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Early, Involuntary Top-Down Guidance of Attention From Working Memory

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Four experiments explored the interrelations between working memory, attention, and eye movements. Observers had to identify a tilted line amongst vertical distractors. Each line was surrounded by a colored shape that could be precued by a matching item held in memory. Relative to a neutral baseline, in which no shapes matched the memory item, search was more efficient when the memory cue matched the shape containing the target, and it was less efficient when the cued stimulus contained a distractor. Cuing affected the shortest reaction times and the first saccade in search. The effect occurred even when the memory cue was always invalid but not when the cue did not have to be held in memory. There was also no evidence for priming effects between consecutive trials. The results suggest that there can be early, involuntary top-down directing of attention to a stimulus matching the contents of working memory.

The visual field usually contains more information than the visual system can process at any given time. Attentional mechanisms are thus crucial to selection of relevant objects for further processing and, perhaps also, to inhibition of those objects that are irrelevant to current goals. How can attention be guided so as to select the appropriate visual information? Attentional guidance can occur in a bottom-up way, as when the sudden appearance of a new object or a salient stimulus change directs our attention to its location (Theeuwes & Burger, 1998; Yantis & Hillstrom, 1994). In addition, the objects with which attention is engaged can guide its deployment over the visual field. For instance, spatial attentional shifts are faster within a selected object than they are across objects (Egly, Driver, & Rafal, 1994; Lamy & Tsal, 2000). Objects can also guide attention even when object-based cuing is not valid (Soto & Blanco, 2004) and when an object's location cannot be explicitly discriminated (Humphreys & Riddoch, 2003). Bottom-up guidance of attention can happen in a largely involuntary manner, without control on the part of the observer, such that attention is driven by the stimulus even when it is not the target of selection. In contrast with these bottom-up forms of guidance, attention can also be guided in a top-down fashion through the activation in memory of object representations or templates associated with the target stimulus (Duncan & Humphreys, 1989). Thus, when an observer looks for a book on a shelf, search may be guided by the activation of the relevant book's features stored in memory.

The present study focuses on the process of top-down guidance of attention. Several lines of evidence suggest a role for working memory (WM) in top-down attentional guidance. For example, studies using single-cell recordings suggest that feedback from object representations in WM modulate neural responses when a stimulus has to be selected for a response (Chelazzi, Duncan, Miller, & Desimone, 1998; Chelazzi, Miller, Duncan, & Desimone, 1993). According to the biased-competition model of visual selection (Desimone & Duncan, 1995), the neural representations of the different objects in the array are mutually inhibitory, competing for access to higher level processing, with object selection being controlled by the preactivation of the neural channels responsive to a particular relevant object. It follows from this account that top-down control signals from object representations in WM can bias selection in favor of the object whose features were preactivated, thus resolving the competition for selection between the objects in the visual scene. Other single-cell recording studies suggest that the source of the top-down bias from WM is likely to be the prefrontal cortex (Miller, Erikson, & Desimone, 1996; see also Cohen et al., 1997, and Courtney, Ungerleider, Keil, & Haxby, 1997, for evidence from human brain-imaging studies).

Converging evidence about a causal role for WM in the control of attentional processes was provided by de Fockert, Rees, Frith, and Lavie (2001). In their study, observers had to classify written

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names of famous people displayed along with congruent or incongruent faces under conditions of low or high memory load. The results showed larger interference effects from distractor faces under conditions of high memory load, suggesting that selection of the target faces was less successful when WM was stressed. Furthermore, as measured by functional MRI, areas of prefrontal cortex known to be involved in WM, and also areas of more posterior cortex involved in face processing, were more activated in conditions of load, consistent with these areas being sensitive to load and to distractor interference (from the irrelevant faces). This suggests that the availability of WM is crucial for top-down control of attention to relevant targets.

Consistent with the biased-competition model of attention, the results of other behavioral studies suggest that the contents of WM can bias the deployment of attention (Awh, Jonides, & Reuter-Lorenz, 1998; Downing, 2000; Pashler & Shiu, 1999). Awh et al. (1998) asked observers to memorize the location of a letter displayed at the beginning of each trial. Subsequently, observers performed a shape-discrimination task, which was followed by another item that was matched to the memory representation for the first item. Performance on the shape-discrimination task was faster if the stimuli fell at memorized locations than if they fell at nonmemorized locations, suggesting that attention can be guided by spatial information held in WM. In Pashler and Shiu's (1999) study, observers were instructed to form a mental image of an object and, immediately after, to detect a target digit embedded in a rapid serial visual presentation (RSVP) stream of stimuli. An object matching the contents of the image an observer formed could be present in the stream either before or after the target digit. Even when observers were encouraged to discard the image once the RSVP stream was displayed, the presentation of the image caused an attentional blink: Target-digit identification was impaired when the image preceded the target digit relative to when the critical object was presented after the digit. Here, a mental image held in WM appeared to produce involuntary detection of the object matching the mental image formed by the observer.

The above studies suggest that attention can be guided by the contents of WM. Also, there is some evidence for this memory guidance occurring even when the maintenance of a WM representation is detrimental to selection of a relevant target (Pashler & Shiu, 1999), suggesting that it may be triggered in an involuntary manner. However, whether any guidance from WM can affect the deployment of attention in spatial search when multiple objects compete for selection, and whether it influences the earliest deployment of attention under these circumstances, is not clear. Downing (2000) asked observers to hold an object in WM prior to the appearance of a two-object display. One of the two objects in the second display matched the object held in WM. The observers had to perform a discrimination task on a shape that fell on one of the two objects in the second display. Reaction times (RTs) were shorter for a target that appeared on the object in the second display that matched the stimulus held in WM compared with when the discrimination target fell on the other object (not held in WM). This result did not occur when observers were merely exposed to the first stimulus but did not have to maintain it for later matching to memory. Downing suggested that this pattern of results confirms that WM exerts an influence over attentional selection. Here again, relatively simple (two-item) displays were used. Also, there was no attempt to separate out early from later occurring attentional effects.

In the present study, we used a procedure similar to that of Downing (2000), but we explored the effects of the item held in WM on search through multiple-item displays, and we also separated out early from later occurring effects by examining the patterns of eye movements during the search tasks. Experiment 1 tested performance in search tasks using multiple-item displays, in which we varied the display size to assess whether the stimulus in WM influenced search efficiency (reflected in the slope of the RT–display-size function). In Experiment 2, we again used multiple-item displays (without varying the display size), but in this case we examined whether the top-down bias influenced early stages of search, reflected in the first eye movement that took place. In Experiment 3, we tested whether the search bias was indeed due to maintenance of a stimulus in WM or was due simply to the first item being presented (even without there being any requirements to hold it in memory). To do this, we presented the first item but did not follow the search display with a memory probe—so there was no longer any incentive to maintain the first stimulus in WM (see also Downing, 2000). If there was automatic priming simply due to the presentation of the first stimulus, then the properties of this stimulus should again modulate performance here. In Experiment 4, we evaluated how much control observers could exert over the effects on search once an item was held in WM. In this experiment, the stimulus held in WM was invalid on all trials in which it appeared in the subsequent search display. Is performance still affected by the memorized stimulus under this circumstance? If this were the case, it would suggest that the guidance of attention from WM can be triggered in an involuntary manner, because under these conditions the memory guidance can only hinder rather than help performance in the search task. In all four experiments, the effects of the first stimulus, when it reappeared in the search display, were compared with a neutral condition, in which the first item did not reappear in the search display. Here, we can ask whether there are both benefits and costs to search from the item held in WM (when, respectively, either the target or a distractor appears in the repeated stimulus on valid and invalid trials) and whether any costs and benefits vary in the same way. We also analyzed performance using all of the RTs recorded or just the RTs from the fast end of the distribution (the 5th and 10th percentiles) to evaluate whether memory effects were present even on trials with fast responses.

In addition to testing for effects of the item held in WM, we also examined whether performance was modulated by any priming that took place on a trial-by-trial basis. A number of authors have now found that visual search can be modulated by trial-by-trial contingencies—for instance, if a target remains constant across trials. For example, Maljkovic and Nakayama (1994) found that pop-out search was faster when the target had the same feature as on the previous trial, and Kristjansson, Wang, and Nakayama (2002) reported similar results in the case of conjunctive visual search (see also Hillstrom, 2000). The effects of intertrial contingencies on search can be influenced not only by whether a given feature property continues to be linked to the target but also by somewhat more abstract properties—such as whether a target continues to be defined along the same perceptual dimension (Müller, Heller, & Ziegler, 1995). When considering the effect of an item held in memory, it may even be the case that performance is sensitive to contingencies based on whether the memory item validly predicted the target on the previous trial (though the present Experiment 4 provides evidence against this, in that the memory item was never valid in that experiment). Possible effects of intertrial contingencies were evaluated using the data from Experiment 2 (in which performance was examined at just a single display size). It may be that search was guided in a bottom-up manner by the stimulus properties that defined the shape surrounding a target on a prior trial (feature-based priming) or by reinforcement that the memory item defined the target's location (reinforcement of the memory stimulus). If so, then search should have been faster when the properties of the shape defining the target were constant across trials (feature-based priming) or when the memory item was valid across consecutive trials compared with when it was invalid and then valid.

Experiment 1: Varying the Size of the Search Display

Method

Participants. Seven naive volunteers (3 men and 4 women) took part. They were drawn from students and staff of the School of Psychology in the University of Santiago de Compostela, Santiago de Compostela, Spain. They ranged in age from 18 to 37 years, and all had normal or corrected-to-normal vision.

Apparatus. A Pentium III computer with a NVIDIA PRO TNT 32-MB graphics card controlled the stimulus displays and responses. The task was programmed using E-Prime (Version 1.0; Psychology Software Tools [PST], 2002). The stimuli were presented on an IBM P275 color monitor. The monitor's resolution was 1,024 × 768 pixels, and its frame rate was fixed at 85 Hz, permitting display times to be varied in steps of approximately 12 ms. The presentation of the stimuli was synchronized with the refresh rate of the monitor. All of the displays had been previously drawn offscreen and then copied for visualization. Copy times were virtually zero ($M = 0.02$ ms). Responses were entered on a PST response box (see Schneider, 1995, for technical specifications). An adjustable chin rest helped to maintain head position.

Task. The display was viewed binocularly from a distance of approximately 60 cm. Each trial began with the presentation of a fixation cross for 505 ms. Then, a prime object (the memory item) was flashed at fixation for three brief presentations of 35 ms each, with blank intervals of 12 ms between them. One hundred and eighty-eight ms after the offset of the prime, a search array appeared with two, four, or eight objects, each containing a line inside of it (see Figure 1). All of the lines were vertical except for one—the target—that was tilted 4.8° to either the left or the right. The prime stimulus could be present in or absent from the search array. When present, it could contain the target or a distractor. The search stimuli were positioned around an imaginary clock face of 6° radius. Starting at 12 o'clock, there were eight possible locations equally separated around the imaginary clock face. The prime could be a circle, a square, or a hexagon. The search array was composed of these three possible shapes, each containing an internal line, and it was displayed until response. The color of the objects could be red, green, or blue, and their size was 1.80° × 1.80° of visual angle for the circle, 1.50° × 1.50° for the square, and 2.38° × 0.95° for the hexagon. The length of the lines was 0.57°, and their width was 0.12°. Lines were presented in white. Observers were instructed to keep the prime in memory (both its color and shape) and to respond to the orientation of the target line by pressing the left key of the response box for left-oriented lines and the right key for right-oriented lines. We included memory-probe trials to make sure that observers kept the prime stimulus in memory. On these probe trials, an object was displayed after

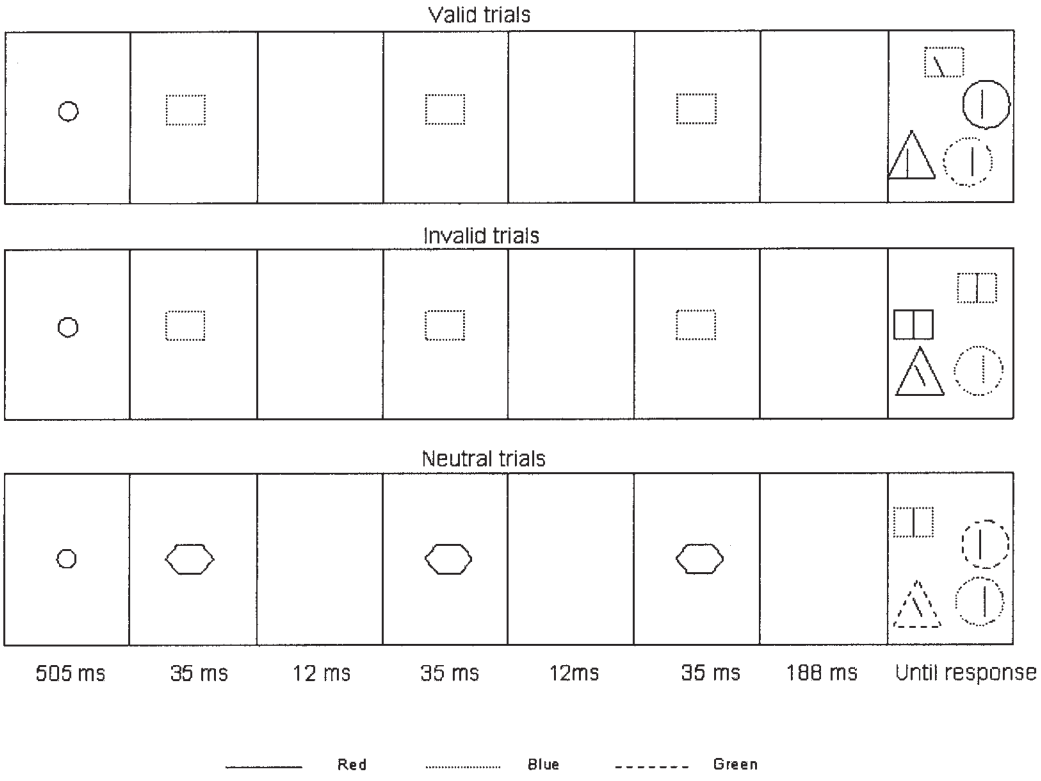

Figure 1. Display sequences in Experiment 1 for each condition of validity of the prime.

observers responded to the target line, and they had to decide whether this object was identical to the prime or not by pressing one of two keys (for *same* or *different*). Observers were asked to perform well on both tasks, and they were encouraged to respond as accurately as possible. Speeded responses were also emphasized in the search task.

Procedure. In the first phase of the experiment, observers performed 25 practice trials. This was followed by three blocks of 54 trials. There were three types of trials, each defined by the validity of the prime (one third of the total number of trials for each type). On valid trials, the target appeared within the primed stimulus. On invalid trials, the primed stimulus contained a distractor line. On neutral trials, the prime was not present in the search array, and the features of the stimuli presented in the array did not match those of the prime. On valid and invalid trials, the prime stimulus could share the shape or the color of any of the other stimuli in the search array, and the nonprimed shapes were drawn at random from the different Shape × Color combinations. This meant that the primed stimulus was more likely to share its shape or color with a nonprimed stimulus in the search array as the display size increased. Note that this would act against priming facilitating search at the largest display sizes. Both the validity of the prime and the display size were varied randomly within each trial. Eighteen trials per each combination of validity and display size were included. Observers were informed about the probabilities assigned to the different types of trials. There were also 8 memory-probe trials per block.

Results

Errors were minimal ($M = 2\%$) and were not analyzed further. Performance on memory-probe trials was high ($M = 83\%$). The error data are shown in Table 1.

In all of the experiments in this study, we analyzed RTs for correct responses in the search–identification task, but to maximize the data included, we did not exclude RTs of trials with errors in the memory task. In the following analyses of variance (ANOVAs), all p values for main or interaction effects were computed using the conservative Greenhouse–Geisser method with corrected degrees of freedom.

First, we carried out a 3 (prime validity: valid, invalid, neutral) × 3 (display size: two, four, eight) repeated measures ANOVA on median RTs. The effect of prime validity was significant, $F(2, 12) = 39.22$, $p < .0001$. Pairwise comparisons showed slower performance in the invalid than in the neutral condition and faster performance in the valid than in the neutral condition ($p < .002$). The effect of display size was significant, $F(2, 12) = 164.37$, $p < .0001$. The differences between each pair of display sizes were significant ($ps < .0001$), showing that RTs increased with display size. The effects of validity and display size interacted significantly, $F(4, 24) = 9.82$, $p < .006$. The slopes of the search functions were larger in the invalid condition (176.00 ms/item) than in the neutral condition (133.00 ms/item), and slopes were smaller in the valid condition (71.00 ms/item). Figure 2 depicts this pattern of results.

Second, we examined RTs in terms of benefits (neutral-trial − valid-trial RT) and costs (invalid-trial − neutral-trial RT) across the different display sizes. A 2 (benefits, costs) × 3 (display size) ANOVA was carried out. The results showed that the benefits (242 ms) were larger than the costs (176 ms), $F(1, 6) = 42.91$, $p < .001$. Furthermore, the relative magnitude of costs and benefits interacted with display size, $F(2, 12) = 13.74$, $p < .008$. To find out the source of this interaction, we carried out two ANOVAS with display size as the factor for both the benefits and the costs. Display size did not have a reliable effect on the size of any costs, $F(2, 12) = 4.16$, $p = .082$, but it did affect the size of the benefits, $F(2, 12) = 8.87$, $p < .013$. Pairwise comparisons indicated that benefits increased from a display size of two to display sizes of four ($p < .01$) and eight ($p < .03$). The size of the benefits did not differ between display sizes of four and eight.

Lastly, we divided the distribution of RTs for the different conditions into two bins containing RTs up to, respectively, the 5th and the 10th percentiles, to test whether effects emerged on the fastest responses. We conducted two 3 (prime validity) × 3 (display size) ANOVAS, one for each bin. The results for the RTs in the 5th percentile showed a significant effect of prime validity, $F(2, 12) = 11.72$, $p < .007$. Comparisons performed between each pair of conditions within this factor showed reliable differences between the valid and the neutral condition ($p < .002$) and also between the invalid and the valid condition ($p < .009$). However, the differences between invalid and neutral conditions were not significant. The effect of display size was significant, $F(2, 12) = 33.48$, $p < .0001$. The differences between each pair of display sizes were significant ($ps < .01$), showing that RTs increased with display size. The interaction between validity and display size did not reach significance (although there was a clear trend; see Figure 3A for the data). The slopes of the search functions for the data from the 5th percentile were 35.19 ms/item in the invalid condition, 42.01 ms/item in the neutral condition, and 18.86 ms/item in the valid condition. Analyses of RTs for the 10th percentile also showed effects of prime validity, $F(2, 12) = 17.76$, $p < .002$, and the differences between each validity condition were reliable ($p < .04$ for the comparison between invalid and neutral, $p < .002$ for the comparison between invalid and valid, and $p < .001$ for the comparison between valid and invalid). There was also a significant effect of display size, $F(4, 24) = 63.79$, $p < .0001$, with highly reliable differences between each pair of levels within this factor ($ps < .001$). Finally, a trend for the interaction between prime validity and display size was observed, $F(4, 24) = 3.035$, $p = .081$. The slopes of the search functions for the data from the 10th percentile were 41.57 ms/item in the invalid condition, 48.10 ms/item in the neutral condition, and 19.00 ms/item in the valid condition. Figure 3B represents this pattern of results.

Table 1
Proportions of Error as a Function of Prime Validity and Display Size in Experiment 1

	Prime validity		
Display size	Invalid	Neutral	Valid
2	.02	0	.01
4	.01	.03	0
8	.02	.03	.02

Discussion

Experiment 1 examined the robustness of the top-down effects from WM when the competition between the objects in the search array was varied. Our results suggest that the maintenance of an

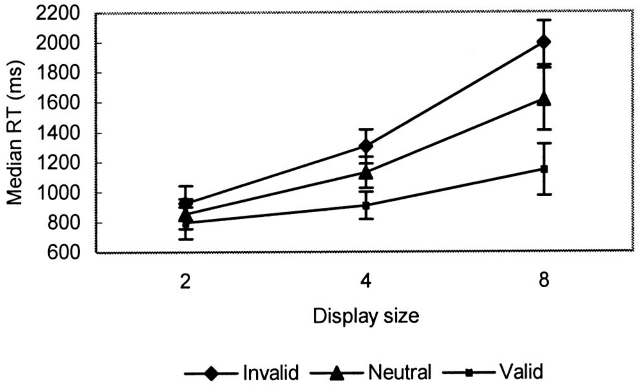

Figure 2. Data from Experiment 1. Means of median reaction times (RTs) of correct responses as a function of prime validity and display size. Error bars represent standard errors.

irrelevant object in WM can elicit a bias to deploy attention, confirming previous findings (Downing, 2000). There are both benefits to search—when the target is present in the primed stimulus (on valid trials)—and costs—when the primed stimulus is present but does not contain the target (on invalid trials). These top-down effects also occur "early" after the onset of the array, as suggested by the pattern of performance when the shortest RTs were analyzed. Both benefits and costs were present when just the shortest RTs in the experiment were considered. Our results also extend previous findings by examining the effects as the size of the search display increased. Here, we found differential results on costs and benefits. Benefits tended to increase as a function of display size. In contrast, costs were not reliably greater at the large relative to the small display size. Across all conditions, however, search was relatively slow and inefficient. This suggests that even with top-down priming, there remained costs of the number of the colored shapes in the search display. This could at least in part reflect the presence of nonprimed shapes that shared their color or shape with the prime. These nonprimed stimuli could have drawn attentional resources from the item held in WM (see Bundensen, 1990, for a formal account of this phenomenon), or they could have disrupted selection by grouping with the primed stimulus (cf. Duncan & Humphreys, 1989).

The early effects of the primed stimulus suggest that it impacts on performance from the start of the search display, biasing selection toward the stimulus that matches the colored form held in WM. As the display size increases, some distractors may be selected prior to the primed item, though given the effects on short RTs, the primed item may still be one of the first stimuli selected. When the prime is invalid, this item (and the template guiding search) can be discarded and search continued until the shape containing the target is selected. This will produce an overall RT cost that is relatively additive with the display size. The interaction between the benefits to search and the display size may then arise because a further factor (the orientation of the target itself) combines with the prime in WM to bias search toward the target. Previous evidence suggests that targets differing by 1.0° or 2.0° from the vertical can be discriminated, but a difference of about 15.0° is needed for efficient search (Foster & Ward, 1991). The orientation of the target here (4.8° from the vertical) was likely not sufficient to generate efficient search (as indicated by the search slopes), but it still could have combined with top-down preactivation from WM. There would thus have been a greater bias signal on valid than on invalid trials, providing additional guidance to search at the larger display sizes. This would explain why benefits were, on average, greater than costs.

Experiment 2: Effects on Eye Movements

Experiment 1 suggests that the active maintenance of object representations in WM can modulate attentional deployment even in a relatively difficult search task. Experiment 2 introduced a direct measure of attentional effects in search based on the pattern of eye movements. There is evidence suggesting that eye movements and attention are linked, with the eyes falling at the locations or objects on which attention is engaged (Hoffman & Subramaniam, 1995; McPeek, Maljkovich, & Nakayama, 1999). Here, we examined the position of the first fixation after the onset of the search array. If the top-down bias exerts an early influence on search, we would expect more fixations to land at the location of the stimulus matching the contents of WM than at the location of nonmatching stimuli. Furthermore, if the target line itself also serves to guide attention, we would expect more fixations to land

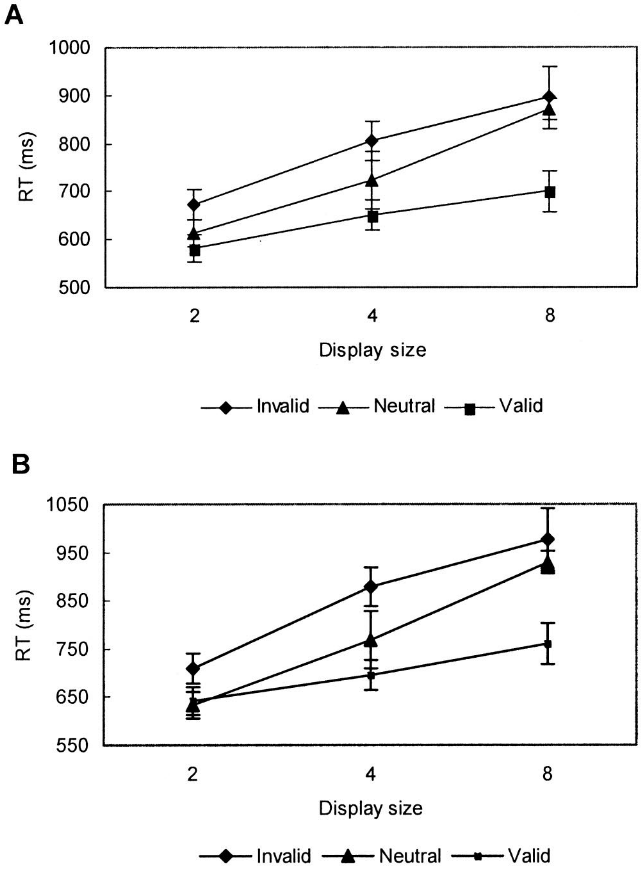

Figure 3. Data from Experiment 1. A: Reaction times (RTs) for the 5th percentile of the data as a function of prime validity and display size. B: RTs for the 10th percentile of the data as a function of prime validity and display size. Error bars represent standard errors.

at the location of primed objects when they contain the target than when they contain a distractor. To optimize data collection in this experiment, we used only one display size (four items). This meant, though, that we could also vary the relations between the stimulus held in WM and the match stimuli in the search display (when this stimulus was present). Because a display size of four alone was used, we presented shapes in the search display that always differed in terms of both their shape and their color. The primed stimulus then differed from the nonprimed stimuli in both of the attributes that defined the prime (shape and color). This meant that the prime could match one stimulus in the display in terms of either its shape, its color, or both its shape and color. By comparing performance across these different matching conditions, we could assess whether (a) feature properties alone were sufficient to guide selection or (b) conjunction information (shape and color) also played a role.

Method

Participants. Ten naive volunteers (4 men and 6 women) took part. They were drawn from students and staff members of the School of Psychology of the University of Birmingham, Edgbaston, Birmingham, United Kingdom. They ranged in age from 18 to 29 years, and all had normal or corrected-to-normal vision.

Apparatus. A Pentium IV computer with an ATI RAGE PRO 128-MB graphics card controlled the stimulus displays and responses. The task was programmed and run on this computer using E-Prime (Version 1.0; PST, 2002). The stimuli were displayed on a SAMSUNG SynchMaster 753s color monitor. Monitor resolution was 1,024 × 768 pixels. Frame rate was fixed at 85 Hz, permitting display times to be varied in steps of approximately 12 ms. Eye movements were monitored with a SensoMotoric Instruments eye tracker, which used reflections from the fovea and cornea to measure the location of the left eye. The sampling frequency for the location was 50 Hz, and the resolution was about 0.3°. An adjustable chin rest helped to maintain head position.

Task. A fixation display was presented for 505 ms at the beginning of each trial, followed by a prime object displayed at fixation for three brief presentations of 35 ms each, with a blank interval of 12 ms between the successive presentations. The prime could be a circle (1.80° × 1.80° of visual angle), a diamond (1.91° × 1.91°), a square (1.50° × 1.50°), a triangle (2.00° × 1.50°), or an hexagon (2.38° × 0.95°). The lines were presented in white. The color of the objects could be red, green, blue, yellow, or pink. One hundred and eighty-eight ms after prime offset, a search array composed of four lines embedded in four different objects was displayed. Three lines (0.57° × 0.12°) were vertical, and one (the target) was tilted 4.8° to either the left or the right. Each of the stimuli surrounding the line was unique in color and shape. The objects were arranged around an imaginary clock face of 6° radius. Each object could be at one of eight possible locations within the clock face (see Experiment 1), each being positioned on any of the four possible 90° quadrants (12–3, 3–6, 6–9, or 9–12 o'clock). Observers were instructed to memorize both the color and the shape of the prime object and to discriminate the orientation of the target line. They were encouraged to perform well in both tasks. They were informed that only accuracy would be examined in the memory task, and they were asked to respond as accurately and quickly as possible in the search task. Eight memory-probe trials were included in each block. Observers were informed about these contingencies.

Procedure. First, the observers were familiarized with the task, and they performed 25 practice trials. Then, they performed four blocks of 72 trials each. There were three different match conditions. In the color-match condition, one object in the search array shared its color, but not its shape, with the prime. In the shape-match condition, one object in the search array shared its shape, but not its color, with the prime. In the conjunction condition, one stimulus in the search display matched both the color and the shape of the prime. In all of the conditions, the other stimulus differed in both color and shape from the prime. The different match conditions occurred with the same probability on valid trials (on which the target appeared within the primed stimulus) and invalid trials (on which the primed stimulus contained a distractor). A neutral condition was also included, in which none of the features of the prime stimulus was shared by any of the stimuli in the search array. Figure 4 illustrates examples of the different priming conditions for valid trials. Match condition and prime validity were varied randomly within each trial. There were 96 trials for each level of validity of the prime (valid, invalid, neutral). On valid and invalid trials, there were 32 trials for each match condition (color, shape, conjunction). Eight memory-probe trials were also included in each block.

Results

Errors in the search–identification task were minimal ($M = 2\%$) and were not analyzed further. The mean percentage of correct trials in the memory task was 91%. Errors across the conditions are shown in Table 2.

Analyses of RTs. We carried out a 2 (prime validity: valid, invalid) × 3 (match condition: color, shape, conjunction) repeated measures ANOVA using median RTs of the correct responses. Because there were no feature matches between the prime and the items of the search array in the neutral condition (in which the prime was absent from the search array), this condition was omitted from this analysis, but it was included in subsequent analyses to examine the pattern of costs and benefits across the different match conditions. The results gave a main effect of prime validity, $F(1, 9) = 34.18$, $p < .0001$, with faster performance on valid than on invalid trials. The main effect of match condition, $F(2, 18) = 2.36$, was not significant. Match condition interacted significantly with prime validity, $F(2, 18) = 10.04$, $p < .005$. To assess the source of this interaction, we performed three ANOVAS with prime validity (valid, neutral, invalid) as a repeated measures factor for each match condition (color, shape, conjunction). Validity effects were significant in the color-match condition, $F(2, 18) = 19.19$, $p < .001$. Pairwise comparisons showed reliable costs, with longer RTs on invalid than on neutral trials ($p < .008$), and benefits, with shorter RTs on valid than on neutral trials ($p < .01$). Validity effects were also significant in the conjunction condition, $F(2, 18) = 27.48$, $p < .0001$. This was reflected in both costs, with reliable differences between neutral and invalid trials ($p < .002$), and benefits, with faster performance on valid than on neutral trials ($p < .001$). Further comparisons indicated that benefits were larger in the conjunction condition than in the color-match condition ($p < .032$). Validity effects approached significance in the shape-match condition, $F(2, 18) = 3.62$, $p = .057$. Figure 5 represents this pattern of results.

Lastly, we analyzed performance for the shortest RTs. Analyses for the data up to the 5th percentile showed a reliable effect of prime validity, $F(1, 9) = 19.30$, $p < .002$, and also a reliable interaction between prime validity and match condition, $F(2, 18) = 15.62$, $p < .001$. Validity effects were significant in the color-match condition, $F(2, 18) = 9.93$, $p < .007$. Responses were faster in the valid than in the invalid condition ($p < .007$) and slower in the invalid than in the neutral condition ($p < .016$). The differences between the valid and the neutral condition were not reliable. In the conjunction condition, validity effects were highly robust, $F(2, 18) = 18.13$, $p < .001$, and all differences between

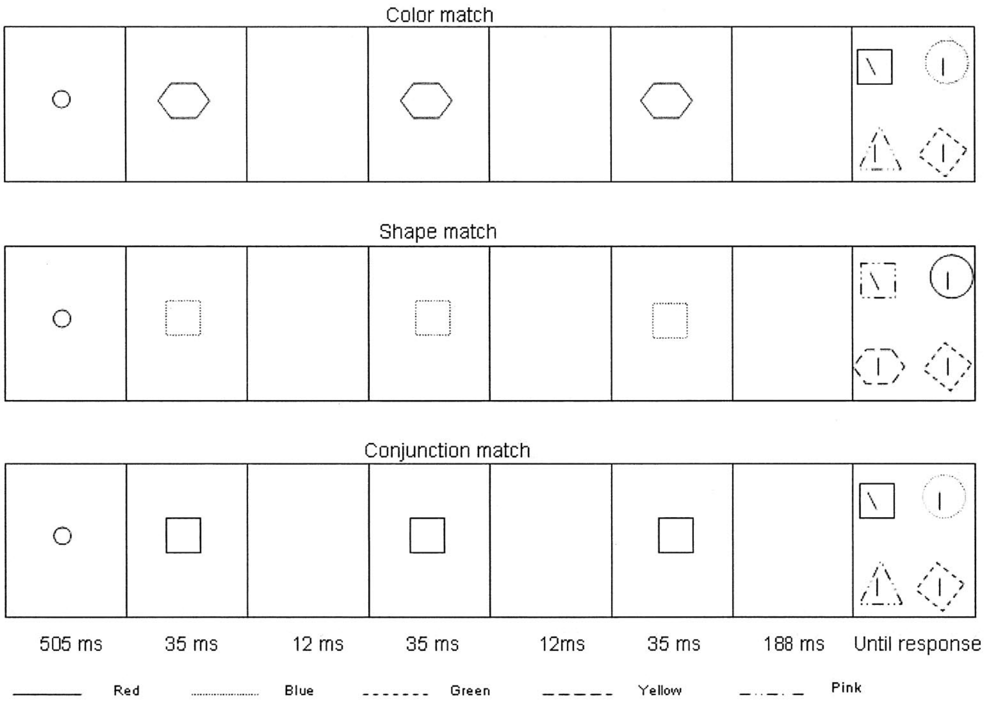

Figure 4. Examples of display sequences in Experiment 2 for the different match conditions on valid-prime trials.

each pair of levels within this factor were reliable (*p*s < .01). Validity effects were absent from the shape-match condition, *F*(2, 18) = 1.20. Figure 6A depicts this pattern of results. Analyses for data up to the 10th percentile showed a main effect of prime validity, *F*(1, 9) = 31.66, $p < .0001$, and also an interaction between prime validity and match condition, *F*(2, 18) = 19.67, $p < .001$. Further ANOVAS revealed reliable validity effects in the color-match condition, *F*(2, 18) = 14.53, $p < .001$. Responses were faster in the valid than in the invalid condition ($p < .002$) and slower in the invalid than in the neutral condition ($p < .007$). The differences between the valid and neutral conditions were not reliable. In the conjunction condition, validity effects were highly robust, *F*(2, 18) = 30.81, $p < .0001$, and all differences between the levels of this factor were highly reliable (*p*s < .005). Validity effects were absent from the shape-match condition ($F < 1$). These results are illustrated in Figure 6B.

Eye movements. The data were analyzed only when correct responses were made and for first fixations falling outside the spatial area occupied by the prime. The landing positions for saccades were partitioned according to whether the fixation fell into one of the eight 45° quadrants that delimited the possible positions of the stimuli.

First, we examined the percentages of first saccades that fell in the quadrant occupied by the primed object in the search array. Neutral trials were omitted (because, by definition, the primed object never appeared in the search display in the neutral condition). A 2 (prime validity) × 3 (match condition) ANOVA showed a higher percentage of first saccades to the primed object in the valid than in the invalid condition, *F*(1, 9) = 23.9, $p < .001$. The effect of match condition also was significant, *F*(2, 18) = 8.89, $p < .005$. Pairwise comparisons revealed a larger number of

Table 2
Proportions of Error as a Function of Prime Validity and Match Condition in Experiment 2

	Prime validity		
Match condition	Invalid	Neutral	Valid
Shape	.02	.01	.03
Color	.02	.01	.02
Conjunction	.03	.01	.02

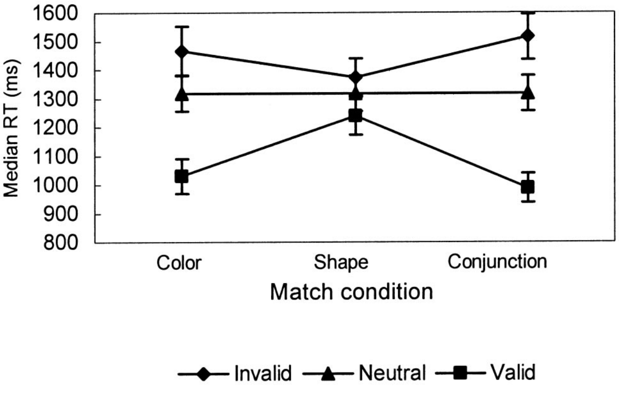

Figure 5. Data from Experiment 2. Means of median reaction times (RTs) for correct responses as a function of prime validity and match condition. Error bars represent standard errors.

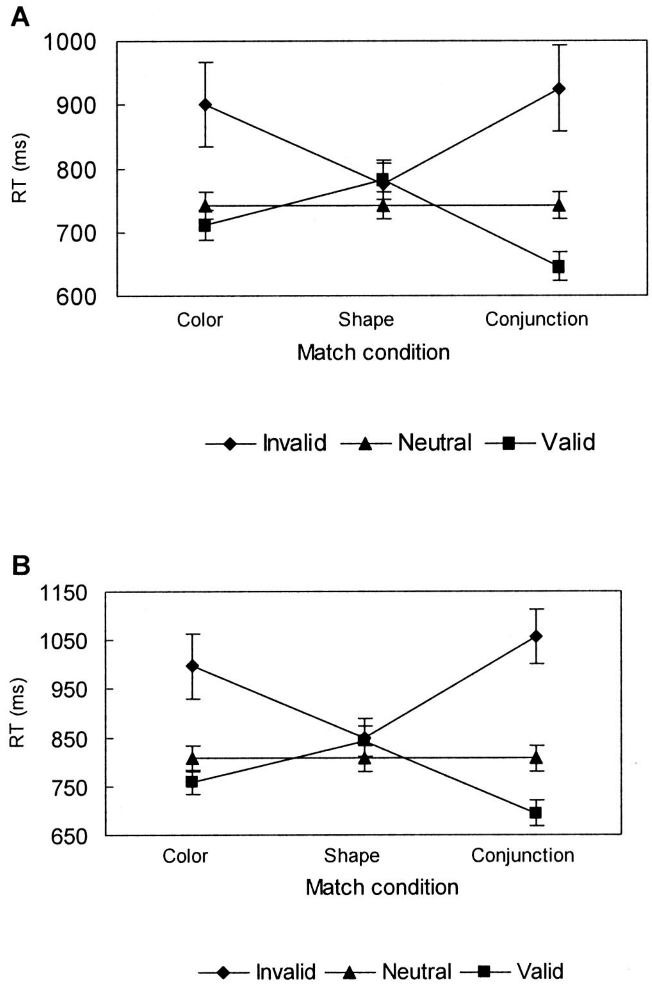

Figure 6. Data from Experiment 2. A: Reaction times (RTs) for the 5th percentile of the data as a function of prime validity and match condition. B: RTs for the 10th percentile of the data as a function of prime validity and match condition. Error bars represent standard errors.

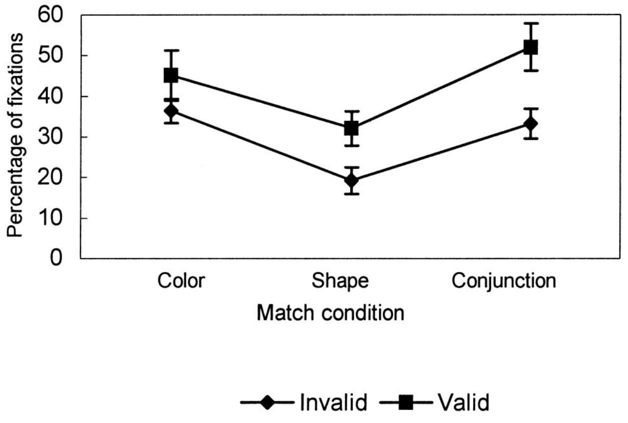

Figure 7. Eye movement data from Experiment 2. Percentages of first fixations landing at the location of the primed object on valid and invalid trials and for each match condition. Error bars represent standard errors.

saccades falling in the quadrant of the primed object in the color-match ($p < .004$) and conjunction ($p < .012$) conditions than in the neutral condition. This pattern of results is illustrated in Figure 7.

Second, we analyzed the number of first saccades directed to the target's location by means a 2 (prime validity) × 3 (match condition) repeated measures ANOVA. There was a significant effect of prime validity, $F(1, 9) = 15.66$, $p < .003$. The percentage of fixations landing at the target's location was larger on valid than on invalid trials. The main effect of match condition was not reliable ($F < 1$). The interaction between prime validity and match condition reached significance, $F(2, 18) = 9.46$, $p < .004$. To assess the source of this interaction, we carried out three ANOVAS with prime validity as a factor for each match condition. In the color-match condition, there was a significant effect of prime validity, $F(2, 18) = 8.13$, $p < .013$. Pairwise comparisons showed a smaller number of fixations toward the target's location in the invalid condition than in the neutral condition ($p < .009$). The differences between valid color-match trials and neutral trials approached significance ($p < .057$). In the conjunction-match condition, there was also an effect of prime validity on the pattern of first saccades, $F(2, 18) = 18.28$, $p < .001$. There were more fixations toward the target's location in the valid than in the neutral condition ($p < .01$) and fewer fixations in the invalid than in the neutral condition ($p < .0001$). There was no effect of the shape of the prime in the shape-match condition, $F(2, 18) = 0.08$. Figure 8 represents these results.

Lastly, we compared the number of first saccades in the neutral condition landing at the target's location and the number of saccades toward any of the remaining seven positions that could be occupied by the different distractors. The ANOVA showed a significant effect of position over the pattern of saccades, $F(7, 63) = 42.70$, $p < .0001$. There were significantly more saccades toward the target's location than toward any of the other locations. This is illustrated in Figure 9.

Discussion

The results again suggest that the maintenance of an object in WM can elicit a bias to deploy attention. RTs were shorter to

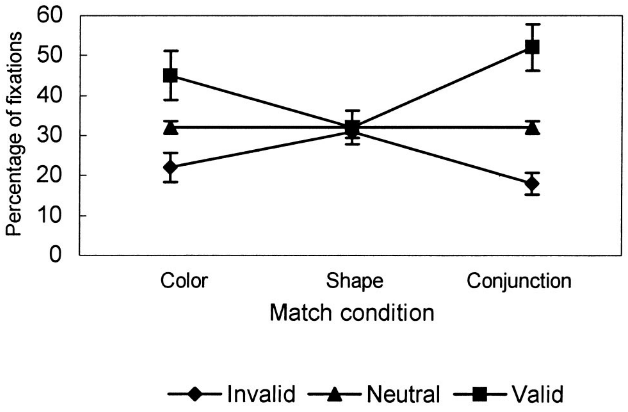

Figure 8. Eye movement data from Experiment 2. Percentages of first fixations landing at the target's location as a function of prime validity and match condition. Error bars represent standard errors.

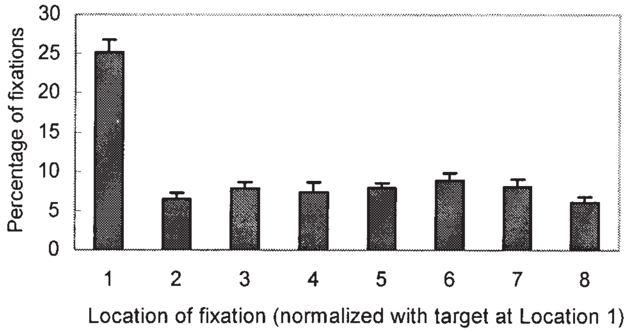

Figure 9. Eye movement data from Experiment 2. Percentage of first fixations landing at any of the eight possible locations in the array in the neutral condition. Location 1 represents fixations at the target's location. Error bars represent standard errors.

targets appearing at the locations of objects that matched the color or both the color and the shape of the prime activated in WM (when compared with the neutral baseline, in which the prime was absent from the search display). Likewise, performance suffered when the primed object contained a distractor (on invalid relative to neutral trials). The pattern of the eye movements matched the behavioral data: More fixations landed at the locations of objects matching the color or both the color and the shape of the prime than at the locations of other stimuli in the search display.

These results extend previous findings (Downing, 2000) by showing that prime representations activated in WM can guide attention on the basis of featural overlap between the prime and stimuli in the search display. Here, the prime was generally effective in guiding attention even when there was just a color match with one of the stimuli in the search display. There was also some evidence for conjunctive information (or at least both color and shape) being effective in biasing search in that the beneficial effects of priming from WM were larger in the conjunction than in the color-match condition. However, shape overlap alone was ineffective. As in Experiment 1, the effects of top-down priming were evident even for the shortest RTs (see Figure 6).

In these data, there is some support for the idea that color can have a stronger effect than shape in guiding attention. For instance, Williams (1966), using a search paradigm, showed faster performance and larger numbers of fixations landing at the location of a target that was specified by color relative to a target specified by shape. However, there is also evidence showing that shape information can be useful for attentional guidance (Egly et al., 1994; Ghirardelli & Egeth, 1998) and for directing eye movements (Findlay, 1997; Viviani & Swensson, 1982). The fact that we found little evidence for shape effects may be linked to the relative similarity of the different shapes used in our experiment, especially given that the shapes were displayed away from fixation. Caution should be exercised in generalizing these results to other shapes.

A second novel result concerns the effect of the WM prime on the initial saccades made by observers. A larger number of fixations fell at the target's location when both the primed object and the target occurred at the same location compared with when they fell at different locations. It is interesting to note that in the neutral condition, a larger number of saccades were directed toward the target's location than to any of the remaining locations.

This last result suggests that some information is available from the target alone to guide attention and eye movements. However, any effect of this information is enhanced when the target's location matches that of the WM prime. Furthermore, an invalid prime can redirect a first saccade from a target toward the location of the stimulus sharing properties with the stimulus held in WM. Apparently, in the present experiment, top-down feedback from WM had a stronger effect in guiding attention than did the bottom-up signal generated by the target.

The evidence for a convergence of bottom-up and top-down cues on target selection is congruent with the guided search model of attention (Wolfe, 1994; Wolfe, Cave, & Franzel, 1989). According to this model, a salience map of a scene results from the combination of bottom-up activation from the stimulus and top-down activation from an observer's knowledge about an expected target. Attention is guided to the location with the largest activation. Our results suggest that top-down activity is associated with critical features held in WM. Furthermore, the effects of top-down knowledge occur early enough to influence the first saccade and the shortest RT.

Experiment 3: Discarding a Bottom-Up Priming Account

The aim of Experiment 3 was to test whether (a) the search bias observed in the previous experiments resulted from the active maintenance of the prime in WM or (b) priming the representation of the object without WM requirements can be enough to bias attentional deployment. This experiment examined performance under the same conditions used in Experiment 2, but now observers were not asked to maintain the prime in WM for a later report. If similar effects were observed with the mere presentation of the prime, this would favor a bottom-up priming account. However, the absence of effects under this condition would mean that the prime has to be attended and maintained in WM to generate the effect.

Method

Participants. Ten naive undergraduates (5 men and 5 women) from the University of Santiago de Compostela participated for academic credits. They ranged in age between 18 and 23 years, and all had normal or corrected-to-normal vision.

Apparatus. This was the same as in Experiment 1.

Task and procedure. The task and stimulus parameters were virtually identical to those of Experiment 2. As in the previous experiments, observers were informed about the probability of validity of the first stimulus across the different match conditions. The only difference was that now observers were not required to keep the first item in memory for later matching with a probe.

Results

Errors were minimal ($M = 2\%$) and were not analyzed further. Errors across the conditions are shown in Table 3. Median RTs of correct responses were entered into a 2 (prime validity: valid, invalid) × 3 (match condition: color, shape, conjunction) repeated measures ANOVA. There was no effect of prime validity ($F < 1$), and neither the main effect of match condition, $F(1, 9) = 1.86$, nor its interaction with prime validity, $F(2, 18) = 1.37$, reached

Table 3
Proportions of Error as a Function of Prime Validity and Match Condition in Experiment 3

	Prime validity		
Match condition	Invalid	Neutral	Valid
Shape	.02	.03	.01
Color	.02	.03	.02
Conjunction	.03	.03	.01

significance. Figure 10 depicts the means of median RTs across conditions.

Discussion

The results of Experiment 3 eliminate the possibility that the search biases reported in Experiments 1 and 2 were caused by a bottom-up priming mechanism. We failed to observe priming effects under conditions in which the prime did not have to be maintained in WM (see also Downing, 2000, Experiment 3). The fact that the mere exposure of the prime was not sufficient to guide attention in the spatial search task used in our experiments suggests that primes need to be attended and maintained in WM to guide attentional deployment. In sum, top-down feedback from activated representations in WM seems to be involved in biasing attention under the conditions of the present experiments.

Experiment 4: Automatic Attentional Guidance From WM

In the previous experiments, the probability that the target appeared within the object of the search array that matched some of the contents of WM was low (one third of the trials). This raises the question of whether the information held in WM guides attention automatically even when the prime never predicts the target's location. This was tested in Experiment 4. We compared search in a control baseline (in which prime features were not present in the search array) with a condition in which the primed stimulus was present in the search display but never contained the target. Here, it would be beneficial for observers to ignore the prime. Would they be able to do this?

Method

Participants. Ten naive undergraduates (5 men and 5 women) from the School of Psychology of the University of Birmingham participated for academic credits. They ranged in age between 19 and 21 years, and all had normal or corrected-to-normal vision.

Apparatus. This was the same as in Experiment 2.

Task and procedure. The task and stimulus parameters were virtually identical to those of Experiment 2. The main difference here was that the primed object was always invalid across the different match conditions. We also included a neutral condition identical to that of the previous experiments. Seventy-five percent of the trials were invalid, and the remaining 25% were neutral. Observers were instructed that the primed object would never contain the target. They performed 25 practice trials, followed by three blocks of 72 trials. Eight memory-probe trials per block were also included.

Results

Errors were minimal ($M = 1\%$) and were not analyzed. Observers performed quite accurately on memory-probe trials ($M = 90\%$). The data are given in Table 4.

Analyses of RTs. To assess whether there was an overall difference between the neutral and invalid conditions, we computed an overall mean for the RTs across the different match conditions. There was a significant overall difference between the invalid and neutral conditions, $F(1, 9) = 9.12$, $p < .014$. RTs were longer in both the color-match condition, $t(9) = 2.89$, $p < .018$, and the conjunction condition, $t(9) = 3.05$, $p < .014$, relative to the neutral baseline. The difference between the shape-match condition and the neutral condition was not statistically reliable, $t(9) = 1.42$. These results are illustrated in Figure 11.

Analyses of RTs for the 5th percentile revealed no significant differences between each match condition and the neutral condition, $t(9) = 1.18$ (color match vs. neutral) and, $t(9) = -0.36$ (shape match vs. neutral). There was, however, a trend for the conjunction condition to be slower than the neutral baseline, $t(9) = 1.93$, $p = .085$. Analyses of RTs for the 10th percentile showed no reliable differences between the color-match, $t(9) = 1.39$, or the shape-match, $t(9) = -0.72$, conditions and the neutral baseline. In contrast, RTs were longer in the conjunction condition than in the neutral condition, $t(9) = 3.25$, $p < .01$. Figure 12 represents this pattern of results.

Lastly, we compared the size of the costs (invalid-trial RT − neutral-trial RT) in Experiment 4 with those in Experiment 2 by means of a 2 (experiment) × 3 (match condition) ANOVA. The size of the cost differed across the different match conditions, $F(2, 36) = 5.01$, $p < .012$. Costs were larger in both the color-match ($p < .04$) and the conjunction ($p < .012$) conditions relative to the shape-match condition. However, the size of the costs did not differ between experiments ($F < 1$).

Eye movements. To assess whether there was an overall difference between the neutral and invalid conditions on the pattern of fixations to the target, we computed an overall mean for the percentage of fixations across the different match conditions. There was a significant overall difference between the invalid and

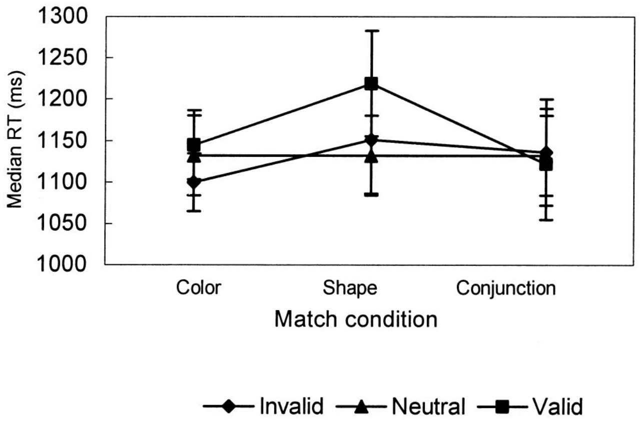

Figure 10. Data from Experiment 3. Means of median reaction times (RTs) of correct responses as a function of prime validity and match condition. Error bars represent standard errors.

Table 4
Proportions of Error as a Function of Prime Validity and Match Condition in Experiment 4

	Prime validity	
Match condition	Invalid	Neutral
Shape	0	.01
Color	.01	.01
Conjunction	.01	.01

neutral conditions, $F(1, 9) = 8.13$, $p < .019$. Then, we compared the number of first saccades toward the target's location in the different match conditions with that in the neutral condition. The results showed that there were fewer first fixations to the target in the color-match condition than in the neutral condition, $t(9) = -2.42$, $p < .39$. The same result was obtained for the comparison between the conjunction condition and the neutral condition, $t(9) = -3.03$, $p < .14$. In contrast, the differences between the shape-match condition and the neutral condition were not reliable, $t(9) = -0.74$. This pattern of results is illustrated in Figure 13.

Finally, in the invalid condition only, we compared the number of first fixations landing at the location of the primed object and the number of fixations landing at the target's location in both Experiment 4 and Experiment 2 by means of a 2 (experiment) × 2 (locus of fixation) × 3 (match condition) ANOVA. A three-way interaction between experiment, locus of fixation, and match condition was observed, $F(2, 17) = 6.73$, $p < .007$. To assess the source of this interaction, we conducted two 2 (locus of fixation) × 3 (match condition) ANOVAs on each experiment. Analyses for Experiment 2 revealed a significant interaction between locus of fixation and match condition, $F(2, 18) = 17.24$, $p < .002$. Further analyses demonstrated the source of this interaction. More fixations fell at the location of the prime stimulus than at the target's location in both the color-match ($p < .024$) and conjunction ($p < .017$) conditions (though not in the shape-match condition, $p < .03$). For Experiment 4, no reliable effects were observed, showing that the number of fixations to the target did not differ from the number of fixations to the primed object.

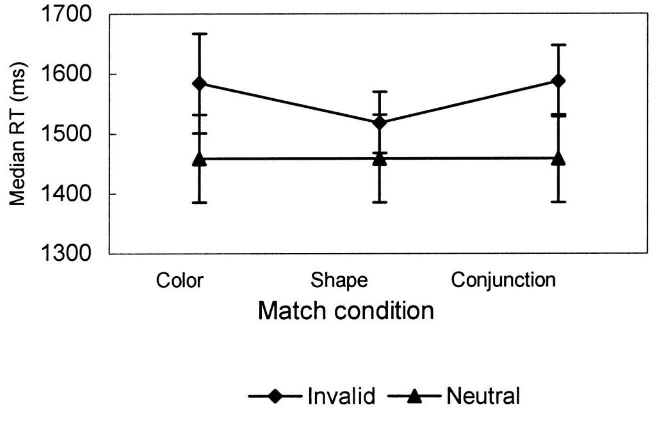

Figure 11. Data from Experiment 4. Means of median reaction times (RTs) of correct responses as a function of prime validity and match condition. Error bars represent standard errors.

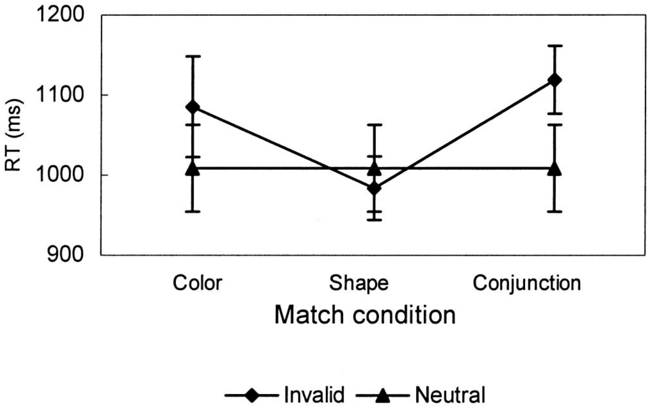

Figure 12. Data from Experiment 4. Reaction times (RTs) for the 10th percentile of the data as a function of prime validity and match condition. Error bars represent standard errors.

Discussion

In this experiment, the contents of WM were, if anything, detrimental to task performance, because the properties of the prime always predicted the location of a distractor rather than the target's location. Nevertheless, the prime continued to affect performance. RTs were longer when the prime object reappeared in the search display than when it did not occur there (in the neutral baseline). The prime also affected the first eye movement in the search task. There were fewer first fixations to the target in the invalid condition than in the neutral baseline. As in Experiment 2, these effects were reliable when a stimulus in the search array shared its color with the prime, and this effect was enhanced when both the color and the shape of the stimulus matched. For example, for the shortest 10% of RTs, a disruptive effect of an invalid prime occurred only in the conjunction condition.

The pattern of results suggests that both the eyes and attention tend to be drawn by the contents of WM even when these contents are detrimental to task performance, and in this sense, WM exerts an involuntary influence over visual selection that observers cannot easily control. Previous research on attentional capture has stressed the role of bottom-up factors (e.g., the saliency of an

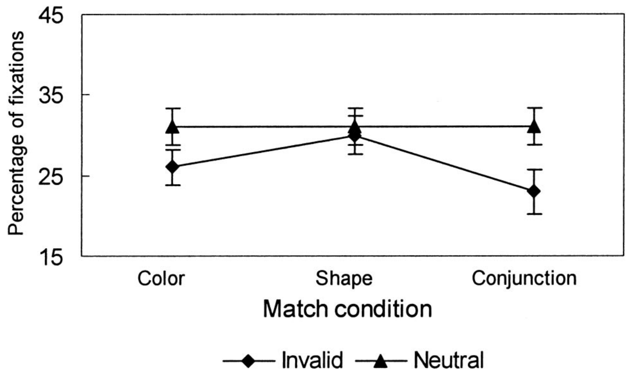

Figure 13. Eye movement data from Experiment 4. Percentage of first fixations landing at the target's location as a function of prime validity and match condition. Error bars represent standard errors.

irrelevant singleton in a display; see Theeuwes, 1991, 1992; Theeuwes & Burger, 1998), though there has been some suggestion that bottom-up singleton effects may themselves depend on the attentional "control setting" of the observer (Bacon & Egeth, 1994; Folk & Remington, 1999; Folk, Remington, & Johnston, 1992; Yantis & Egeth, 1999; though see Olivers & Humphreys, 2003, for some counterevidence). To the best of our knowledge, evidence for an involuntary effect from WM to attention in spatial search has not been demonstrated hitherto. Pashler and Shiu (1999), as reviewed in the introduction, showed an impairment on performance when the target of a RSVP stream was preceded by an object matching the mental image that observers had formed, in a manner similar to the attentional-blink effect. Because observers were encouraged to discard the image once the RSVP stream was displayed, this result suggests that the object matching the mental image was detected involuntarily. However, it has to be noted that Pashler and Shiu's study did not involve spatial search as ours did in that, in their study, attention was focused at the same location during the presentation of the RSVP stream.

It remains an empirical question, now, as to how general this result is. For example, if the effect of WM on selection is fully automatic (cf. Humphreys, 1985; Shriffrin & Schneider, 1977), then it should be observed even when observers are required to carry out other, secondary load tasks. We doubt that this is the case. For example, with a load that itself requires WM capacity, we would expect the representation of the prime in WM to be affected (e.g., be degraded) such that its influence might decrease. Some evidence consistent with this has been reported by Downing and Dodds (2004). These investigators showed participants two shapes as primes, one of which was a target in a subsequent search display and one of which had to be remembered for later verification. They found that the item to be remembered did not affect selection in the immediate search task when it was presented as a distractor. The lack of an effect of the distractor in this case may reflect interference between the items in WM. Similarly, as noted in the introduction, de Fockert et al. (2001) found a reduced influence of top-down control on visual selection under conditions of increased mental load. Our results for early and involuntary effects of WM may reflect the fact that only a single item was maintained, optimizing the WM effect. Also, top-down effects in our experiment were found under conditions in which the differences between target and distractors were small. Although we showed that some information about the target line was available to guide attention and eye movements, it may be that top-down effects from WM to attention are reduced with pop-out targets (i.e., a line tilted 45°). These speculations need to be put to empirical test.

Previous work on bottom-up attentional capture has shown that irrelevant singletons direct not only covert attention but also the eyes (Theeuwes, de Vries, & Godijn, 2003). We too have established that the eyes tend to be captured by the contents of WM. Nevertheless, there is some suggestion in our data that eye movements were influenced, at least to some degree, by the volitional control of the observer. In Experiment 2, in which the WM representation was valid on one third of the trials, the first saccade on invalid trials went to the prime stimulus more frequently than to the stimulus containing the target. In Experiment 4, this pattern did not hold; on invalid trials, the first saccade went to the target equally as often as to the primed object. Hence, the effect of the WM representation had a reduced influence on overt orienting in Experiment 4, and it no longer necessarily overruled the effects of bottom-up guidance to the target line. However, costs to RTs as a result of attention being directed in a top-down way by the prime did not differ between Experiments 2 and 4. This could suggest that volitional control affects eye movements more than it affects covert attention (the latter measured through effects on RTs). Against this last assertion, though, we also found weaker effects of the prime on short RTs in Experiment 4 than in Experiment 2. For example, there were reliable cost effects of invalid trials for the 5th percentile of RTs in Experiment 2; in Experiment 4, reliable effects emerged only for the fastest 10th percentile of the data. This in turn indicates an influence of volitional control on covert as well as overt attention. For example, it may be that an intentional expectancy based on the item held in WM increases a basic effect originating from that item's just being maintained. This produces even earlier modulation of target selection through covert selection and a larger effect on eye movements. Thus, though an involuntary influence from WM can be observed, any effect is enhanced by conscious expectancy. Alternatively, the somewhat stronger effects observed in Experiment 2 (on both covert and overt attention) may arise because there is a form of perceptual learning taking place across trials when the prime objects sometimes contains the target. This perceptual linkage of the prime stimulus to the target may not be mediated by a conscious expectancy, but it may increase effects of top-down guidance on the subsequent trial. This could then produce a greater memory effect when the target is valid on even just one third of the trials (Experiment 2) relative to when it is always invalid (Experiment 4). Note, however, that any linkage between the target and the prime would have to have been relatively abstract, because the prime itself changed across trials. In this respect, any effect would be different from feature- and dimensional-carryover effects that have been observed in search when targets carry the same feature or are from the same dimension across consecutive trials (cf. Found & Müller, 1996; Maljkovic & Nakayama, 1994). Against this suggestion, we examined repetition effects of the type mentioned above in Experiment 2 (in which only a single display size was manipulated), and we failed to observe such effects. Performance on a valid trial did not depend on whether the previous trial was valid or invalid, $t(9) = 1.68$, *ns*, even when there was color matching between successive primes, $t(9) = 0.69$, *ns*. It is worth noting that our experiments were not designed to examine this issue. So, the contrast between any conscious top-down expectancy and perceptual learning across trials can be evaluated through examination of intertrial contingencies in a study adequately designed to explore this issue. For now, we conclude only that there was no evidence for such priming effects in our study.

General Discussion

We have reported four experiments on the effects on visual selection of an item held in WM. We have found the following:

1. The effects of the prime held in WM interact with the number of items in a subsequent search display; in particular, benefits from valid primes increase at larger display sizes (Experiment 1).

2. The effects of the prime are influenced by featural over-

lap based on color as well as by conjunctive overlap of color and shape (Experiments 2 and 4).

3. The effects influence the first saccade made in search (Experiments 2 and 4), and they influence the shortest RTs in the search task (Experiments 1, 2, and 4).

4. The effects also occur even when the prime is never valid and is always invalid (i.e., contains a distractor rather than a target) when it reoccurs in the search display (Experiment 4).

5. There are, nevertheless, some effects of the overall validity of the prime, with the effects being more pervasive and occurring earlier in time when the prime is valid on at least some trials (Experiment 2 vs. Experiment 4).

6. The effects are not observed when observers are merely exposed to the prime without having to keep it in memory for a later report (Experiment 3).

The results extend prior studies that have examined top-down modulation of visual selection (Downing, 2000). First, unlike Downing, we incorporated a neutral baseline condition into our design. In this way, we were able to show that there are both costs and benefits from memory guidance—there are benefits when primes contain the target and costs when primes contain a distractor relative to when the prime does not reappear in the search display. The separation of invalid and neutral primes was particularly useful for showing an effect of the prime even when it was never valid (Experiment 4).

Second, we demonstrated in Experiment 1 that priming from WM influenced search efficiency. The benefits from valid priming increased at larger display sizes. This suggests that top-down activation from WM amplified any weak bottom-up signal from the target, enabling attention to be directed more efficiently to the target on valid than on neutral trials. In contrast, cost effects were generally additive with the display size. We propose that the prime stimulus (along with its internal line) was selected early on in search. On invalid trials, this item was rejected as not containing the target, and search for the target continued but with an overall increment to performance resulting from the incorrect initial assessment. The argument for top-down effects occurring early on is also supported by the analysis using just the shortest RTs (the 5th and 10th percentiles), in which priming effects were again evident.

Third, in Experiments 2 and 4, we found that primes affected the first saccades made in the search task. This occurred even though primes were never valid in Experiment 4. Nevertheless, the effects were stronger when primes were sometimes valid. In Experiment 4, RT differences did not emerge reliably until data from the 10th percentile were included. Also, the first saccade was equally likely to go to the target as to an invalid prime. In contrast, in Experiment 2 (valid prime on one third of the overall trials), RT effects were apparent at the 5th percentile, and the first saccade went more often to an invalid prime than to the target present in the same display. It may be that an expectancy developed for sometimes-valid primes amplifies any involuntary effect caused simply by holding an item in WM. Alternatively, there may be some perceptual learning across trials on which primes are sometimes valid that enhances top-down effects. This learning would need to be based on something like a sensitivity to an enhanced signal generated from the involuntary convergence of activation from the prime and target, which would be further amplified when the prime is sometimes valid. Against this last view, we failed to find evidence of trial-by-trial learning in a post hoc evaluation of Experiment 2. However, this should be tested more strongly in a study with more power to assess trial-by-trial contingency effects.

We have also shown that the present effects result from primes being held in WM. Like Downing (2000), who found positive effects of valid primes (on valid relative to invalid trials), we showed reliable effects of the memory item on both covert and overt attention when primes had to be retained in memory, but we failed to demonstrate effects when observers did not have to maintain the prime in memory. The results suggest that, at least to affect search under the present conditions, an item needs to be held in WM. However, once held in WM, an item can guide initial parts of the search process in an involuntary manner.

The results of the current study fit well with the biased competition model of selection (Desimone & Duncan, 1995). According to this framework, the competition between multiple objects in the visual scene can be resolved by top-down feedback from object representations activated in WM such that attention is biased in favor of the object whose features were preactivated. We have shown that once an object is held in WM, it can guide early parts of the search process in an involuntary manner. Other recent evidence suggesting a strong role of top-down, memory-based guidance on search comes from Moores, Laiti, and Chelazzi (2003). These researchers found that search for a target object (e.g., a motorbike) was influenced by the presence of distractors that were associatively related to the target (e.g., a helmet), even when the target was absent from the search display. As in the present study, this affected the first eye movement made to the display. Moores et al. suggested that search is influenced by a template (cf. Duncan & Humphreys, 1989) set up for a target, but this template can also activate representations for associatively related stimuli, which in turn can affect search. Our data indicate that such a template can direct search once it is held in WM, even if it is not predictive of where a target falls.

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