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Memory-driven attentional capture is modulated by temporal task demands

Silvia Dalvit and Martin Eimer

School of Psychology, Birkbeck College, University of London, London, UK

Previous research has shown that attention is biased towards items that match the current content of working memory (memory-driven attentional capture), but it remains unclear whether this effect is automatic or under voluntary control. Participants memorized a colour for subsequent recall and searched for a target shape among distractors that included a colour singleton which matched or mismatched the memorized colour. Search displays were presented for 200 ms or until response execution. Display duration was blocked or randomly intermixed for different participants. Reaction times (RTs) were slower on trials with memory-matching distractors, reflecting memory-driven attentional capture. Only with blocked display durations, this effect was much smaller for short than for long displays. This demonstrates that attention tasks are prioritized and shielded from interactions with working memory when this is required by high temporal task demands, and suggests that memory-driven attentional capture is controlled by top-down processing strategies.

Keywords: Attentional capture; Selective attention; Working memory.

The question whether and how the current content of visual working memory affects the allocation of selective attention has been addressed in numerous recent experiments that were based on the combination of a working memory and a visual search task (see, for reviews, Olivers, 2008; Soto, Hodsoll, Rotshtein, & Humphreys, 2008). Participants memorized an item for subsequent recall before performing a visual search task. Search costs on trials where distractor items matched the current working memory

Please address all correspondence to Silvia Dalvit, School of Psychology, Birkbeck College, University of London, Malet Street, London WC1E 7HX, UK. E-mail: s.dalvit@psychology.bbk.ac.uk

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content (Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006a, 2006b), and benefits when search targets replaced memory-matching stimuli (Downing, 2000) suggest that attention is captured by such stimuli, even though they are irrelevant in the context of the visual search task (memory-driven attentional capture).

However, the fact that other studies have failed to observe such memory-driven attentional capture effects (e.g., Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Woodman & Luck, 2007) indicates that there are circumstances where visual representations associated with the memory and visual search tasks can be successfully separated and/or prioritized. Attentional capture effects are reduced or eliminated when the working memory task is made more difficult (e.g., by combining articulatory suppression and high working memory load; Soto & Humphreys, 2008), when the location of search targets is validly precued (Pan & Soto, 2010), or when the identity of search targets varies from trial to trial (Olivers, 2009, Exp. 5). Such findings suggest that memory-driven attentional capture is not triggered automatically, but is modulated by the relative priority of memory and attention tasks (e.g., Olivers, 2009). For example, when the difficulty of a search task is increased by the requirement to process new target-related information on every trial (e.g., Olivers, 2009; Pan & Soto, 2010), representations that are not immediately task-relevant (i.e., the to-be-memorized stimulus) are deprioritized, which results in the attenuation or elimination of memory-driven attentional capture.

In the present study, we tested the hypothesis that strategic top-down control affects memory-driven attentional capture by investigating how such capture effects are modulated by the temporal demands of a visual search task. Participants had to memorize a colour for subsequent recall before searching for a target diamond singleton that was accompanied by circle distractors. One of these circles was a colour singleton that either matched or did not match the memorized colour (Figure 1). In the long duration condition, search displays remained present until response execution. In the short duration condition, search displays disappeared after 200 ms. For participants assigned to the blocked duration group, these two conditions were presented in different blocks. For the random duration group, short and long duration trials were randomly intermixed.

When display duration was blocked, participants could adjust their search strategy according to current temporal task demands. In short duration blocks, target detection had to be efficient and fast, as attentional capture by memory-matching distractors might result in a failure to encode targets. Strategic prioritization of the attentional over the working memory task was therefore more important than in long duration blocks, where demands on target selection efficiency were less severe. If memory-driven attentional capture is modulated by the relative priority of attention and memory tasks,

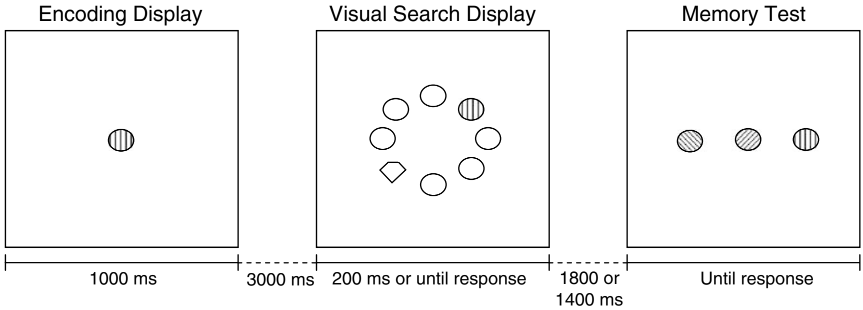

Figure 1. Schematic illustration of the sequence of events in a trial. Encoding displays were followed by visual search displays and memory test displays. Search displays contained a diamond target among circle distractors. One distractor was a colour singleton that matched or did not match the to-be-memorized colour. Search displays could be presented for 200 ms or until response execution. For different groups of participants, display durations were either blocked or randomly intermixed across trials.

it should be substantially reduced in short relative to long duration blocks. Because no such strategic prioritization was available to the random duration group, display duration should have no impact on the size of memory-driven capture effects in this group.

METHOD

Participants

Forty-four participants (26 females, aged 19–47 years, mean age 26 years) with normal or corrected-to-normal vision were tested.

Stimuli, procedure, and data analysis

Participants sat in a dimly lit sound attenuated cabin. Stimuli were presented on a CRT monitor (Samsung SyncMaster 1100 MB, 100 Hz refresh rate) against a dark grey background at a viewing distance of 120 cm. E-Prime software (Psychology Software Tools, Pittsburgh, PA) was used for stimulus presentation and response collection.

On each experimental trial an encoding display, a visual search display, and a memory test display were presented in succession (Figure 1). Encoding displays contained a circle (size: 0.7°) that was presented centrally against a dark grey background (CIE x/y values: .297/.325, luminance: 2.8 cd/m^2). The colour of the circle was randomly selected from nine alternatives (three shades of pink, blue, and green; luminance and CIE x/y values as shown in Table 1). Visual search displays contained a circular array of eight equidistant items (angular size: $0.7° \times 0.7°$) that were located at a radial

TABLE 1
CIE x/y and luminance values of all colours employed in this experiment

	CIE x value	*CIE y value*	*Luminance (cd/m^2)*
Pink 1	.322	.239	12.6
Pink 2	.350	.307	14.8
Pink 3	.332	.263	13.5
Green 1	.287	.416	18.6
Green 2	.322	.459	19.2
Green 3	.251	.380	18.0
Blue 1	.229	.243	12.0
Blue 2	.244	.254	13.6
Blue 3	.221	.256	13.0

distance of 1.7° from a central grey fixation point (angular size: 0.1° × 0.1°, CIE x/y values: .284/.316). Each array included six grey circles, one grey cut diamond, and one coloured circle. The luminance and CIE x/y values of all grey items were .284/.316 and 16.2 cd/m^2, respectively. Memory test displays contained three horizontally aligned circles (size: 0.7°, horizontal separation: 1.7°) at the screen centre. One circle matched the colour shown in the encoding display; the others had a different shade of the same colour.

Participants had to memorize the shade of the circle in the encoding display, in order to report its position in the memory test display. They also had to detect the diamond in the visual search array and to report the location of its cut (top or bottom), while ignoring the colour distractor circle. Target diamonds appeared randomly at one of the six lateral positions, but never at the top or bottom of the search array. Cut location (top or bottom) was selected randomly on each trial. The coloured distractor circle was presented with equal probability at one of the five lateral positions that were not occupied by the target diamond. In match trials, this circle had one of the three shades of the to-be-remembered colour, and in mismatch trials, it had one of the two other colours.

Trials started with a 1000 ms fixation display, followed by a 1000 ms encoding display, by a second fixation display (3000 ms duration), and by the visual search display. In the short duration condition, each search display was presented for 200 ms. In the long duration condition, search displays remained visible until the onset of a manual response. After search array offset, a fixation display was shown for 1400 or 1800 ms in the long and short duration condition, respectively, and was followed by the memory test array that remained on screen until a response was recorded (see Figure 1). Each duration condition included 156 trials. For half of the participants, long and short duration conditions were delivered in separate experimental halves (blocked duration group), and the order of duration conditions was counterbalanced. For the other half, both duration conditions were randomly intermixed in each block (random duration group). After every 20 trials, participants were given onscreen feedback about their performance in the visual search and memory tasks, and could take a self-timed break.

Participants signalled the position of the cut (top or bottom) of target diamonds in the visual search task by pressing the top or bottom key of a vertically oriented external keypad with their left or right index finger, with hand-key assignment counterbalanced across participants. In the memory test, they reported the location of the memorized colour (left, middle, or right) by pressing the "b", "n", or "m" keys of a computer keyboard with the right hand.

Data were analysed with mixed ANOVAs for the within-subject factors distractor type (match vs. mismatch) and display duration (long vs. short), and group (blocked vs. random duration group) as between-subject factor. Follow-up analyses were conducted separately for both groups.

RESULTS

Accuracy

Performance in the memory test was good (mean accuracy: 78.05%) and was not affected by display duration, distractor type or group (all *F*s ≤ 1). Visual search accuracy was generally very good, and was lower on trials with matching (mean 97.5%) than with mismatching (mean 98.2%) distractors (Figure 2), resulting in a significant effects of distractor type, $F(1, 42) = 5.67$, $p < .05$. No other significant effects or interactions were present.

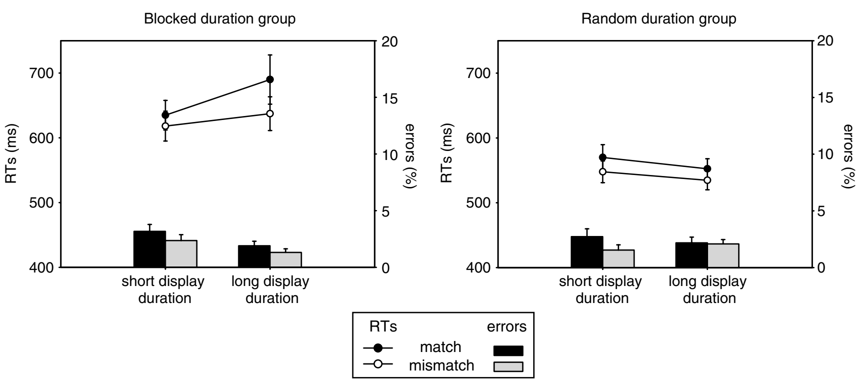

Figure 2. RTs (line graphs) and error rates (bar graphs) in the visual search task for the blocked and random duration groups, displayed separately for short and long display durations, and for match and mismatch trials. Error bars represent standard errors of mean.

Visual search RTs

Only trials where both search and memory responses were correct were analysed. Mean RTs were generally delayed on trials with matching as compared to mismatching distractors (611 ms vs. 584 ms), $F(1, 39) = 24.12$, $p < .001$ (Figure 2). In the blocked duration group, this effect was much larger with long relative to short display durations (53 ms vs. 17 ms). No such differential effect of distractor type was observed for participants who were presented with randomly intermixed search display durations (17 ms and 22 ms, for long and short displays, respectively). This difference between groups was confirmed by a significant three-way interaction between distractor type, display duration, and group, $F(1, 42) = 4.78$, $p < .05$. Main effects of distractor type were significant in both groups, both Fs(1, 21) > 12.2, both ps < .05. In the blocked duration group, the RT delay for match relative to mismatch trials was significant both with long and with short search display durations, $t(21) = 3.02$ and 2.88, respectively, both ps < .05. This was also the case for the random duration group, $t(21) = 2.91$ and 3.41, respectively, both ps < .05. However, an interaction of distractor type and display duration was only present for the blocked duration group, $F(1, 21) = 4.58$, $p < .05$, and not for the random duration group, $F < 1$.

RTs were generally faster in the random duration relative to the blocked duration group, $F(1, 42) = 10.20$, $p < .05$. There was also an interaction between group and display duration, $F(1, 42) = 4.21$, $p < .05$. In the blocked duration group, there was a nonsignificant trend for faster RTs in short duration blocks, $F(1, 21) = 2.39$, $p = .14$, but there was a trend in the opposite direction in the random duration group, $F(1, 21) = 3.06$, $p = .09$.

In the blocked duration group, the RT difference between match and mismatch trials in the short duration condition was reliably present for participants who had previously completed the long duration condition (30 ms), $t(10) = 3.7$, $p < .05$, but not for participants who had started with the short duration condition (4 ms), $t < 1$. This was confirmed by a significant interaction between distractor type and the between-subject factor order of conditions (long first versus short first), $F(1, 20) = 6.89$, $p < .05$. No such interaction was found in a corresponding analysis of RTs in the long duration condition, $F < 1$.

DISCUSSION

This study investigated the hypothesis that memory-driven attentional capture is modulated in a top-down fashion by task priorities. Participants memorized a colour for subsequent recall, and then performed a visual search task where targets were presented together with memory-matching or mismatching colour singleton distractors. For one group, search display duration (200 ms or until response execution) was blocked, for the other, it varied randomly across trials. As in previous studies (e.g., Olivers, 2009; Olivers et al., 2006; Soto, Wriglesworth, Bahrami-Balani, & Humphreys, 2010), search RTs were slower and accuracy was lower on trials with matching colour distractors than on mismatch trials, indicating that attention was captured by task-irrelevant items that matched the current content of working memory.

The critical new finding was that search display duration strongly modulated the size of this memory-driven attentional capture effect, but only when it was blocked and therefore predictable. In the blocked duration group, capture effects were reliably present, but were numerically small (17 ms) when search displays were presented for only 200 ms. When they remained present until response execution, memory-driven attentional capture more than tripled in size (53 ms). Participants in this group could adjust their search strategy to current temporal task demands. In short display duration blocks, attentional target selection had to be fast and efficient, and attentional capture by memory-matching colour distractors needed to be minimized, as it would have interfered with the rapid detection and analysis of target shapes. In long display duration blocks, more time was available to process visual search arrays, and memory-driven attentional capture by colour distractors was less likely to prevent target detection. The reduction of capture effects in short relative to long display duration blocks suggests that the search task can be prioritized, and the current content of working memory effectively shielded, when this is required by the temporal demands of this task. When these demands are less exacting, as in the long duration blocks, the prioritization of visual search and the shielding of working memory is reduced, resulting in larger memory-driven attentional capture effects.

No modulation of capture effects by display duration was observed for the random duration group. Because short and long search displays were randomly intermixed, temporal task demands were unpredictable, and no differential top-down adjustment of search strategies could be applied. The size of memory-driven capture effects in response to both short and long search displays in the random duration group was comparable to the effect observed for the other group in blocks with short displays, suggesting that a search strategy adjusted to high temporal task demands was active throughout when display duration was unpredictable. Importantly, the absence of an interaction between distractor type and display duration in the random duration group rules out strategy-independent interpretations of this interaction in the blocked duration group. With longer display durations, stored memory representations may have more time to interact with matching colour information in the search display, or eye movements towards matching distractors may be more likely, resulting in larger interference effects. If this was the case, similar modulations of memory-driven capture by display duration should have been observed in both groups. The presence of such modulations in the blocked duration group and their absence in the random duration group provides strong evidence against low-level accounts, and points towards a critical role of strategic task prioritization.

Overall, the current results provide new evidence that memory-driven attentional capture effects are not primarily an automatic phenomenon, but are strongly modulated by top-down task strategies. The dramatic impact of predictable search display duration on the magnitude of attentional capture demonstrates that the temporal demands of a visual search task are among the variables that determine the degree to which visual search is prioritised and shielded from the current content of visual working memory. However, this does not imply that these temporal factors are the only parameters that control memory-driven capture. For example, Olivers (2009) has recently demonstrated that capture effects are eliminated under varied mapping conditions where target identity changes from trial to trial, and suggested that the additional requirement of having to remember the current visual search target reduces the priority assigned to the current working memory content, and results in an effective separation of visual representations involved in memory and attention tasks.

Such an active separation and prioritization of the representations that are relevant for the two tasks may only take place when it is made necessary by current task demands, whereas the parallel activation of two task sets represents the default state. In line with this hypothesis, Soto et al. (2006a) found that patients with frontal lobe lesions had a much stronger tendency than age-matched controls to allocate attention to items matching the content of working memory. This supports the idea that, by default, representations associated with different task sets interfere with each other and an additional mechanism is necessary to segregate them. Further evidence for this assumption comes from the pattern of transfer effects across the two duration conditions observed in the blocked duration group: Participants who completed the long duration condition first showed larger attentional capture effects (i.e., less efficient separation between memory and attentional processing) in the short duration condition than did participants who started with the short duration condition. In contrast, capture effects in the long duration condition were generally larger, and remained unaffected by the order in which conditions were completed, in line with the idea that they represent a default state.

In summary, the present study has provided clear evidence that memory-driven attentional capture effects are strongly modulated by the predicted temporal demands of an attentional selection task. Effects of working memory on attentional selectivity are not automatic, as interactions between attention and working memory are controlled in a top-down fashion by current processing strategies.

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