analyzed. In this experiment, participants responded correctly to both tasks on 94% of trials. Response times were reliably faster to probes at the location of memory-match faces ($M = 579$ ms) than to probes at the location of nonmatch faces ($M = 595$ ms), $F(1, 9) = 5.8$, $MSE = 218$, $p < .05$. There was no sign of a speed-accuracy trade-off. In fact, participants were more accurate on trials on which the memory-match was probed (95% correct) than on nonmatch trials (93% correct), $F(1, 9) = 3.9$, $MSE = 0.0005$, $p = .08$.

Discussion

Maintaining a face in working memory shifts attention toward matching faces, compared with novel ones. Might participants have strategically attended to the matching face in the memory interval in order to help them perform the memory task? Some features of this experiment reduce the likelihood of this possibility. First, subjects were required to make a speeded discrimination judgment on the probes, reducing their capacity to deliberately attend to other aspects of the stimuli within the brief presentation time. Second, the demands on working memory were minimal, reducing the incentive to strategically attend to the matching items. The memory interval was quite brief (less than 3.5 s), and the memory test involved rejecting foils that were quite different from the samples (e.g., often of a different race or gender). As a result, across the four experiments reported here, which tested working memory under similar conditions, mean accuracy on the working memory part of the task was generally high.

These results, then, support the conclusion that visual working memory and selective attention share a key functional component: The contents of working memory guide attention even when there is no explicit search task. In the General Discussion, I consider more fully the question of whether this effect occurs automatically.

EXPERIMENT 2

The second experiment tested the generality of the results of Experiment 1. So that it could be determined whether working memory influences attention independently of object type, two stimulus classes, faces and line drawings of objects, were compared. Additionally, as a check to ensure that the previous results were not an artifact

of the bracket-discrimination task, a second task (adapted from Christie & Klein, 1995) was tested. In this task, one of the two items appearing in the memory delay jumped slightly, either up or down, and participants reported the direction of motion. It was predicted that increased attention to one of the two items appearing in the memory interval would speed processing of the motion of that object.

Participants

Twenty undergraduates at the Massachusetts Institute of Technology participated for cash compensation.

Materials

The faces used in Experiment 1 were used again in this experiment, in addition to 160 gray-scale drawings of common objects.

Procedure and Design

Half of the participants were tested with the motion task, and the other half with the discrimination task from Experiment 1. Faces and objects were tested within subjects, in two separate blocks. The order of these blocks and the assignment to task condition were counterbalanced.

For participants given the motion-judgment task, two items appeared in the memory interval for 187 ms, after which one of the items jumped slightly either up or down to a new position approximately 0.5 cm away. After 53 ms, both items disappeared. Participants reported the direction of the object's motion by pressing one of two keys.

For participants given the discrimination task, the procedure was modified from that in Experiment 1 to match the motion task more closely. The probed items were presented for 187 ms, followed immediately by the bracket, which remained for 53 ms. As before, participants reported the orientation of the bracket. In all other respects (e.g., presentation of the sample and memory test), this experiment was identical to the first.

Results

The response times from this experiment were analyzed in an analysis of variance (ANOVA) with three factors (see Fig. 2): task (motion or discrimination, between subjects), item type (faces or objects, within subjects), and probed item (match or mismatch, within subjects). The main effect of probed item was significant, $F(1, 18) = 47.14$, $MSE = 346$, $p < .001$. Responses to the memory-match probes were faster ($M = 657$ ms) than responses to the nonmatch probes ($M = 685$ ms). The main effect of stimulus type approached significance, $F(1, 18) = 3.9$, $MSE = 5,218$, $p = .063$; response times were faster to probes on faces ($M = 655$ ms) than to probes on objects ($M = 687$ ms). No other main effects or interactions reached significance, all $p > .10$. An analogous ANOVA on accuracy (overall $M = 92\%$ correct) showed only a significant effect of task, $F(1, 18) = 6.2$, $MSE = 0.025$, $p < .05$. The motion task ($M = 88\%$ correct) was more difficult than the discrimination task ($M = 96\%$ correct).



Fig. 2. Response times to attention probes in Experiment 2, for the motion task (left) and for the discrimination task (right), as a function of whether the matching or nonmatching object was probed. Error bars represent the standard error after removing between-subjects variance (cf. Loftus & Masson, 1994).

Discussion

Attention shifts to an item matching the contents of working memory, regardless of whether that item is a face or an object. This effect was observed with two different measures of the allocation of attention. These results demonstrate that the results of Experiment 1 generalize to other stimuli and tasks.

EXPERIMENT 3

Are the results of the first two experiments a result of actively maintaining the sample in working memory? Perhaps mere exposure to the sample, without a memory requirement, would produce the same effect. For example, seeing the sample may facilitate the processing of matching objects appearing in the memory interval, independently of working memory. More specifically, priming an object's representation might shift attention to that object, compared with a novel one.

This study compared the working memory task with a task that had matched perceptual input but lacked a memory requirement. Two groups of participants were tested. One group performed the working memory and motion-judgment tasks, as in the preceding experiment. The second group made an immediate binary size judgment on the

sample object and then performed the motion-judgment task, also as in the previous experiment. For this group, however, the trial ended at that point. Thus, the size-judgment task required participants to attend to the sample item but did not make any explicit demands on working memory. If the effect observed in the previous two studies is due specifically to working memory maintenance, it should not generalize to the size-judgment task.

Participants

Sixteen undergraduates at the Massachusetts Institute of Technology participated for cash compensation.

Materials

The stimuli were drawn from a set of 200 line drawings of common objects. Each picture was used only once in the experiment.

Procedure and Design

Two groups of 8 participants each were tested. Participants in the size-judgment group were told to make an immediate size discrimi-

nation on the sample object, indicating with a key press whether the depicted object was larger or smaller than a basketball. The items used in the study were selected to include objects that were obviously larger or smaller than a basketball. Participants in the memory group were instructed to keep the sample item in memory through the duration of each trial.

The size-judgment and working memory conditions were matched as closely as possible. Each trial began with a central fixation point appearing for 1,506 ms, followed by the sample object, which appeared for 1,506 ms. After a blank interval of 1,506 ms, two objects were presented for 187 ms, after which one moved slightly up or down. After 53 ms, both objects disappeared. Subjects in both groups reported the direction of motion. For the participants in the memory group, a final memory-test object was presented. Half of the time this item matched the sample, and half of the time it was novel. Eighty trials were conducted, with the first 16 discarded.

Results

Three participants from the size-judgment group and 1 from the memory-judgment group were replaced because of overall performance below 70% correct. Exclusion of these data did not change the pattern of results.

The response times on the attention-probe task were analyzed in an ANOVA with task (size or memory, between subjects) and probed object (match or nonmatch, within subjects) as factors (see Fig. 3). Only the interaction reached significance, $F(1, 14) = 11.0$, $MSE = 2,298$, $p < .01$. Participants performing the memory task responded more quickly to probes on the matching object ($M = 587$ ms) than to probes on the nonmatching object ($M = 638$ ms). Participants making the size judgment showed the opposite effect, with faster response times to probes on the nonmatch object ($M = 727$ ms) compared with

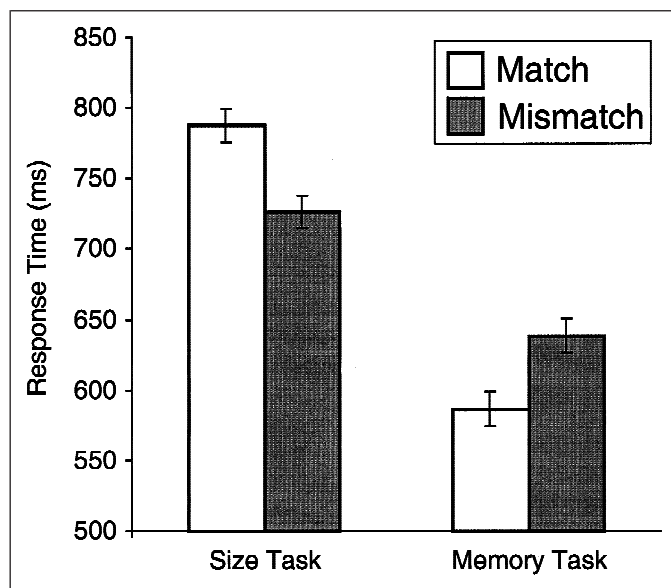


Fig. 3. Response times to attention probes in Experiment 3, as a function of whether the matching or nonmatching object was probed. Data for the size task and memory task are shown separately. Error bars represent the standard error after removing between-subjects variance.

the match object ($M = 788$ ms). Direct comparisons within each task group revealed a marginally significant simple effect of probed object for the memory group, $F(1, 7) = 4.4$, $MSE = 2,440$, $p = .075$, and a significant simple effect of probed object for the size group, $F(1, 7) = 6.9$, $MSE = 2,155$, $p < .05$. Finally, the main effect of task approached significance, $F(1, 14) = 4.2$, $MSE = 39,617$, $p = .06$. Response times were faster overall in the working memory group ($M = 612$ ms) than in the size-judgment group ($M = 757$ ms).

An analogous ANOVA on accuracy (correct response to both required judgments) showed a marginal main effect of task, $F(1, 14) = 4.1$, $MSE = 0.011$, $p = .06$. Performance was better on the memory task ($M = 87\%$) than on the size task ($M = 80\%$). Additionally, there was a marginal interaction between task and probed object, $F(1, 14) = 4.0$, $MSE = 0.004$, $p = .065$. There was no speed-accuracy trade-off; the accuracy results mirrored the response time data.

Discussion

The effects observed in the first two experiments do not generalize to a closely matched task that does not require working memory. This result rules out the possibility that mere exposure to the sample shape is sufficient to direct attention toward matching objects. Additionally, the size-judgment task was more difficult than the working memory task. This rules out the possibility that the working memory effect is due to the general difficulty of active maintenance.

Why did attention favor the novel item compared with the matching item for participants making the size judgment? One possibility is suggested from the findings of Miller and Desimone (1994), who recorded from IT cells in monkeys performing two variants of a delayed-match-to-sample task. In one variant, a sample was presented, followed by a sequence of unique foil items. Each trial ended with another presentation of the sample, at which point the monkey released a lever to obtain a reward. Miller and Desimone found a subset of neurons that responded more weakly to the second presentation of the sample than to the first, showing an adaptation of response to stimulus repetition. In the second variant of the task, task-irrelevant repetitions were included among the foil items. The monkey was rewarded only for responding to repetitions of the sample; other repetitions were to be ignored. In this case, a separate subset of neurons showed an enhanced response to task-relevant repetitions (i.e., of the sample). Miller and Desimone suggested that these distinct populations of neurons reflect the operation of two distinct forms of memory. One is a passive, automatic registration of repetition, whereas the other represents an active maintenance of goal-relevant information.

Turning to the present study, we might speculate that the working memory task, but not the size-judgment task, engaged this active memory system. Thus, the population of neurons responsible for maintaining the representation of the sample provided a competitive advantage for the same object when it appeared again in the memory interval. In contrast, the size-judgment task required no active maintenance of the sample. In this case, only the passive memory system registered the repeated occurrence of the sample, and it did so by responding more weakly. This weakened response would in turn confer a competitive disadvantage to the object in question, a possibility consistent with the results observed here.

From the preceding account, the following general prediction can be made. When a stimulus has been seen recently, but not actively maintained in memory, it will suffer from a competitive disadvantage

relative to novel stimuli. In contrast, active maintenance of a stimulus will result in increased attention to that item, relative to novel stimuli (cf. Desimone, 1996).

EXPERIMENT 4

The final experiment addressed another possible explanation for the results described so far. In the preceding experiments, participants compared the final test item with the item in working memory. Perhaps, having prepared to make this judgment, they could not inhibit performing it on the two probed items presented in the memory interval. Recent research (e.g., Allport, Styles, & Hsieh, 1994) has demonstrated the difficulty of switching from one task to another, even when the switch can be anticipated. In itself, a failure of task switching would not produce the advantage for matching items found here. However, it is plausible that matching tasks are performed as a search for evidence in favor of a match. If this search fails, a “non-match” judgment is made. If participants initiate a search for matching information during the memory interval, we would expect the same results obtained in the preceding studies, for reasons having nothing to do with working memory.

In Experiment 4, working memory was tested with a task that did not require a matching judgment. Participants held a novel geometric shape in memory on each trial, and made one of three judgments about it at the end of the trial: Is it symmetric about the vertical axis? Does it have any curved edges? or Does it have only right angles? In contrast to preparing for the matching task, preparing for any of these tasks would not encourage shifting attention disproportionately to either a matching or a mismatching object. Furthermore, participants did not know from trial to trial which judgment they would be required to make. They were thus encouraged to maintain the shape itself in memory, rather than to prepare the correct response to all three possible judgments.

Participants

Ten undergraduates at the Massachusetts Institute of Technology participated for cash compensation.

Materials

The stimuli were 26 simple, novel, filled contours, drawn in black on a white background. They were approximately 3 cm square in size. Half were symmetric about the vertical axis, 18 had at least one curve, and 5 were composed only of right angles.

Procedure and Design

The timing of the stimulus sequence was the same as in the working memory condition of Experiment 3. Attention was probed with the motion task described earlier. At the end of each trial, the required judgment was indicated with a phrase: “Symmetric?” “Any curves?” or “Only right angles?” Participants answered the question by pressing either the “Y” or the “N” key, and were given up to 8 s to make their response. Five blocks of 24 trials were tested; the first block was practice.

Results

Overall performance was 94% correct. Response times were faster to probes on match items ($M = 593$ ms) than to probes on nonmatch items ($M = 609$ ms), $F(1, 9) = 5.1$, $MSE = 247$, $p = .05$. There was no significant difference between these conditions in accuracy, $F < 1$.

Discussion

The results of this experiment show that even when tested without a matching task, attention shifts to items matching the contents of working memory. Therefore, this effect cannot be explained as an artifact of task switching.

GENERAL DISCUSSION

The present studies tested a prediction derived from the biased-competition framework (Desimone & Duncan, 1995). Active maintenance of an object in memory shifts selective attention toward that object, even when there is little reason or opportunity for participants to select it strategically. This result generalized across three types of stimuli, two measures of selective attention, and two working memory tasks. It did not generalize, however, to a comparable task that did not require working memory, suggesting that the effect is not merely a result of priming.

These results confirm a specific prediction about the relationship between two fundamental cognitive functions. Although attention is typically discussed as a gate operating to allow only selected information into working memory, these findings indicate that working memory shapes the action of the attentional filter as well. Other recent results further develop this relationship. For example, Awh, Jonides, and Reuter-Lorenz (1998) showed that working memory maintenance of a spatial location generates a shift of attention to that location. Participants in their experiments were faster to respond to discrimination probes occurring at locations being maintained in working memory than to probes at other locations. In terms of Ungerleider and Mishkin’s (1982) distinction between *what* and *where* pathways in the visual system, the results of Awh et al. demonstrate interactions within the *where* pathway. In contrast, the present results demonstrate an interaction between the two pathways: A match on the *what* dimension shifted attention along the *where* dimension.

In a recent report, Pashler and Shiu (1999) showed that formation of a mental image triggers a search for the imaged item even when it interferes with the subject’s primary task. At the beginning of each trial, subjects were prompted with a verbal cue to form a mental image of an object. Subsequently, a rapid stream of images was presented at the center of the screen. The sequence contained a series of pictures, one of which was the imaged item, as well as a digit, which subjects were to report at the end of the trial. Participants’ ability to identify the digit was 3 to 8% worse when it appeared soon (~165 ms) after the picture matching the subjects’ mental image, compared with when it appeared relatively later (~385 ms). This result suggests that an attentional blink (e.g., Shapiro, Arnell, & Raymond, 1997) was caused by involuntary attention to the stimulus matching the subjects’ mental image. Perhaps the mental image subjects formed persisted in working memory through the trial, in which case the attentional capture observed might be a variety of that seen here. Alternatively, Pashler and Shiu’s result could reflect an automatic priming effect, which would

differentiate it from the present results, which cannot be explained in terms of simple priming.

Several studies (e.g., Johnston, Hawley, Plewe, Elliott, & DeWitt, 1990; Johnston, Hawley, & Farnham, 1993) have suggested that, other things being equal, the less-familiar item in an array will tend to capture attention (novel pop-out; see Christie & Klein, 1995, 1996, for a critical discussion). In this context, the present work, and especially Experiment 3, demonstrates the importance of current goals in modulating the automatic effects of stimulus novelty on attention. Familiar objects will either “win” or “lose” the competition for attention depending on whether they are being actively maintained or passively registered. Recent work on attention capture by the appearance of new objects suggests similar conclusions. New objects tend to capture attention as a default, but this capture can be modulated or overridden depending on the current goals (Folk & Remington, 1999; Folk, Remington, & Johnston, 1992, 1993; Yantis, 1993).

Does maintenance of an item in working memory automatically shift attention to matching items? The experiments presented here were not intended to test for a strongly automatic process, that is, one that operates rapidly and unconsciously, without guidance and without interference from other ongoing processing (Schneider & Shiffrin, 1977). In a pilot study ($N = 11$), I have tested the automaticity of this effect more directly, by requiring subjects to search for one item in an array, while simultaneously maintaining another item in working memory. The critical test compared search rates when the array contained only the search target and search rates when the array contained both the search target and the item held in working memory. The addition of the working memory item to the search array had a negligible effect on search rates, suggesting that subjects can maintain a “barrier” between two items held in working memory. This in turn is evidence that there is not a strongly automatic orienting to any item held in working memory. As suggested for the case of novel pop-out, it may be that a tendency to attend to items in working memory will operate only in the absence of other overriding goals.

Other predictions of the biased-competition framework could be tested with an approach similar to the one developed here. First, according to Duncan and Humphreys’s (1989) analysis of search tasks, increasing similarity between the stimulus and the search template increases attention to that stimulus. It follows from this account that items should capture attention in proportion to their similarity to the contents of working memory. Second, a central claim of this framework is that objects compete for attention as integrated wholes. Therefore, attention to one dimension of an object (e.g., its color) entails attention to its other dimensions as well. If so, working memory for a single feature, such as the color red, should bias attention to any object with the same feature. Finally, using multimodal presentations, we can test whether nonvisual working memory, such as for a spoken word, influences attention to visual stimuli, such as written words.

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