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# On the difference between working memory and attentional set

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ABSTRACT

Previous work has shown that distractors present in a visual search display attract attention when they match objects kept in visual working memory. It seems that maintaining an object in working memory is functionally identical to adopting an attentional set for that object. We test this conjecture by asking observers to perform a memory task as well as a visual search task (in which memory-related distractors could return), but to leave the observer uncertain as to which of these tasks would have to be completed first. This way, observers ought to more readily look for the memorized information, rather than just remember it. Memory-related distractor effects were larger than when participants knew the order of the tasks beforehand, consistent with the idea that trying to attend to something involves additional processes or representations beyond those needed for simply storing an item.


Objects in the visual world compete for representation in our limited-capacity brains. This competition is biased according to the relevance of these objects to our behavioral goals: We attend to certain objects and ignore others depending on what we are looking for. This bias, often referred to as *attentional set*, is evident from experiments showing that when people are looking for a specific object property (e.g. red), then other objects in the visual field carrying the same property automatically attract attention (Eimer & Kiss, 2008; Folk, Remington, & Johnston, 1992).

How is this visual attentional set functionally implemented? Visual working memory appears the prime candidate to maintain the representations of what we are looking for, representations that then bias selection when the target really appears (Desimone & Duncan, 1995). Recent visual search studies have now indeed provided evidence that maintaining a memory for a visual feature is in principle sufficient for inducing an attentional bias towards that feature (Dombrowe, Olivers, & Donk, 2010; Olivers, Meijer, & Theeuwes, 2006; Olivers, 2009; Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006a). In these studies participants typically performed two tasks: First they were asked to memorize a specific feature (usually color), and then to search for a visible target object among several distractor objects. One of these distracters could carry the memorized feature. When it did, search times increased relative to when the distractor carried a different feature, or when the remembered feature no longer needed to be memorized. Such results have spawned the attractive hypothesis that working memory and attention are actually one and the same function (see Olivers, 2008, for a review).

However, although an active working memory representation may be sufficient to generate a selection bias, there remains the distinct possibility that looking for something involves more than merely remembering that thing. An attentional set for an object may involve additional operations or representations that *apply* the stored information to the perceptual input from the current scene. Initial evidence for a dissociation between the two functions comes from an experiment by (Woodman & Luck, 2007, Experiment 5). Like in the Olivers et al. and Soto et al. studies, observers memorized a color and then performed a search task for specific target. At the same time a distractor could carry the memorized color. Important for the present purpose, there were two main conditions: In what we will call the "never" condition, the search item matching the memorized color was never the target. If present, it was always a distractor. In contrast to Olivers and Soto and colleagues, Woodman and Luck (2007) found no additional search costs for the matching distractor – if anything they found a benefit (which was significant in some of their other experiments). In what we will call the "occasional" condition, the target occasionally matched the color of the memorized item, at chance level. This time Woodman and Luck found increased search costs when a distractor matched the memory content (as well as benefits when the target matched the memory content). On the basis of these findings, they argued that when observers know that the target can carry the memorized color, they may actively employ an attentional set for it. This implies that an attentional set for a color (inducing an attentional bias towards that color) is something different than a mere

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memory for that color (inducing either no bias or a bias against that color).

A number of issues may preclude such a conclusion though. The "never" and "occasional" conditions differed in more than just the frequency at which the target could carry the memorized color. For one, in the "occasional" condition, the memory test at the end of the trial always probed for color, whereas in the "never" condition it probed for shape or color, such that on 75% of the trials it sufficed to only remember shape. This may mean that in the "never" condition, color was less strongly represented. Second, the search tasks differed substantially between the two conditions, in terms of the shape of the items, but more importantly, the color configurations. In the "never" condition there was only one distractor (out of six in total) that matched the memorized color. In the "occasional" condition, there were three matching distractors, while the other three items all shared the color of the target item (or vice versa when the target carried the memorized color). This creates differences in display complexity, and may create differences in search strategy. Furthermore, the "never" condition consisted of two blocks of trials, while the "occasional" condition consisted of seven blocks, allowing for differential practice effects. Finally, and despite the additional practice, the "occasional" condition yielded RTs that were overall more than 100 ms slower than in the "never" condition. Each of these factors may have contributed to the differential findings with regard to the influence of memory on search.

The present study therefore sought to provide more direct evidence for the idea that an attentional set for a visual property, although it may require a working memory representation, indeed involves more than that. The experimental procedure is depicted in Fig. 1. In one condition, we asked observers to remember a color for a memory test at the end of the trial. In between the presentation of the to-be memorized color and the memory test, the participants performed a visual search task for a grey diamond target amongst grey disk distracters (see Fig. 1a). Crucially, one of the distractors could match the memorized item in color, or it could have a salient different color (Theeuwes, 1992). Memory-based attention effects were then measured as the RT increase for memory-related distractors (e.g. a different shade of red) relative to unrelated distractors (e.g. blue). To investigate whether such memory-related effects of the color are the same as having an attentional set for that color, we only manipulated the *order* in which the search task and the memory test were presented. All other factors, such as the memory test, search display appearance, and frequency of matching distractors remained identical.[1] Specifically, we compared performance in the described task sequence when order was fixed (*fixed order* condition), with performance in a condition where observers were uncertain as to which task would have to be completed first. In these *mixed order* conditions, on each trial, the memory item could be followed first by the search display (and then the memory test; as in Fig. 1a), or it could be followed first by the memory test (and then the search display; see Fig. 1b). The crucial difference of the mixed condition compared to the fixed condition is that the memorized information may be directly applicable to the very next display (which could be the memory test). In other words, in the mixed condition, observers would not only store the to-be-memorized information, they would also have an expectation for it to appear. Such an attentional set, if any different from simply storing a representation in working memory, would then be expected to add to the memory-related distractor effect observed in the fixed order conditions. In contrast, if working memory and attentional set are functionally identical, the size of this effect should be the same in both conditions.

Note that the mixed order condition may not only differ in terms of the active attentional set, but also in terms of the overall task load (two tasks need to be kept active), and the potential need for task switches when observers prepare more for one task than the other. Previous studies have shown that such overall load or task switch conditions can increase attentional capture by distractors (Lavie & De Fockert, 2005; Lavie, Hirst, de Fockert, & Viding, 2004). However, if so, such overall effects should not only occur for the memory-matching distractor, but also for the unrelated distractor.

## 1. Method

### 1.1. Participants

Twenty students aged 18–26 years participated for course credits or €10. Another participant was removed from analyses because RTs were more than 2.5 standard deviations slower than the group average.

### 1.2. Stimuli, apparatus, procedure and design

E-Prime (Psychology Software Tools, Inc.) was used to generate stimuli and measure responses. All stimuli were presented on a black background (~0 cd/m$^2$) at a viewing distance of 75 cm. Each trial started with a 500 ms instruction – reading "remember" – presented in gray (13 cd/m$^2$) at the center. This instruction was followed by the 1000 ms presentation of a colored disk (radius 1.5° visual angle). It could be any of four main colors (red, green, yellow, or blue, balanced across conditions). The specific hue and chroma of each color (Munsell, 1929) varied randomly between any of nine different combinations, while luminance value was kept constant at around 13 cd/m$^2$ (except for yellow, 42 cd/m$^2$, to make it appear less brown). Participants were instructed to remember the color. After a 2000 ms blank period, either of two tasks could start, depending on Task Order: In the first search then remember condition, the instruction "search" appeared in gray for 1000 ms, which was only there during practice. A visual search display followed until response, consisting of eight gray distractor disks (radius 1.2°) and one gray diamond-shaped target (diagonal 3.0°, all randomly varying between 11 cd/m$^2$ and 15 cd/m$^2$) placed on the rim of an imaginary circle centered on fixation (radius 5.3°). Participants were instructed to find the diamond as quickly and accurately as possible, and indicate whether there was an N or an M inside it (0.2° in size, presented in black), by pressing the corresponding keys with the left middle and index fingers. The letter discrimination task was likely to require an eye movement towards the target. Participants were instructed to minimize eye movements, but to make one if necessary. The distractors contained a symbol resembling an hour glass on its side, matching the line segments of the N and M. A feedback message followed erroneous responses.

The visual search display was followed by a blank display for 500 ms, after which the memory test was presented. This consisted of a central row of three disks of different colors, including the memorized color, in randomized order. To discourage verbal recoding of the color, and promote a more visual memory representation instead, the alternative colors were drawn from the same category (e.g. red) and differed only subtly in shade Participants indicated the memorized color by pressing either "1", "2", or "3" on the numeric keypad, with the right index, middle and ring fingers. This task was unspeeded. An error was followed by feedback. The trial ended with a 1000 ms blank.

In the first remember then search condition, the procedure was the same, but the search task and the memory test were swapped, so that 2000 ms after the to-be-memorized cue, first the memory test appeared. Then, 1000 ms after completion of the memory test, the search display appeared. We chose a longer delay here between the memory test and the search display (compared to the 500 ms between the search display and the memory test in the search first condition) to allow participants to prepare for the speeded search response. Note that this timing difference is not crucial, since (a) it happens *after* the search, and (b) the crucial comparison is between exactly the same sequence of tasks and displays, except that one occurs in a fixed order condition, the other in a mixed order condition, as is explained next.

The critically important factor was Block Type: Search order was either fixed within blocks, or randomly mixed. The final important condition was Distractor Type, of which there were three levels, randomly mixed within blocks: In the no distractor baseline condition, all disks were gray. In the unrelated distractor condition one of the disks was given a color unrelated to the memory item (e.g. green

[1] For the same reason, we did not use the following manipulation even though on the face of it may appear a simpler test of our hypothesis: One could compare a condition in which participants remember a color and the search for a target that may coincidentally carry the memorized color (thus measuring working memory effects on search) to a condition in which participants remember a color and know that the target will always carry that color (cf. Woodman & Luck, 2007). However, this creates inequalities in terms of memory load (in one condition a color and the target-defining feature need to be remembered, in the other only a color), which is known to affect the results (Olivers, 2009). Furthermore, it may create differences in other processes than the selection processes we are interested in. For example, having valid information about two target features (namely its color and identity) reduces uncertainty in post-selective decision processes, compared to when only one feature is available.

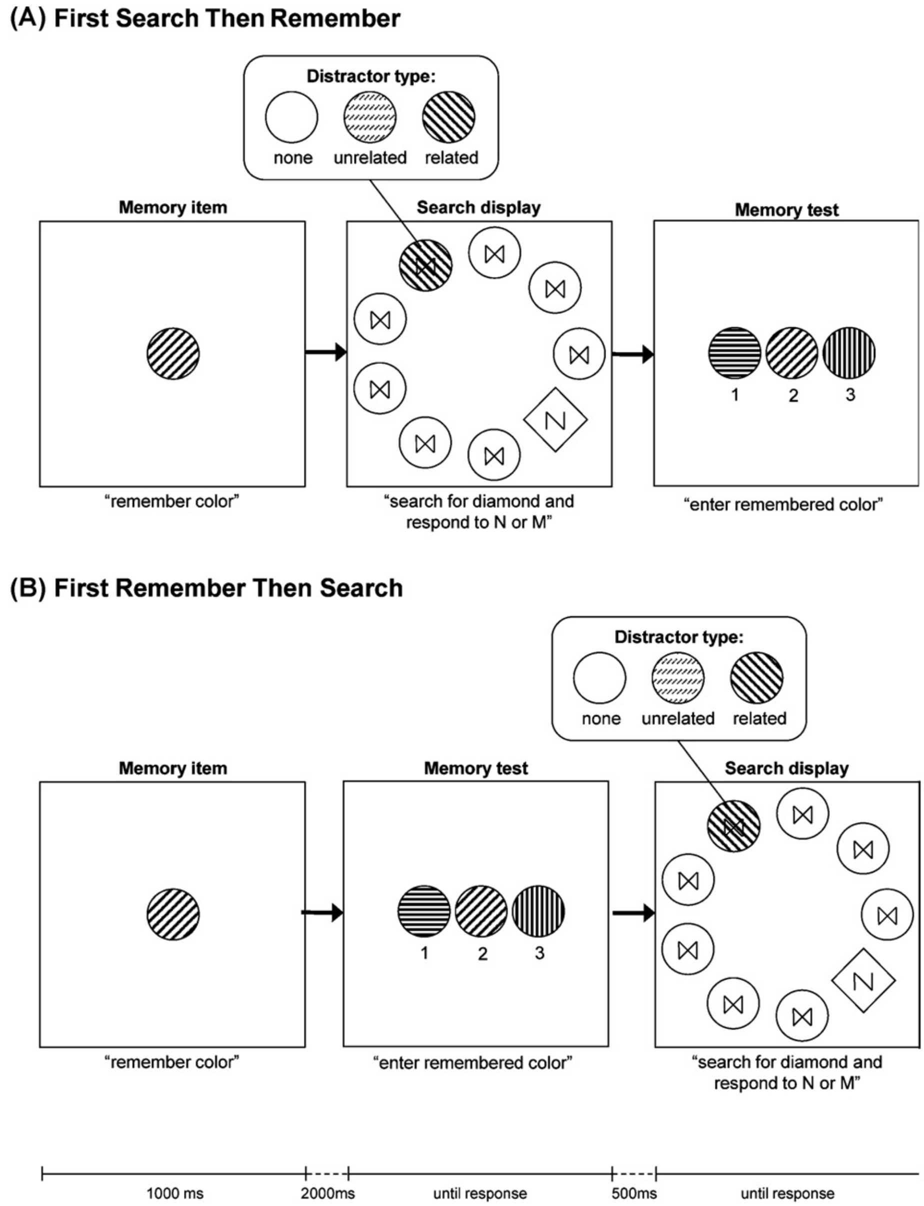


**Fig. 1.** Experimental procedure and example stimuli for Experiment 1. Observers were required to remember a color. In the First Search Then Remember condition (A), they then performed a search for a diamond shape and responded to the N or M inside. At the end of the trial, observers chose the color they remembered from three alternatives. In the First Remember Then Search condition (B), the two tasks were reversed. These two task orders were either fixed, or were randomly mixed within blocks.

when the memory item was red). In the related distractor condition it was given a color that was related (but never identical) to the memory item, by drawing it from the same color category, but with a different hue and/or value (e.g. fuchsia when the memory item was more rusty). Participants were told that distractors were irrelevant and could only interfere with both search and memory.

Participants first practiced a First Remember Then Search block, then practiced a First Search Then Remember block, and then practiced the two conditions mixed within a block. This was followed by 9 blocks (3 First Remember Then Search, 3 First Search Then Remember, 3 Mixed) presented in counterbalanced order, with breaks in between. Each block consisted of 16 Related Distractor trials, 16 Unrelated Distractor trials, and 16 No Distractor trials, randomly mixed. In total, there were 48 trials per cell for the fixed order condition, and 24 trials per cell for the mixed order condition.

## 2. Results

The analyses focused on the mean search RTs for the correct responses. Search responses that were incorrect (3.5%) or that fell outside a 300–3000 ms time frame (0.8%) were removed from the RT analyses. We first assessed whether changing task order and mixing these orders had any overall effects, as would be the case when observers were confused, or actively preparing for a particular order that may then be violated. For this we looked at the no distractor baseline condition. Table 1 shows the mean no distractor baseline RTs and error percentages. An ANOVA with Task Order (first search then remember vs. first remember then search) and Block Type (fixed vs. mixed task order) as factors revealed no effects for RTs, all $Fs < 1.25$, all $ps > .275$, or errors, $Fs < 2$, $ps > .17$.

**Table 1**
Baseline search RTs and error percentages (between parentheses) in the no distractor conditions.

| Block type | Task order | |
|---|---|---|
| | First search then remember | First remember then search |
| Fixed order | 901 ms (3.4%) | 907 ms (3.7%) |
| Mixed order | 889 ms (4.8%) | 905 ms (2.8%) |

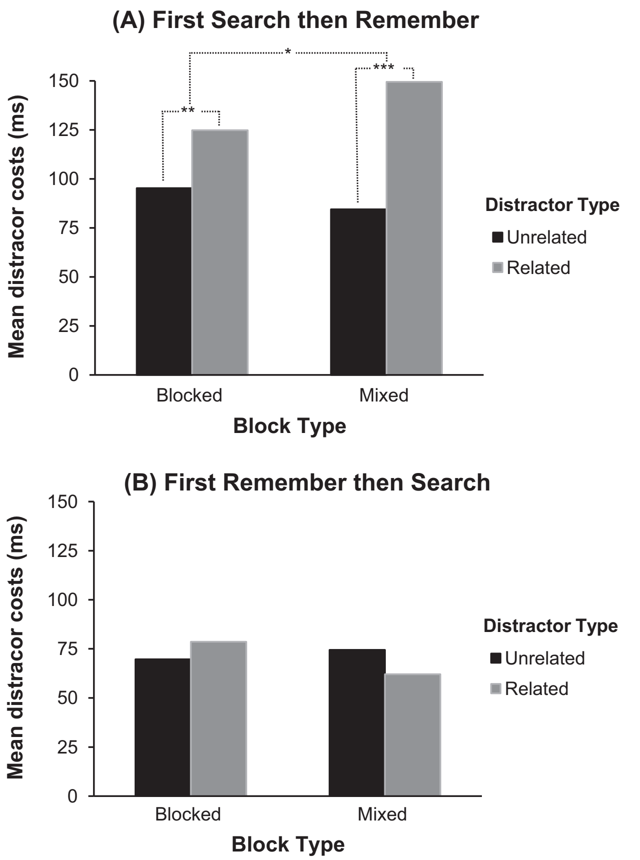


**Fig. 2.** Average distractor costs for memory-related and memory-unrelated distracters as a function of task order (Panel A, first search, then complete the memory task; Panel B, first complete the memory task, then search) and block type (whether task order was fixed or mixed within blocks). $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$.

The next question was how working memory content modulated the distractor interference effects in the visual search task, depending on expectations of task order (i.e. mixed or fixed order). To this end, we calculated the net distractor costs by subtracting the no distractor RTs from the related and unrelated distractor conditions. The crucial comparison was between the fixed and mixed order conditions when participants performed the visual search display *before* the memory test – that is, while the memory item was still relevant. This comparison is shown in Fig. 2a. In this first search then remember condition, an ANOVA with Distractor Type (related vs. unrelated) and Block Type (fixed vs. mixed order) revealed an overall effect of Distractor Type, $F(1, 19) = 18.9$, MSe = 2388.21, $p < 0.001$. Related distracters resulted in more interference than unrelated distracters. Moreover, this effect was stronger in the mixed blocks than in the fixed blocks, as reflected in a Block Type × Distractor Type interaction, $F(1, 19) = 5.87$, MSe = 1073.62, $p = 0.026$. Two-tailed $t$-tests indicated a 30 ms memory-related cost when the search task preceded the memory test in the fixed order blocks, $t(19) = 3.63$, $p < 0.01$, but a 65 ms effect in the mixed order blocks, $t(19) = 3.89$, $p < 0.001$. There was no overall effect of mixing task order, Block Type, $F < 1$, $p > 0.6$, indicating that general task confusion or task switching did not play a major role.

On the basis of previous work, we expected no memory effects on distractor interference when the memory task could be completed before the search task, since the memory item would then be no longer relevant (Olivers et al., 2006). This was also the case here in the first remember then search condition, as shown in Fig. 2b. The ANOVA revealed no effect of Distractor Type or Block Type ($F$s < 1, $p$s > .6), nor an interaction ($F < 1.5$, $p > .24$). This confirms that the memory item only affects search when it is still active. The fact that the first search then remember condition saw effects of memory on search, depending on expected task order, while the first remember then search condition did not, was further confirmed by an omnibus ANOVA showing a three-way Task Order × Block Type × distractor Type interaction, $F(1, 19) = 4.98$, MSe = 1629.09, $p < 0.05$.

The same analyses on search errors only revealed a trend towards a main effect of Task Order, $F(1, 19) = 3.95$, MSe = 0.002, $p = 0.062$. The presence of a distractor led to 1.5% more errors when the search task preceded the memory task rather than vice versa. Memory accuracy was 58.6%, which was comparable to previous studies with this paradigm (Olivers et al., 2006; Olivers, 2009), and significantly above chance level (33%, $t(19) = 23.2$, $p < 0.001$). Except for a main effect of Task Order, $F(1, 19) = 32.26$, MSe = 0.009, $p < 0.001$, there were no effects (all $F$s < 1.25, all $p$s > 0.3). As expected, observers performed better when they received the memory test immediately after they had seen the memory item (62.2%), as compared to when they first had to complete the search task (55.2%).

## 3. Discussion

As in previous studies (Dombrowe et al., 2010; Olivers et al., 2006; Olivers, 2009; Soto et al., 2005, 2006a), distractors that were similar to the contents of working memory caused stronger interference with visual search than unrelated distractors. When observers completed the memory task first and could thus forget about the color, there was no memory-based distractor effect. This indicates that the effects were due to the active maintenance of visual information, and not due to sensory priming. Thus, there appears to be little doubt that working memory and attention operate at least partly on similar representations. However, the results also indicate that looking for something involves stronger biases towards visual feature representations than a memory for that feature alone would do. Memory-related distractor interference was twice as strong when the stored information could be directly applicable to the next visual display (i.e. in mixed blocks), compared to when it would not be immediately required (i.e. in fixed blocks). Note that there is no sign that this increase should be attributed simply to increased task confusion: The mixing of the two task orders did not result in any slowing in the no-distractor condition, nor did it result in additional costs for the unrelated distractor condition. Instead, the increase was specific for the related distractor condition. Observers reported that it was clear from the displays which task should be performed. Furthermore, any overall task confusion or load effects are likely to result in a weaker attentional set for the relevant property (in this case the memorized color), rather than a stronger one (Lavie et al., 2004). We conclude that observers maintained a memory representation for the color in both the blocked and the mixed condition, but had a stronger attentional set for that same color in the latter. Thus, we interpret this as positive evidence that an attentional set should be functionally dissociated from working memory.

Note that memory-based distractor effects only occurred when the color was still relevant. That is, when observers completed the memory task first and could thus forget about the color, there were no such effects. This shows that the memory-based distractor effect is due to the active maintenance of the color information and not for example due to low-level visual priming mechanisms. Interestingly, if we look at the First Remember Then Search condition in the mixed blocks (Fig. 2b), we actually see a small memory-related benefit (−12 ms), rather than a cost. Although this numerical difference was not reliable, it raises the intriguing idea that observers may actually *inhibit* the memorized color after they have performed the memory test, so that they can more easily switch to the search task (e.g. Mayr & Keele, 2000). The inhibition of this color may then carry over to the matching distractor in the search display, thus actually reducing its interference relative to an unrelated distractor. To investigate if this evidence for inhibition after the completion of the memory task was real, we ran another experiment using mixed order, and also varied the interval between the memory test and the search task between 500 and 2500 ms to see if we could maximize the effect. However, we now found no benefits at all for memory-related distractors (a maximum benefit of 1 ms), thus providing no further support for the idea of inhibitory control processes operating between the two tasks.

What is the nature of the additional processes when people adopt an attentional set for a visual property, rather than keep that property active in working memory? One possibility is that attention and working memory are qualitatively different: When looking for something, observers create a separate target representation that then biases lower-level perceptual representations via a different route than working memory does. A more parsimonious model however is one in which attention serves to strengthen a specific memory representation, which then in turn feeds back to perceptual representations. In purely representational terms, the difference between an attentional set and a memory for an object is then essentially quantitative: The same representation is simply stronger under conditions of attention. However, in terms of processes, the difference between the two cognitive functions then still retains a qualitative aspect, because additional control mechanisms must be recruited that select a target and drive the increased activation. Such mechanisms must eventually originate from a higher-order task representation – or the "central executive" in Baddeley and Hitch's (1974) classic model – which after all determines what is currently important. In this respect it has been proposed that there may actually be two types of working memory representation (Cowan, 1995; Oberauer, 2002; Peters, Goebel, & Roelfsema, 2009; see Olivers, 2009 for evidence within the current paradigm). When working memory is filled with multiple items, most of these will be in a relatively suppressed or dormant state of representation. That is, they are readily available, but are not the focus of the current task. Only one representation at a time can acquire the special status of being in the focus of attention and determine what we are currently looking at or thinking of (Houtkamp & Roelfsema, 2009). Items in working memory may then compete for this special status of the attentional template, a competition that is driven by overall task settings. Consistent with this, items in working memory lose their effects on visual search when another memory item is more relevant to the search task (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, 2009). Moreover, when the task goals change, a switching of the template is necessary, which may take time. Indeed, recent studies have shown memory effects on visual search when search is fast and starts early, but not when it is slow or starts late (Dombrowe et al., 2010; Han & Kim, 2009). To summarize, the attentional set may be an integrated part of working memory, yet involves operations that are functionally different from mere working memory activation.

So far we have framed the memory effects on visual selection as a one-way process in which the active content biases perceptual processes. This relationship may be more interactive though. It could be that the colored distractor in the search display initially captures attention in a more bottom-up, stimulus-driven fashion, and that attention is then rapidly disengaged from this distractor because it is not relevant in the context of the visual search task (see Theeuwes, Atchley, & Kramer, 2000, for such a suggestion). The RT costs associated with the capture and disengagement of attention may have been more pronounced for memory-related distractors in the mixed blocks of the current experiment because capture is stronger and/or disengagement is more delayed for colored items under conditions where both the attention and the memory task are active. Note however that such task-based interactions do not take away from our conclusion, namely that an attentional set for a property involves more than an active memory representation for that property. By "more" we mean the specific quality that distinguishes an attentional set from other attentional biases, namely the fact that it is based on current task relevance.

As with many attentional control functions, the prefrontal cortex is probably the source of the signal deciding which memory representation deserves this special status. The prefrontal cortex is known to be involved in setting task priorities, possesses the necessary feedback connections to implement and sustain biases in more sensory-related areas, and may thus well be the seat of the central executive (Miller & Cohen, 2001). Direct evidence for the prefrontal cortex setting priorities in the current type of task comes from a neuropsychological study of Soto, Humphreys, and Heinke (2006b). In a paradigm similar to the one used here, it was found that for patients with inferior frontal lesions, visual search was much more affected by the irrelevant memory content than for age-matched controls. Apparently, the patients had more difficulty separating the working memory and search representations. Conversely, this implies that under normal functioning, working memory and attentional representations can be kept relatively shielded from each other. In all, we conclude that working memory and attention may share the same content representations, but that they are not identical functions.

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