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What Drives Memory-Driven Attentional Capture? The Effects of Memory Type, Display Type, and Search Type

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An important question is whether visual attention (the ability to select relevant visual information) and visual working memory (the ability to retain relevant visual information) share the same content representations. Some past research has indicated that they do: Singleton distractors interfered more strongly with a visual search task when they were identical or related to the object held in memory. However, other research has failed to find such effects despite using very similar procedures. The present study, using the same combined working memory and attentional capture paradigm, demonstrates which factors do (varied mapping, low stimulus energy) and which factors do not (exact type of visual memory method used, difficult nature of search, heterogeneity of displays, and instruction) contribute to this discrepancy.

Keywords: short-term memory, visual working memory, visual attention, attentional capture, saliency

For a long time, psychologists have been interested in how what is currently on our minds affects what we currently look at (Desimone & Duncan, 1995; Farah, 1985; Pashler & Shiu, 1999; Pillsbury, 1908; Sreenivasan, Katz, & Jha, 2007). Recent research on the interactions between visual working memory and visual attention fits in this tradition (e.g., Awh & Jonides, 2001; Downing, 2000; Oh & Kim, 2004; Olivers, Meijer, & Theeuwes, 2006; Soto & Humphreys, 2006). The underlying idea is that visual attention and visual working memory share important processes as well as content representations. After all, functionally, working memory and attention appear very similar, in that both psychological constructs postulate the activation and prioritization of information relevant to the task at hand over information that is currently irrelevant. Moreover, neurophysiological and brain imaging studies have shown a striking overlap in brain areas active during attention and working memory tasks (Cabeza & Nyberg, 1997, 2000; Corbetta & Shulman, 2001; D'Esposito, 2001; Fuster, 1997; Handy, Hopfinger, & Mangun, 2001; Kanwisher & Wojciulik, 2000; Kastner & Ungerleider, 2000). This has led to the hypothesis that visual attention and visual working memory are virtually one and the same—the latter being regarded as attention directed to visual representations in the absence of the actual visual stimulus itself (see Awh, Vogel, & Oh, 2006; and Olivers, 2008, for recent reviews). A clear prediction from this is that when a stimulus is held in visual working memory, and the same stimulus then appears in reality, it should receive priority over other objects in the field, because its visual representations have already been pre-activated. In other words, a memorized object should capture attention.

Note that this prediction is less trivial than it may seem. Indeed, we know from studies on contingent attentional capture that when observers are looking for something specific, objects matching the target object will involuntarily capture attention (Folk, Leber, & Egeth, 2002; Folk, Remington, & Johnston, 1992; see Moores, Laiti, & Chelazzi, 2003, for evidence that contingent capture may even occur at a semantic level). Apparently, observers adopt an attentional set for relevant information but cannot fully avoid selection of similar, but irrelevant information. Moreover, it is more than likely that such an attentional set involves a good deal of working memory, especially when a task is new. After all, one needs to remember what one is looking for. However, the question discussed here is not one of attentional set. The question is not whether involuntary attentional capture occurs on the basis of a representation of something that one is currently looking for. The question is whether involuntary attentional capture occurs on the basis of a representation of something that one is currently *not* looking for but still trying to visually hold on to for later use. Note further that by "involuntary" I mean an automatic but not a pure bottom-up attentional mechanism. After all, the capture is assumed to be contingent on the content of working memory and thus dependent on top-down context. In other words, capture here is memory driven and not stimulus driven.

Evidence From Visual Search

Evidence for the memory-driven attentional capture hypothesis comes from a number of visual search studies, including one by Olivers, Meijer, and Theeuwes (2006). I will describe this study first in some detail, as this will help in clarifying later arguments. Figure 1A shows the main procedure. Observers were asked to remember a particular color (red, green, blue, or yellow). At the end of the trial, their memory was tested by asking them to choose the original color from a set of three alternatives. There were two versions of the memory task. In what was assumed to be the *more verbal* version, the memory test consisted of easily distinguishable

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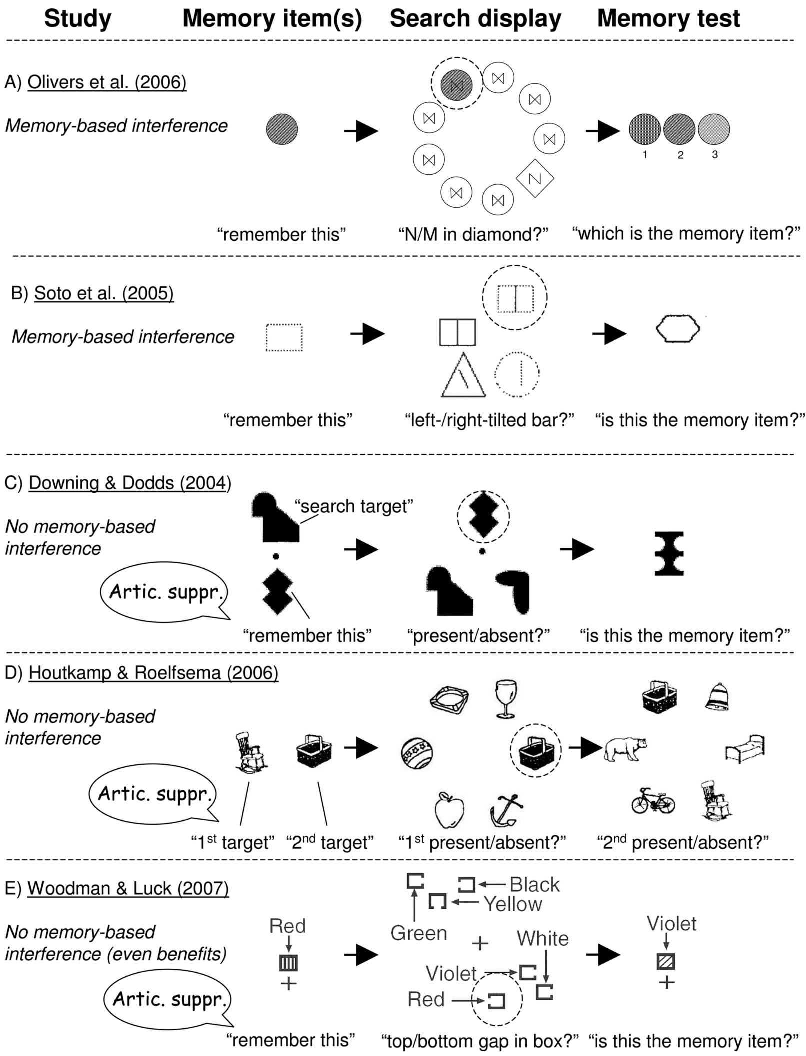

Figure 1. Display types. A: Olivers, Meijer, and Theeuwes (2006). From "Interactions Between Visual Working Memory and Visual Attention," by C N. L. Olivers, F. Meijer, and J. Theeuwes, 2006, *Journal of Experimental Psychology: Human Perception and Performance, 32,* p. 1245. Copyright 2006 by the American Psychological Association. B: Soto, Heinke, Humphreys, and Blanco (2005). From "Early, Involuntary Top-Down Guidance of Attention From Working Memory," by D. Soto, D. Heinke, G. W. Humphreys, and M. J. Blanco, 2005, *Journal of Experimental Psychology: Human Perception and Performance, 31,* p. 250. Copyright 2005 by the American Psychological Association. C: Downing and Dodds (2004). From "Competition in Visual Working Memory for Control of Search," by P. E. Downing and C. M. Dodds, 2004, *Visual Cognition, 11*, p. 689. Used with permission of Taylor & Francis Ltd. (http://www.informaworld.com). D: Houtkamp and Roelfsema (2006). From "The Effect of Items in Working Memory on the Deployment of Attention and the Eyes During Visual Search," by R. Houtkamp and P. R. Roelfsema, 2006, *Journal of Experimental Psychology: Human Perception and Performance, 32,* p. 425. Copyright 2006 by the American Psychological Association. E: Woodman and Luck (2007). From "Do the Contents of Visual Working Memory Automatically Influence Attentional Selection During Visual Search?," by G. F. Woodman and S. J. Luck, 2007, *Journal of Experimental Psychology: Human Perception and Performance, 33,* p. 365. Copyright 2007 by the American Psychological Association. Note that studies C, D, and E also used articulatory suppression (Artic. suppr.) tasks in various conditions.

alternatives for which verbal labels were readily available, for example "red" or "green." In this task it is sufficient to store the verbal label without having to put much effort in trying to create a visual memory of the exact shade of red. In contrast, in the *more visual* version, the to-be-remembered color had to be distinguished from highly similar colors from the same category. For example, a particular shade of red had to be distinguished from other shades of red. It was assumed that observers would use their visual working memory—probably not exclusively so, but more so in this condition than in the more verbal condition.

Then, a few seconds after the to-be-remembered item had disappeared, the task changed to a visual search task. The target was always a gray diamond among gray disk-shaped distractors. Participants responded to the identity of the letter presented inside the diamond. On many trials, however, one of the distractors carried a unique color. Previous studies have shown that such salient distractors capture attention, as indicated by elevated response times (RTs) relative to conditions in which no such distractor is present (Theeuwes, 1991, 1992). The important finding here was that the interference was stronger for distractors that matched the content of memory than for unrelated color distractors. The other important finding was that this was the case only for the *more visual* memory condition. In the *more verbal* condition, there was no effect of the relationship between the visual distractor and the contents of memory. Note that participants had no reason to attend to the distractor: It only interfered with the goal of responding to the gray diamond. Thus, these results are consistent with the idea that visual working memory and visual attention share the same content. Moreover, follow-up experiments excluded a number of alternative explanations in terms of implicit perceptual priming, perceptual encoding, strategic memory updating, and delayed attentional disengagement.

Around the same time, Soto and colleagues published a series of similar experiments with very similar results (Soto, Heinke, Humphreys, & Blanco, 2005; Soto, Humphreys, & Heinke, 2006a, 2006b). Their task is illustrated in Figure 1B. Participants were asked to remember both the shape and the color of an object (e.g., a blue triangle) until the end of the trial (when either of these properties could be tested). After the to-be-remembered object, a visual search display appeared in which the target was a tilted bar among vertical bars. Each bar appeared inside a colored shape, one of which could match the remembered object (in color, shape, or both). Soto and colleagues found search to be faster when the matching object surrounded the target bar and slower when it surrounded one of the distractor bars. As the matching object was not predictive of the target, Soto and colleagues concluded that the contents of working memory automatically guide attention.

Counterevidence From Visual Search

It is interesting that a couple of years earlier, Downing and Dodds (2004) had failed to find any interactions between working memory content and visual search using, again, very similar procedures. An example of their displays is shown in Figure 1C. On each trial, they presented observers with two meaningless shapes. One shape had to be remembered for the memory test concluding each trial (the memory object), and the other shape was the target for the subsequent search task. As in the studies described above, the memory object could return as a distractor in the visual search task. However, this time there was no effect (despite an admirable number of attempts): Search RTs were not affected by the presence or absence of a memory-matching distractor. Downing and Dodds concluded that attentional and mnemonic representations can be separated and/or differentially prioritized.

The Downing and Dodds (2004) study is not the only one that reached that conclusion. Houtkamp and Roelfsema (2006) also failed to find a clear effect of memory-matching distractors on visual search. Their procedure is outlined in Figure 1D. Observers were instructed to conduct two visual search tasks in a row, using two consecutive displays of everyday objects. The two search targets changed from trial to trial and were presented prior to the search displays. Thus, while the participant searched for one target in the first display, the target for the second display presumably had to be kept in working memory. The crucial manipulation was that the second target could be presented as a distractor in the first display. However, this did not lead to increased search RTs when the first target was also present (it did slightly when the first target was absent).

Again using very similar procedures, Woodman and Luck (2007) too failed to find evidence for memory-driven attentional capture. On the contrary, they even found evidence for faster search when distractors matched the content of visual working memory (a similar effect actually also occurred in some conditions of Downing and Dodds, 2004). An example from Woodman and Luck's procedure is shown in Figure 1E. Participants were asked to remember a colored outline box with a gap on one of its sides, after which they searched for another box with a gap at the top or bottom. The memorized item could return as a distractor. When it did, there was no increase in search RTs, and in some conditions Woodman and Luck even found a significant decrease. They concluded that the memory content does not lead to automatic attentional capture and can even be flexibly utilized to inhibit and avoid matching distractors.

The Present Study

We are left with contradicting results. There are studies pointing toward automatic memory-driven attentional capture in visual search (Olivers et al., 2006; Soto et al., 2005, 2006b), whereas other studies, using comparable procedures, have failed to find such capture effects or even report memory-driven inhibition (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Woodman & Luck, 2007). In the present study, I explored a number of factors that might account for this discrepancy. Even though experimental procedures were overall very similar, some relatively subtle but crucial differences may account for the different results. For example, the studies that failed to find a memory effect used an additional articulatory suppression task to enforce the use of visual working memory, whereas the studies that found an effect did not use such a task. Experiment 1 therefore looked at the consequences of using an articulatory suppression task. Experiment 2 investigated whether differences in display heterogeneity might play a role, whereas Experiments 3 and 4 looked at the effects of difficult versus easy search. Experiments 3 and 4 also looked at the effects of similarity between search target and memory item, as well as distractor ratio. Experiment 5 tested the hypothesis that the consistency (vs. variability) of the target template from trial to trial plays an important role—a hypothesis first raised by Oh and Kim (2003). Experiment 6 investigated the influence of low-level stimulus energy on memory-based capture effects. Finally, Experiment 7 explored whether different instructions might have an effect on whether memory-driven attentional capture occurs or does not occur.

Experiment 1: Articulatory Suppression Versus Difficult Distinction

Olivers et al. (2006) found memory-driven attentional capture when, at the memory test at the end of the trial, the to-be-memorized color was difficult to distinguish from the other two alternatives (as they were drawn from the same color category, e.g., all red). Memory accuracy was around 60%–65%. No memory-driven capture effects were found when the colors were easy to distinguish (as they were drawn from different categories, e.g., red, yellow, and blue), and performance was up at 95%. Olivers et al. referred to the difficult and easy distinction conditions as the *more visual* and *more verbal* conditions as it was likely that observers had to rely more on their visual memory in the former but could rely on their verbal memory in the latter. The use of a more visual memory thus appears crucial for obtaining interactions with visual memory.

The studies that failed to find a memory-driven effect used different methods to induce visual rather than verbal memory, all involving additional articulatory suppression tasks. At least two of these studies used stimuli that were in principle easy to verbalize (i.e., distinctive color categories and everyday objects; Houtkamp & Roelfsema, 2006; Woodman & Luck, 2007). Given the overall high memory performance in these studies (above 90%), it is possible that the articulatory suppression task was not as effective in preventing verbal labeling of the stimuli as was the difficult distinction task used by Olivers et al. (2006). Downing and Dodds (2004), in addition to an articulatory suppression task, used a wide range of meaningless shapes that were presumably hard to verbalize. Yet, with accuracy at 70%–80%, here too the memory task may have been a little easier than in Olivers et al. (2006), possibly allowing for some leakage from visual to verbal memory.

Alternatively, the presence of an additional task may hinder memory-based effects because the participant now needs to coordinate three tasks rather than two. The extra task burden may go at the expense of the initiation or fidelity of the visual memory representation (and thus at the expense of capture effects), especially since such representations require some effort to maintain. This may occur without memory performance noticeably suffering because the memory task was so easy to start with. In support of this, Soto and Humphreys (2008) recently found reduced memory-based interference when the memory task was accompanied by an articulatory suppression task.

To test whether the articulatory suppression task is at all effective in inducing visual working memory, or perhaps even hinders it, the present experiment repeated the easy distinction (*more verbal*) and difficult distinction (*more visual*) conditions of Olivers et al. (2006; see Figure 1A) but added an articulatory suppression task (identical to the one used by Woodman & Luck, 2007). Thus, in the easy distinction memory task, the only method for inducing visual working memory was the presence of the articulatory suppression task. This condition is referred to as the *articulatory suppression only* condition. According to the verbal memory hypothesis, the easy distinction may still allow for verbal categorization, and thus we should not see a memory-driven attentional capture effect, unless the articulatory suppression task is successful. In the *articulatory suppression + difficult distinction* condition, the colors used in the memory test were difficult to distinguish. Together with the articulatory suppression task, this should result in the use of predominantly visual working memory representations and, thus, a memory-driven attentional capture effect—unless the additional burden of the articulatory suppression task in any way hinders the creation or maintenance of such representations.

Method

Participants. Twelve volunteers, aged 18 to 28 years (average 21.3 years) participated in exchange for a payment of €7 per hour. Two participants were male, and 2 were left-handed. All reported having normal or corrected-to-normal acuity and color vision. One participant was replaced because he performed at chance level on the memory task and produced an RT effect 10 times the group average.

Stimuli, apparatus, procedure, and design. A HP Compaq d530 CMT Pentium IV computer running E-Prime (Psychology Software Tools, Inc., Pittsburgh, PA) generated the stimuli on an Iiyama Vision Master Pro 454 SVGA 120 Hz screen and acquired the necessary response data through the standard keyboard. All stimuli were presented on a black background (~0 cd/m^2) at a viewing distance of 75 cm. During the practice part, each trial started with a 500-ms instruction—reading *repeat*—presented in gray (13 cd/m^2, letter height 0.2°) at the center of the display. This instruction was followed by the 500-ms presentation of two centered gray digits, which the participant was required to repeat out loud throughout the remainder of the trial (until the memory test), at a rate of about four digits per second. The digits were drawn from the set 2 to 9 and were 1.0° in height.

After a 1,000-ms blank, the instruction term *remember* appeared for 500 ms. The instruction referred to what the participant should do with the subsequently presented item, which was a colored disk (radius 1.5° visual angle), presented for 1,000 ms at the center of the display. It could be any of five main colors (red, green, yellow, blue, or magenta) as was randomly determined with the constraint that each color featured equally often in each condition. Furthermore, for each color, the specific hue and chroma could vary randomly between any of nine different combinations chosen on the basis of Munsell's (1929) color system. The value (brightness) of each color was roughly kept constant at around 13 cd/m^2, except for yellow, which was overall brighter (42 cd/m^2) to make it appear less brown. These were only approximations of Munsell's original colors, due to screen limitations.

Participants were informed that the memory task was separate from the visual search task and were asked to remember the color. The initial disk was then followed by a 1,500-ms blank period, after which another instruction term appeared for 900 ms, reading *search* (in gray, 13 cd/m^2, letter height 0.2°). This was followed by a visual search display, 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°). The search display remained visible until response. Participants were instructed to find the diamond as quickly as possible without making too many errors and to indicate whether there was an *N* or an *M* inside it (0.2° in size, presented in black), by pressing *N* or *M* on the keyboard with the left middle and index finger, respectively. In case of an incorrect response, a feedback message (*Incorrect!*) appeared for 100 ms. Inside the distractors a black symbol resembling an hour glass on its side was drawn (×; matching the line segments of the *N* and *M*), to which no response was required.

There were two *singleton distractor type* conditions, which were randomly mixed within blocks: In the *unrelated* condition (50% of the trials), one of the gray disks was replaced with a disk of a color unrelated to the memory item (e.g., green when the memory item was red). In the *related* condition (50% of the trials), one of the gray disks was replaced with a disk of a color that was related (but never identical) to the memory item, by drawing it from the same color category, but giving it a different hue and/or value (e.g., it might be dark red when the memory item was orange red). Participants were informed about the possible relatedness of the distractor but were told that this was irrelevant to the task.

After 500 ms, the visual search display was followed by the memory test. This consisted of a central row of three disks of different colors, including the memorized color, in randomized order. Below the disks were the numbers 1, 2, and 3. The participants were instructed to indicate the memorized color by pressing *1*, *2*, or *3* on the numeric keypad, with the right index, middle, or ring finger, respectively. An incorrect response was again followed by an *Incorrect!* feedback message for 750 ms. There were two types of memory task, which were blocked, and they differed only in the type of memory test presented at the end of the trial: In the memory test of the articulatory suppression only condition, the participant was required to distinguish the memorized color (e.g., red) from two other main colors (e.g., green and blue). Because the colors were so different, a verbal representation would in principle suffice to do the task if it were not for the simultaneous articulatory suppression task. In the articulatory suppression + difficult distinction condition, observers had to distinguish the memorized color (e.g., red) from other shades of the same color (e.g., a slightly less saturated red and a slightly more rusty red). These shades were randomly chosen from the nine different chroma and hue combinations mentioned earlier. The idea was that a verbal label would be less useful.

All participants first practiced the articulatory suppression only condition for 20 trials, then the articulatory suppression + difficult distinction condition for another 20 trials. After practice, four blocks of each condition were completed in alternating order, counterbalanced across participants (resulting in a total of eight blocks). During the real experiment the instruction terms *repeat*, *remember*, and *search* were replaced with fixation crosses (+). Each block consisted of 30 trials: 15 related singleton distractor trials and 15 unrelated singleton distractor trials, randomly mixed. There were breaks between blocks, in which participants were notified of their search RTs, search accuracy, and memory accuracy. If memory accuracy dropped below 67%, participants received another request to try their best on the memory task. The experiment lasted about 45 min in total.

Results and Discussion

RTs. RTs shorter than 200 ms and longer than 3,000 ms were excluded, resulting in a loss of 0.69% of data points. Figure 2 shows the mean of the remaining correct RTs, as a function of memory task (articulatory suppression only vs. articulatory suppression + difficult distinction) and singleton distractor type (unrelated vs. related). A within-subject analysis of variance (ANOVA) with these same factors revealed a main effect of memory task, $F(1, 11) = 6.51$, $MSE = 3{,}022.72$, $p < .05$, $\eta_p^2 = .372$, and a main effect of singleton distractor type, $F(1, 11) = 11.17$, $MSE = 783.00$, $p < .01$, $\eta_p^2 = .504$, with no interaction, $F < 1$. Averaged across memory task, 11 of the 12 participants showed a memory-related cost. RTs were overall higher when the memory task was more difficult. Regardless of the type of memory task, RTs were higher when singleton distractors were related to the memory content than when they were unrelated.

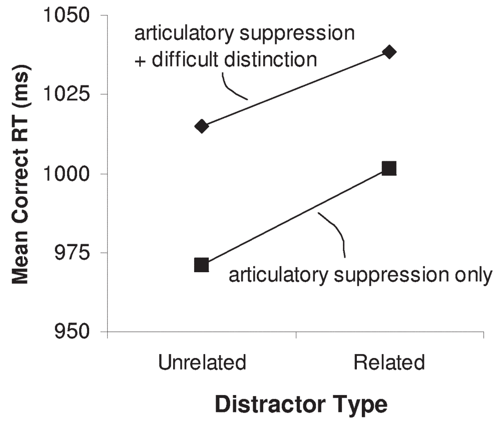

Figure 2. Response time (RT) results of Experiment 1 when singleton distractors were unrelated or related to the memory content, under different visual memory representations (articulatory suppression only or in combination with a difficult distinction at memory test).

Errors. In the articulatory suppression only condition, search errors amounted to 5.8% when singleton distractors were related and 5.4% when singleton distractors were unrelated. In the articulatory suppression + difficult distinction task, errors were 5.2% and 4.2%, respectively. None of these differences were significant, all Fs < 2.3, ps $> .15$. Memory errors were more substantial, especially in the articulatory suppression + difficult distinction condition. In that condition, 34.6% errors were made when distractors were related and 40.3% when distractors were unrelated. In the articulatory suppression only condition, those percentages were 4.6% and 7.3%, respectively. The main effect of memory task was significant, $F(1, 11) = 165.14$, $MSE = 0.007$, $p < .001$, $\eta_p^2 = .938$, as was the main effect of singleton distractor type, $F(1, 11) = 9.05$, $MSE = 0.002$, $p < .02$, $\eta_p^2 = .451$. There was no interaction, $F < 1$. The overall better memory performance after related distractors is somewhat unexpected, since one imagines that a closely related color would interfere more with one's color memory. There is the possibility here that observers used the distractor to successfully contrast with the memory item, but since no such effects were found in our previous study (Olivers et al., 2006) or in the subsequent experiments mentioned in this article, I believe such an explanation is unlikely.

The rest of the results are clear: The precise way in which the use of visual working memory is induced does not matter for visual memory-driven attentional capture to occur. Singleton distractors that were related in color to the content of working memory caused greater interference than unrelated singleton distractors, regardless of whether the memory task involved an easy distinction (with performance around 95% and only an articulatory suppression task to induce visual memory) or a difficult distinction (with performance around 60%, plus an articulatory suppression task). Combining these results with the findings of Olivers et al. (2006), we can now sketch the following picture:

1. No memory-driven attentional capture when the memory test is easy (i.e., easily verbalizable) and there is no articulatory suppression task.

2. Memory-driven attentional capture when the memory test is easy and there is an articulatory suppression task.

3. Memory-driven attentional capture when the memory test is difficult (i.e., not easily verbalizable) and there is no articulatory suppression task.

4. Memory-driven attentional capture when the memory test is difficult and there is an articulatory suppression task.

Thus, either the articulatory suppression or the difficult distinction method is sufficient, and neither is necessary, to induce visual memory-driven attentional capture. In other words, the presence or absence of the articulatory suppression task is not the reason why some failed to find such capture effects, nor does the articulatory suppression task hinder the formation of a memory representation.

Experiment 2: Homogeneous Versus Heterogeneous Displays

The studies that failed to find memory-based attentional capture (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Woodman & Luck, 2007) all used heterogeneous search displays consisting of multiple different objects (e.g., all different colors, shapes, and/or everyday objects). In contrast, Olivers et al. (2006) used rather homogeneous displays in which all items were gray disks, except for the target (which was a gray diamond) and the singleton distractor (which was uniquely colored). Perhaps, then, memory-based distractor effects are contingent on the distractor being sufficiently salient in the first place, as is the case in homogeneous surroundings. That is, only when the distractor pops out of the display can it cause further costs when it matches the memory content.[1] To test whether display homogeneity is a crucial factor in memory-driven attentional capture, I compared a homogeneous display condition, in which the singleton distractor was indeed a color singleton among gray distractors, with a heterogeneous display condition, in which the crucial distractor was just one of many differently colored disks. If a lack of a memory effect is due to display heterogeneity, we should see the increased interference for memory-related distractors disappear in the heterogeneous condition.

Method

The method was the same as in Experiment 1, except for the following changes. Twenty-four volunteers, aged 17 to 25 years (average 19.8 years), participated in exchange for a payment of €7 per hour. Ten participants were male, and 2 were left-handed. All reported having normal or corrected-to-normal acuity and color vision. Two participants were replaced because they performed at chance on either the search or the memory task. I used only the difficult distinction visual memory task in which remembered colors had to be distinguished from subtle variants. No articulatory suppression task was used, and any displays related to this task were dropped. In the search task, there were two display types. The homogeneous display type was the same as that used in Experiment 1: Participants searched for a gray diamond among gray distractors, including one uniquely colored singleton distractor (nine items in total). As before, the singleton distractor could be related or unrelated in color to the memory content. In the heterogeneous display type, the search items were of various colors (red, green, yellow, blue, magenta, and gray). There was also a uniquely colored singleton distractor. Note that this distractor had a unique color (e.g., it was the only red item on screen), but it was no longer a singleton (as it was not the only colored item on the screen). Again it could be related or unrelated to the memorized color. Of the six main colors, one was assigned to memory and one to the singleton (if unrelated to memory). The four remaining colors were distributed over the eight remaining search items (including the target), such that there were two items for each color. Display type (homogeneous vs. heterogeneous) was blocked with order counterbalanced across participants; singleton distractor type was randomly mixed within blocks.

Results and Discussion

RTs. RTs shorter than 200 ms and longer than 3,000 ms were excluded, resulting in a loss of 0.77% of data points. Figure 3 shows the mean of the remaining correct RTs as a function of display type (homogeneous vs. heterogeneous) and singleton distractor type (unrelated vs. related). A within-subject ANOVA with these same factors revealed a trend toward a main effect of display type, $F(1, 11) = 3.45$, $MSE = 4{,}754.05$, $p = .076$, $\eta_p^2 = .130$; a main effect of singleton distractor type, $F(1, 11) = 9.55$, $MSE = 1{,}943.69$, $p < .01$, $\eta_p^2 = .293$; and no interaction, $F < 1$. Averaged across display type, 21 of the 24 participants showed a memory-related cost. RTs were overall higher for homogeneous displays than for heterogeneous displays. This makes sense because in the homogeneous condition, the crucial distractor was really a salient singleton distractor, causing interference with visual search. In the heterogeneous condition, the crucial distractor was no longer a salient singleton, resulting in overall faster search times. In any case, regardless of the display type, RTs were increased by 28 ms when singleton distractors were related to the memory content compared with when they were unrelated.

Errors. Overall, more search errors were made in the homogeneous conditions than in the heterogeneous conditions, $F(1, 23) = 5.20$, $MSE = 0.001$, $p < .05$, $\eta_p^2 = .184$. No other effects were significant, $F\text{s} < 2.5$, $p\text{s} > .13$. In the homogeneous display condition, search error rates amounted to 6.6% when singleton distractors were related and 4.6% when singleton distractors were unrelated. In the heterogeneous displays these were 4.4% and 4.2%, respectively. Memory errors were more numerous. In the homogeneous condition, 46.2% errors were made when distractors were related and 44.2% when distractors were unrelated. In the heterogeneous condition, percentages were 47.4% and 46.0%,

[1] A priori, it seems that display heterogeneity cannot be the explanatory factor since Soto et al. (2005) have reported memory-based effects despite using rather heterogeneous displays involving multiple different shapes of different colors. However, note that the search target was not actually one of these shapes. Instead, the target was a tilted bar that could be presented inside any one of them, whereas the distractors were all vertical bars. So at the level of search items there was homogeneity.

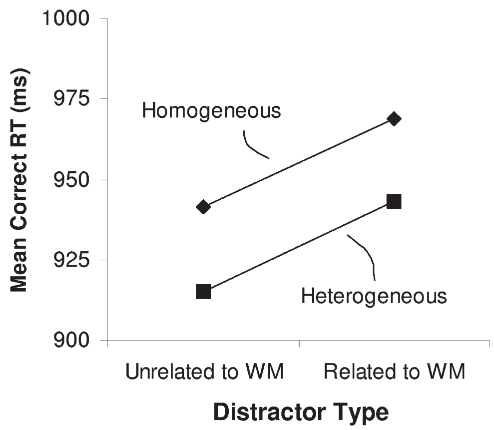

Figure 3. Response time (RT) results of Experiment 2 when singleton distractors were unrelated or related to the memory content, for different display types (homogeneous vs. heterogeneous).

respectively. None of the differences were significant, $F\text{s} < 2.4$, $p\text{s} > .13$.

In all then, I conclude that display heterogeneity is not the key to why memory-based capture effects do or do not occur.

Experiment 3: Effortless Versus Effortful Search

Another difference between studies that found memory-driven attentional capture and those that did not appears to be the difficulty of the search task. Although search slope data are not available for every experiment, studies that failed to find an effect used search tasks that were likely to be more difficult, more effortful, potentially more serial, and less efficient (probably also due to the earlier described heterogeneity of the displays; Duncan & Humphreys, 1989), whereas those that found effects used search tasks that were in general easier, less effortful, more parallel, and more efficient in nature. For example, whereas in Woodman and Luck's (2007) study the search target was a box with a gap at the top or bottom among very similar boxes with gaps at their sides (known to yield inefficient search; Woodman, Vogel, & Luck, 2001), in the Olivers et al. (2006) study the search target was a diamond among disks (known to yield efficient search; Theeuwes, 1991, 1992). Recently, Soto and colleagues found memory-driven attentional capture in both efficient and inefficient search (Soto et al., 2005, 2006b), but since these involved different groups of participants and slightly different procedures, it is difficult to assess the relative contribution of search efficiency.

There are several ways in which search efficiency may affect the influence of memory-related distractors. According to Theeuwes (2004; see also Belopolsky, Zwaan, Theeuwes, & Kramer, 2007), attention reduces its spatial window when in a more effortful search mode. Such a narrow spatial window may result in many distractors being effectively ignored, including the memory-related distractor. In contrast, under effortless, parallel search conditions, attention may be more distributed across the displays, encompassing the crucial distractor. Alternatively, the parallel search displays may have allowed for what has been called *singleton detection search mode*, in which observers look for salient objects in general, rather than for a specific target feature (Bacon & Egeth, 1994). In contrast, effortful search is likely to involve *feature search mode*, in which observers look for a specific feature or combination of features (see Theeuwes, 2004, for this argument), and more effectively ignore irrelevant features. Again, these different search modes determine how attention is distributed, now across features rather than space. Note that both under the spatial window hypothesis and under the differential search mode hypothesis, attentional capture is not strictly bottom-up, as it depends on the overall state attention is in. Although important, this issue is not central to the current research question, which is to determine what modulates memory-driven attentional capture.

To test whether the type of search affects memory-driven attentional capture, Experiment 3A compared the effects of memory-related distractors under more and less efficient search conditions. In the *easy* search condition, displays were homogeneous, and the target was a unique diamond target among gray disk distractors (including a color singleton). Previous research has shown numerous times that these displays yield flat search slopes (e.g., Theeuwes, 1991, 1992). In the *difficult* search condition, displays were heterogeneously colored, and the target was now a disk just like the other disks in the displays. The only way in which the target could be distinguished from the distractors in this condition was through the small *N* or *M* presented inside it (whereas the distractors contained *X*s). As will be shown in Experiment 4 (which used the same displays but also varied set size), search for this task was found to be highly inefficient, with slopes averaging 110 ms/item. If the absence of memory-driven attentional capture is due to small spatial windows or feature search mode, then we should see the effect disappear in the difficult search condition. To generalize the findings, and for reasons that will become apparent in the Results section, Experiment 3B repeated the *difficult* search condition but with a smaller set size and accompanied by an articulatory suppression version of the visual memory task, rather than the difficult distinction version used in Experiment 3A.

Method

The method was largely the same as before. In Experiment 3A, 28 volunteers, aged 18 to 26 years (average 20.6 years) participated in exchange for a payment of €7 per hour. Twelve participants were male, and 3 were left-handed. All reported having normal or corrected-to-normal acuity and color vision. Two participants were replaced because of exceptionally long RTs (beyond three standard deviations from the group mean) as well as chance performance at the memory task. Two more were replaced because of effect sizes beyond three standard deviations from the group mean (one revealing a 476-ms effect in one direction, the other a 411-ms effect in the other direction; leaving these participants in did not alter the pattern of results, it only added noise). In Experiment 3B, 10 volunteers participated, aged 19 to 24 years (average 21.6 years), of which 2 were male and 1 was left-handed. In Experiment 3A, only the difficult distinction visual memory task was used, without the articulatory suppression task. There were two search types. The *easy* search type was the same as the homogeneous conditions in Experiments 1 and 2: Participants searched for a gray diamond among gray distractors, including one uniquely colored singleton distractor. There were nine search items in total. As before, the singleton distractor could be related or unrelated in color to the memory content. The *difficult* search type was the same as the heterogeneous display type of Experiment 2, except that the target was now not a unique diamond, but a disk, like any other item in the display. The only way the target could be distinguished from the distractors was by the fact that it carried an *N* or *M* rather than an hourglass *X*-shaped object inside it. In this display the items had various colors, but as before, one of the distractors had a unique color that could be related or unrelated to the memorized color. Search type (easy vs. difficult) was blocked with order counterbalanced across participants; singleton distractor type was randomly mixed within blocks. Because of the more difficult search task, 40 instead of 20 practice trials were run. Six blocks of 20 trials were run, resulting in 30 trials per cell. In Experiment 3B, only the articulatory suppression version of the memory task was used, and only the difficult search task was run. Set size was now six instead of nine. Six blocks of 20 trials resulted in 60 trials for each singleton distractor type (related vs. unrelated).

Results and Discussion

RTs. RTs shorter than 200 ms and longer than 3,000 ms (in the easy search condition) or longer than 6,000 ms (in the difficult search condition) were excluded, resulting in a loss of 0.94% of data points. Figure 4 shows the mean of the remaining correct RTs, as a function of search type (easy vs. difficult) and singleton distractor type (unrelated vs. related) for Experiment 3A (easy and difficult search under a difficult distinction memory task) and Experiment 3B (difficult search under an articulatory suppression task). A within-subject ANOVA on the RTs of Experiment 3A revealed a main effect of search type, $F(1, 29) = 559.7$, $MSE = 65{,}529.06$, $p < .0001$, $\eta_p^2 = .936$; a main effect of singleton distractor type, $F(1, 27) = 4.46$, $MSE = 5{,}133.43$, $p < .05$, $\eta_p^2 = .142$; and no interaction, $F < 1$. Averaged across search type, 20 of the 28 participants showed a memory-related cost. Search was overall slower in the difficult search task (2,014 ms) than in the easy search task (924 ms). Regardless of search type, related singleton distractors led to slower search than unrelated singleton distractors, by an average of around 29 ms.

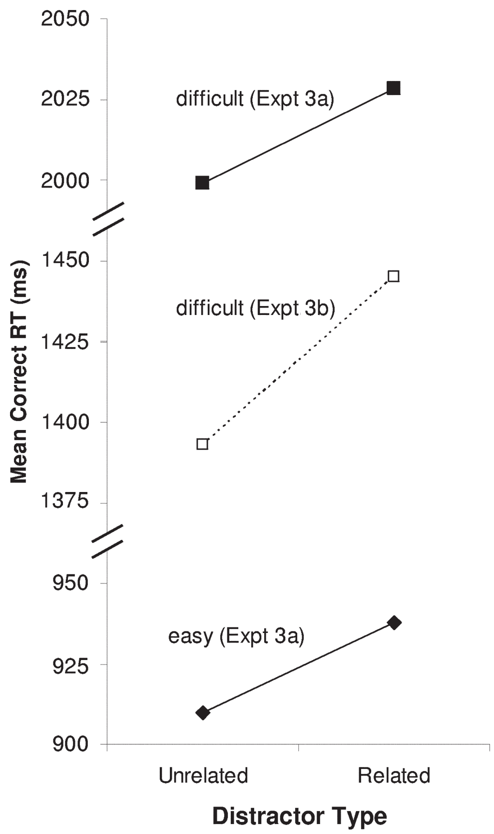

Figure 4. Response time (RT) results of Experiment (Expt) 3 when singleton distractors were unrelated or related to the memory content, for different search types (easy vs. difficult, with Experiment 3B employing an overall easier search task than Experiment 3A).

However, even though the interaction was nonsignificant, the underlying distractor effects differed in one aspect between the difficult and easy search conditions: Whereas in the easy search condition, the effect of singleton distractor type (related vs. unrelated) was highly reliable, $t(27) = 3.74$, $p = .001$, in the difficult search condition this was not the case, $t(27) = 1.06$, $p = .30$, due to considerably larger variance (on an effect of 29 ms, the standard error was 28 ms; 10 of the 28 participants showed an effect in the opposite direction). Any conclusion about the difficult condition would be compromised by this variance. Experiment 3B was therefore designed to repeat the difficult search condition but reduce the variance by (a) reducing the set size from nine to six items, and (b) replace the difficult distinction memory task with the easier articulatory suppression memory task (see Experiment 1). The results are also shown in Figure 4. As expected, overall RTs were significantly reduced relative to the difficult condition of Experiment 3A, $F(1, 36) = 32.89$, $MSE = 158{,}533.48$, $p < .001$, $\eta_p^2 = .477$. What is more important is that the 52-ms difference between related and unrelated distractor singleton types was now reliable, $t(9) = 2.67$, $p < .05$ (with 9 of 10 participants showing an effect in the same direction). Experiment 4 will once more replicate this result for each of three different set sizes.

Errors. In the easy search condition of Experiment 3A, search error rates amounted to 4.0% when singleton distractors were related and 3.7% when singleton distractors were unrelated. In the difficult search condition these were 4.8% and 4.1%, respectively. These differences were nonsignificant, all Fs < 1. In Experiment 3B, error percentages were 3.3% and 2.7% for related and unrelated distractors, respectively, and again there was no significant difference, $t < 1$. For the difficult distinction memory task of Experiment 3A, errors measured a few tenths of percentage points from 44% in all conditions, with no significant differences, all Fs < 1. For the easier articulatory suppression task of Experiment 3B, errors measured 10.5%, which was significantly less than in Experiment 3A, $F(1, 36) = 125.63$, $MSE = 0.013$, $p < .001$, $\eta_p^2 = .777$, with again virtually no difference between distractor conditions, $t < 1$.

All in all then, there is little evidence that the type of search (difficult or easy) plays an important part in whether memory-driven attentional capture effects occur or not. These results converge with those reported by Soto and colleagues, who also found memory-driven capture in relatively difficult search (Soto et al., 2005) as well as relatively easy search (Soto et al., 2006b). Apparently, any presumed change in spatial window or singleton/feature search mode does little to change the working memory–attention interaction.

Experiment 4: Increasing the Distractor Ratio

Experiment 3 failed to get rid of memory-driven attentional capture, despite search being effortful. Compare this to Woodman and Luck (2007), in which search was presumably also effortful, yet memory-related distractors either had no effect or led to RT benefits rather than costs. The latter result was especially apparent when Woodman and Luck increased the ratio of matching distractors to the number of items in the display: The greater the proportion of matching distractors, the stronger the benefits. Woodman and Luck concluded that observers may strategically inhibit memory-matching distractors if they know that these will always be irrelevant.

Perhaps then, performance is ultimately determined by two processes: one attentional capture mechanism (resulting in costs) and one inhibitory mechanism trying to inhibit or reject the very same object. The relative success of these two processes may then depend on the proportion of matching distractors, perhaps because they operate under different time frames or have different properties. For example, whereas capture may be tied to a single item, inhibition may spread from a rejected distractor to similar distractors in the display, eventually resulting in benefits (e.g., Humphreys & Müller, 1993). To test this idea, we increased the number of distractors that could be related to the content of memory from one to two. Furthermore, we varied the overall set size between 3, 6, and 9. This way, the distractor ratios varied among 2:3, 2:6, and 2:9. Note that in Experiments 1, 2, and 3A, the ratio was 1:9, and in Experiment 3B it was 1:6. If the relative proportion of distractors has any effect, we should see the memory-based effects being reduced here relative to those experiments, especially in the low set size conditions.

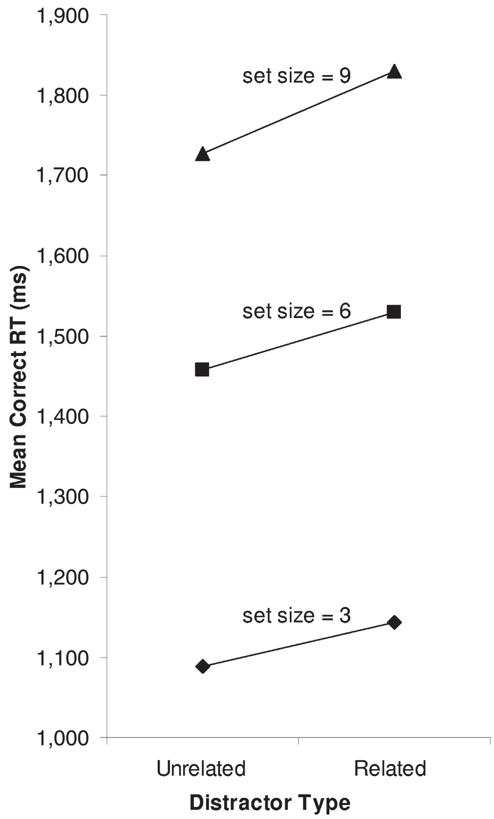

Figure 5. Response time (RT) results of Experiment 4 when singleton distractors were unrelated or related to the memory content, for different set sizes (which correlated with distractor ratio).

Method

The method was virtually the same as in the difficult search condition of Experiment 3A, except that (a) set size was now manipulated between 3, 6, and 9, and (b) there were now always two distractors (instead of one) that could be related to the memory content. Hence, for the set sizes 3, 6, and 9, the ratio of the number of matching distractors to the total number of items in the display was 2:3, 2:6, and 2:9, respectively. Sixteen volunteers participated, aged 18 to 27 years (average 21.1 years). Seven participants were male; 2 were left-handed. After a practice block of 30 trials, participants completed four blocks of 60 trials each, with set sizes and distractor type (related vs. unrelated) mixed within blocks. This resulted in 40 trials per cell.

Results and Discussion

RTs. RTs shorter than 200 ms and longer than 6,000 ms were excluded, resulting in a loss of 2.2% of data points. Figure 5 shows the mean of the remaining correct RTs as a function of set size (3, 6, and 9) and distractor type (related vs. unrelated). An ANOVA with the same factors revealed a main effect of set size, $F(2, 30) = 140.43$, $MSE = 225{,}192.87$, $p < .001$, $\eta_p^2 = .903$, and a main effect of distractor type, $F(1, 15) = 17.98$, $MSE = 7{,}842.74$, $p = .001$, $\eta_p^2 = .545$. RTs increased with set size, resulting in a search slope of 110 ms/item. Regardless of set size, related distractors led to slower search than unrelated distractors, by on average 77 ms. This effect was significant for all set sizes, all ts > 2.1, all ps $< .05$. Averaged across set sizes, 13 of the 16 participants showed a memory-related cost. There was no interaction, $F < 1$.

Errors. Errors amounted to 7.5%, 5.0%, and 5.0% for set sizes 3, 6, and 9, respectively, in the related distractor condition. They were 7.8%, 4.4%, and 4.1%, respectively, in the unrelated distractor condition. The main effect of set size was significant, $F(2, 30) = 3.72$, $MSE = 0.002$, $p < .05$, $\eta_p^2 = .199$, all other Fs < 1. Thus, errors decreased with set size, which goes against the RT pattern. However, since there was no interaction with distractor type, we will leave this error pattern for what it is. In terms of memory performance, there were no significant differences between conditions, all Fs < 2.2, all ps $> .13$. Accuracy was 51.7%, 47.3%, and 48.5% for set sizes 3, 6, and 9, respectively, in the related distractor condition; it was 48.0%, 48.8%, and 43.3%, respectively, in the unrelated condition.

Again, memory-based interference was present, despite search being inefficient (as indicated by the steep search slope) and despite (or perhaps even because of) there now being two related distractors. Hence, the relatively high related distractor ratio at the smaller set sizes did not alter the results.

Note that Experiments 3 and 4 also tested for another possible factor that could explain the discrepant results between previous studies. In the studies that failed to find memory-based effects, the search target always resembled the object that had to be kept in mind. That is, they would share similar features or would be drawn from the same category (e.g., both would be boxes with gaps in Woodman & Luck, 2007; both would be meaningless shapes in Downing & Dodds, 2004; and both were everyday objects or colored patches in Houtkamp & Roelfsema, 2006). In contrast, in the studies that did find effects, the search target was rather dissimilar from the memory object (e.g., gray diamond vs. colored disk in Olivers et al., 2006; tilted bar vs. colored outline shape in Soto et al., 2005). Perhaps observers find it difficult to keep two very similar things activated without the one interfering with the other, and they decide to actively suppress or drop one item from memory, which then leads to reduced memory-based effects. The results of Experiments 3 and 4 argue against this scenario. In the difficult search conditions, the search target and the memory object were very similar (i.e., both were colored disks), yet the memory-based effect was as present as before.

Experiment 5: Consistent Versus Varied Mapping

As was first noted by Oh and Kim (2003), one potentially crucial difference between studies that found memory-driven attentional capture and those that did not is that the majority of the latter type of studies changed the search target from trial to trial—a procedure that was referred to as *varied mapping* by Schneider and Shiffrin (1977). This means that prior to the search display, participants were presented not only with the memory object, but also with the search target, both of which had to be remembered (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; but not Woodman & Luck, 2007). Possibly then, the search target was given priority over the memory object within visual short-term memory, degrading or expelling the latter to a more passive representation. As a consequence, the memory object would have little effect on search.

In contrast, all studies that reported memory-driven attentional capture used visual search tasks in which the target object remained the same on every trial (Olivers et al., 2006; Soto et al., 2005, 2006b). Such a procedure has been referred to as consistent mapping, and, with training, is thought to develop into more automatic target selection mechanisms. Implicit repetition priming from trial to trial may aid such automation. Within the present type of paradigm, consistent mapping may mean that there is little working memory involved in maintaining the target template, therefore freeing resources to create a strong and active representation of the to-be-memorized object. In turn, this will then lead to stronger interference with the search task when a matching distractor is present.

To test this hypothesis, two main conditions were created. In the *consistent mapping condition*, the target could be of any color but was always defined in the same way: It was the only disk with a notch cut out at the top or bottom (and participants had to decide *top* or *bottom*) among distractor disks that had notches cut out from their sides. In the *varied mapping* condition, the target was again a colored disk with a notch cut out from the top or the bottom. However, now the distractors could also have a notch at the top or bottom, and so the only way to distinguish the target was by providing participants with information on its color. To this end, prior to the search display, participants were presented not only with the to-be-memorized color, but also with the to-be-searched for color, both of which varied randomly from trial to trial. As before, one of the distractors in the search display could be related to the to-be-memorized color. If the type of mapping is indeed an important factor in memory-based attention effects, then we should expect such effects in the consistent mapping condition but not in the varied mapping condition.

Note that the response features changed from an *N* or *M* presented inside the target disk to a notch cut out from the top or bottom of the disk. The reason for this had to do with the fact that Woodman and Luck (2007) failed to find memory-driven attentional capture, despite their search task's involving consistent mapping. Some other difference between their task and the one used by Olivers et al. (2006) would thus have to account for the discrepancy. One such difference was the fact that in the Olivers et al. (2006) experiments (and also in Soto et al., 2005), the response feature was perceptually rather separate or abstract relative to the target object (an *N* or an *M* has little in common with the target disk or diamond itself), whereas in Woodman and Luck's study, the response feature was integrated with the target object—that is, it was part of the target shape (namely, a gap in the top or bottom side of the box). Moreover, in Woodman and Luck's task, the response feature was very similar to one of the features that needed to be remembered, as observers were required to remember not only the color of the to-be-memorized object, but also the direction of its notch. Thus, to equate the tasks as much as possible, the current experiment switched to objects with integrated response features, in both the memory and the search task. If this is indeed the crucial difference, then the memory-based effects should disappear in the consistent as well as the varied mapping conditions.

Method

Fourteen volunteers, aged 19 to 24 years (average 21.3 years) participated in exchange for a payment of €7 per hour. Nine participants were male, and none were left-handed. All reported having normal or corrected-to-normal acuity and color vision. Three participants were replaced because of chance performance on the search and/or memory task. One participant was replaced because the computer crashed before the end of the experiment.

The difficult distinction version of the visual memory task was used (without articulatory suppression). The disks in the visual search displays were always heterogeneously colored. Instead of an *M* or an *N* as response feature, the target disk had a round notch (about 0.35° in radius) cut out from the top or the bottom. Participants responded to the target disk by pressing the *J* key (for top) or the *M* key (for bottom).

There were two main conditions: In the *consistent mapping* condition, the target could be of any color (except the memorized color or the singleton distractor color), and it was always the only item with a notch at the top or bottom. The distractor disks had randomly assigned notches on the left or right. Hence, participants could always search for the same type of target, and the memory task consisted only of a single to-be-memorized colored disk with a notch on the left or right (which also had to be remembered), presented for 1,000 ms (followed by a 1,500-ms blank). As before, a distractor in the search task could be related or unrelated to this memorized color.

In contrast, in the *varied mapping* condition, the search target was now always of a particular color, which randomly changed from trial to trial. Again it had a notch at the top or bottom, but this was also the case for some of the distractors—thus, observers needed to know the target color. This target color was specified in advance, together with the standard to-be-memorized item. Both colors were presented next to each other at the center of the screen, for 2,000 ms in total (followed by a 1,500 ms blank). Thus, in this condition, participants always had to remember two colors: One for the immediately-following search task, and one for the memory test at the end of the trial. A search distractor could again be related or unrelated to the latter color.

Because of the additional task involved, the practice session consisted of 40 instead of 20 trials per condition. Participants always first practiced the fixed mapping condition, then the varied mapping condition. They then completed four blocks of 60 trials each, in counterbalanced order, resulting in 60 trials per cell. The type of mapping (fixed vs. variable) was blocked, and singleton distractor relationship (related vs. unrelated) was randomly mixed within blocks.

Results and Discussion

RTs. RTs shorter than 200 ms and longer than 3,000 ms were excluded, resulting in a loss of 1.2% of data points. Figure 6 shows the mean of the remaining correct RTs as a function of type of mapping (consistent vs. variable) and distractor type (related vs. unrelated). An ANOVA with the same factors revealed a main effect of mapping, $F(1, 13) = 8.83$, $MSE = 26{,}444.67$, $p < .02$, $\eta_p^2 = .404$, and a mapping by distractor-type interaction, $F(1, 13) = 10.91$, $MSE = 3{,}702.60$, $p < .01$, $\eta_p^2 = .456$. Overall, RTs were faster in the varied mapping condition. This makes sense, because only in this condition do participants know beforehand which color the target is. In the consistent mapping condition, they know only that it is the only item with a notch at the top or bottom, but not which color it is. Most interesting was the significant 80-ms increase in interference for related distractors relative to unrelated distractors in the consistent mapping condition, $t(13) = 4.00$, $p < .01$ (with 12 of 14 participants showing the effect), but no such increase in the varied mapping condition: −27 ms, $t < 1$, *ns* (7 of 14 showing a reduction in memory-based interference; 6 of 14 showing strong opposite effects).

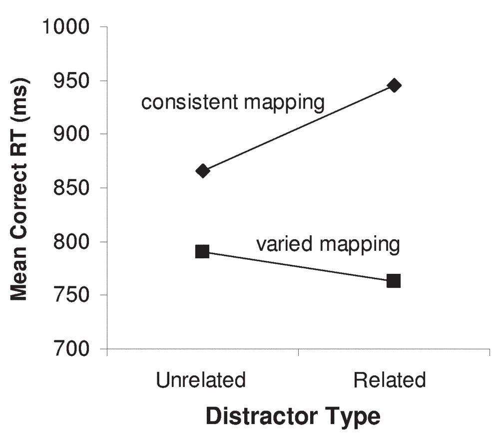

Figure 6. Response time (RT) results of Experiment 5 when singleton distractors were unrelated or related to the memory content, for consistent target definitions ("always find the one with a notch at the top or bottom") versus target definitions that varied from trial to trial (e.g., "now find the blue one and determine whether the notch is at the top or bottom").

Errors. In the consistent mapping condition, search error rates measured 3.3% in the related distractor condition and 3.8% in the unrelated distractor condition. In the varied mapping condition, these rates were 7.5% and 6.3%, respectively. Only the main effect of target mapping was significant, $F(1, 13) = 5.73$, $MSE = 0.003$, $p < .05$, $\eta_p^2 = .306$, all other Fs < 1. Memory errors in the consistent mapping condition amounted to 34.1% when singleton distractors had been related, and to 31.8% when they had been unrelated. Memory errors were somewhat more numerous in the varied mapping condition: 38.5% and 38.7%, respectively, resulting in a main effect of mapping, $F(1, 13) = 9.51$, $MSE = 0.005$, $p < .01$, $\eta_p^2 = .422$, all other Fs < 1.

For the first time in this series of experiments, the memory-based attentional capture effect disappeared. When the target definition varied from trial to trial (varied mapping condition), there was no increase in interference for distractors that were related to the to-be-memorized information. It appears then that having to remember two things—what to remember and what to look for—works at the expense of one of them, in this case the to-be-memorized object. Thus, in line with Oh and Kim (2003), this experiment identified one important factor in the occurrence of memory-driven attentional capture in some studies (Olivers et al., 2006; Soto et al., 2005) but not others (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006).

The present experiment is reminiscent of another recent study by Woodman, Luck, and Schall (2007) that, on the surface, appeared to yield contrasting findings. They asked participants to look for a black landolt-C type target among similar black distractors. As here, the target either remained constant (consistent mapping condition, in which case the same target was shown at the start of each trial) or it changed from one trial to the next (varied mapping condition, in which case the new target was shown at the start of each trial). In addition, in the memory condition, observers saw a grid of four to-be-remembered colors. Search performance in the memory condition was compared with the condition when nothing had to be remembered except the search target. Woodman, Luck, and Schall found that the additional memory task affected search efficiency, but only in the varied mapping condition. It appears that the additional memory load jeopardizes the active maintenance of the search target in working memory when trial-to-trial changes require such maintenance. No such maintenance may be necessary in the consistent mapping condition.

In contrast, the present experiment showed an effect of memory on search in the consistent mapping condition and not in the varied mapping condition. Note, however, that these studies address quite different questions: The Woodman et al. (2007) study investigated the effect of memory *load* on subsequent visual search through quite unrelated objects (memory contained colors, whereas search involved black Cs) and shows that actively maintaining a target template may suffer from such additional load. The present experiment, however, investigated the effect of memory *content* on subsequent search. It suggests that the content of working memory is sufficiently activated to affect subsequent search only when no additional items (such as targets) need to be remembered. In fact, the two studies perfectly complement each other: Additional memory load may push out the target template (as in the varied mapping condition of Woodman et al., 2007), or the target template may push out the memory content (as in the varied mapping condition here). Both studies show that target templates and other memory content are competing.

Experiment 6: Low Stimulus Energy Makes the Effect Disappear

One other hypothesis that may at least partially explain why some found memory-based capture while others did not may be phrased in terms of stimulus energy. The present experiments (as well as Olivers et al., 2006) used relatively large, fully filled shapes. In other studies, the visual search stimuli may have been less well-defined. Woodman and Luck (2007) used relatively small, outlined shapes made of relatively thin lines. Similarly, Houtkamp and Roelfsema (2006), who also failed to find memory-driven capture, used relatively complex outline drawings of everyday objects in some of their experiments. It is possible that memory-driven attentional capture effects are contingent on sufficient differential bottom-up stimulus energy in the displays. For example, for red objects present in the outside world to start resonating with the memory representation of a red object, there must be sufficient energy in the redness channels to begin with. To test this possibility, this experiment used the consistent mapping condition of Experiment 5 (which did yield memory-based capture effects), but the stimuli were now changed into very thinly outlined shapes by simply removing the filling. This reduced the stimulus energy by a factor 18. If stimulus energy is a factor in memory-driven attentional capture, then such capture effects should be reduced here.

Method

Twenty volunteers, aged 18 to 26 years (average 21.0 years) participated in exchange for a payment of €7 per hour. Twelve were male, and 2 were left-handed. All reported having normal or corrected-to-normal acuity and color vision.

The experiment was exactly the same as the consistent mapping condition of Experiment 5, except that the circular shapes were now not filled. They consisted of a circular outline of 1 pixel thickness (approximately 0.03°). Since the radius of the circles was 36 pixels, the stimulus energy was reduced by a factor of 18 (i.e., $\pi r^2/2\pi r = r/2$). Participants completed one practice block of 30 trials, followed by six experimental blocks of 30 trials each (resulting in 90 related distractor trials, 90 unrelated distractor trials).

Results and Discussion

RTs shorter than 200 ms and longer than 3,000 ms were excluded, resulting in a loss of 2.9% of data points. Figure 7 shows the mean of the remaining correct RTs as a function of singleton distractor type (related vs. unrelated) for Experiment 6. For comparison the results of the consistent mapping condition of Experiment 5 are also plotted. A two-tailed, paired-samples *t* test revealed no effect of distractor type on RTs, $t < 1$, $p > .5$. Nor were there any significant effects on error rates in either the search (2.5% for related, 2.0% for unrelated) or the memory tasks (30.8% and 32.1%, respectively), $ts < 1.05$, $ps > .3$. A mixed-design ANOVA compared performance in Experiment 6 against that for the consistent mapping condition of Experiment 5 (which used filled rather than open shapes). There was a trend toward a main effect of experiment, $F(1, 32) = 2.83$, $MSE = 126{,}172.0$, $p =$ $.102$, $\eta_p^2 = .081$, as overall RTs tended to be slower in the open objects displays of Experiment 6. There was also a main effect of singleton distractor type, $F(1, 32) = 9.76$, $MSE = 2{,}536.25$, $p <$ $.01$, $\eta_p^2 = .234$. It is important that there was an Experiment × Distractor type interaction, $F(1, 32) = 11.07$, $MSE = 2{,}536.25$, $p < .01$, $\eta_p^2 = .257$, reflecting the fact that memory-based capture effects were present in Experiment 5 but not in Experiment 6. This provides support for the idea that bottom-up stimulus energy must be sufficiently high for memory processes to latch on. It provides at least a partial explanation for why Woodman and Luck (2007), who used outline shapes, failed to find a memory-based attentional capture effect.

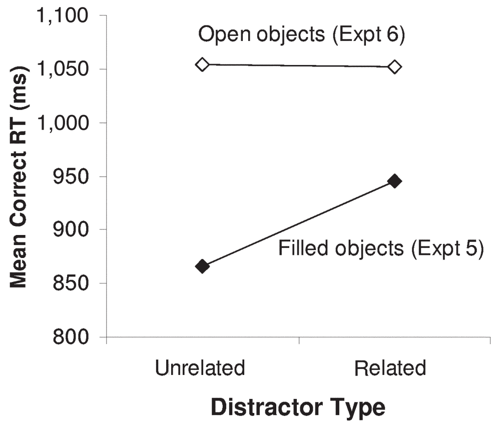

Figure 7. Response time (RT) results for related and unrelated distractors in Experiment (Expt) 6 when the display elements were thin outline shapes ("open objects"), compared with the results of Experiment 5, in which filled objects were used.

Note however, that the present results cannot explain all of Woodman and Luck's (2007) findings. In some of their experiments they actually found a significant *reduction* in search RTs when a distractor matched the memory content. No such reduction was found here. Furthermore, it is difficult to see how a stimulus-energy-based process might account for such a reduction. As Woodman and Luck argued, the benefits associated with memory-matching distractors may reflect strategic use of the memory information. Since the observers know that the memorized item will never be the target, they employ the strategy of actively ignoring (i.e., inhibit) the matching item. Furthermore, Boucher and Woodman (2005) reported that individuals differ in their propensity to be attracted to or to avoid the matching distractor. The present experiments do not exclude this possibility. In the present data (Experiment 6), 11 of the 20 participants showed a benefit for matching distractors, and the remaining 9 showed a cost. Although this may of course just be random fluctuation around a null effect, it may also reflect genuine strategy differences. In any case, whatever strategy observers were using, it was not sufficient to prevent interference in most of the other experiments in the present study.

Experiment 7: Different Instructions Do Not Reduce Memory-Driven Capture

Perhaps another way of reducing the impact of a memory-matching distractor is to alter the instructions. This might work if memory-driven attentional capture is indeed under strategic control, as proposed by Woodman and Luck (2007). So far, the instructions at the start of our experiments (here and in Olivers et al., 2006) have explained the memory task as exactly that: a memory task that should be treated as independent of the subsequent search task. Participants were informed that the distractor might be related to the memory content but that this was irrelevant. In Experiment 7, the instructions changed. The memory task was never explained as being a memory task; instead it was presented as a useful tool providing perfectly valid information on which item should be avoided in the subsequent search task (since the target would never carry the memorized color). In other words, the memory item was presented as relevant to the search task. The memory test at the end of the trial was then explained as a check to see if participants would "use" the information provided. By emphasizing the need to avoid the matching distractor, one might expect to find reduced interference. Of course, by emphasizing the to-be-avoided distractor, we may actually achieve the opposite effect, namely that observers cannot help looking at it—akin to the "attentional white bear phenomenon" reported by Tsal and Makovski (2006), who found evidence that to-be-avoided distractor locations actually received more attention than empty locations.

To maximize the opportunity for strategic effects, the easily verbalizable version of the memory task was now used (see Olivers et al., 2006, and the lead-up to the present Experiment 1). Previously, this version did not result in memory-driven attentional capture effects, in that there were no additional costs for memory-matching distractors. The idea was then that an additional emphasis on avoiding the distractor may possibly further push performance toward a *benefit* for matching distractors, as was found by Woodman and Luck (2007). For the same purpose, the matching distractor was now made identical in color to the memorized item and not merely related. Finally, on the basis of Experiment 6, we increased the line thickness of the shapes to ensure that the colors of the shapes would be sufficiently distinguishable to be useful.

Method

Twelve volunteers, aged 17 to 26 years (average 20.0 years) participated in exchange for course credits or a payment of €7 per hour. Two were male, and 2 were left-handed. All reported having normal or corrected-to-normal acuity and color vision. The experiment was the same as Experiment 6, except for the following changes: The line thickness of the outline shapes was now 5 pixels (about 0.17°). The memory test at the end of the trial featured easily distinguishable colors such as red, green, and blue, as was used in one of the conditions of Experiment 1, but without the articulatory suppression task. Most important, the instructions changed from one explaining the memory task and the search task as separate tasks to one emphasizing the usefulness of the memory information for avoiding distractors in the search task (without ever mentioning words like memory or remember). Translated from Dutch, the crucial part of the instruction read as follows:

> Look for the colored "C" that has a gap at the top or bottom. It can be of any color. However, BEFORE the search task, you will see a color that the C will certainly NOT have. You should use this information. For example, if you see RED, then you know that the C you're looking for will not be RED. Thus, try to avoid that color. To check if you really use this information, afterward we will ask you which color was shown.

There were two conditions randomly mixed within blocks, one involving *identical* distractors in the search task, the other involving *unrelated* distractors. After a practice block of 30 trials, six blocks of 40 trials each followed (20 per condition), resulting in 120 trials per cell.

Results and Discussion

RTs. RTs shorter than 200 ms and longer than 3,000 ms were excluded, resulting in a loss of 1.0% of data points. The mean correct RT for search displays with unrelated distractors was 1,099 ms; with identical distractors it was 1,159 ms. The difference of 60 ms was significant according to a two-tailed pairwise t test, $t(15) = 3.49$, $p < .01$, with 10 of 12 participants showing the effect.

Errors. Search error rates measured 1.2% in the unrelated condition and 1.8% in the identical distractor condition, a nonsignificant difference, $t = 1.33$, $p > .2$. In the memory task, errors amounted to 5.3% and 5.2%, respectively, again a nonsignificant difference, $t < 1$, $p > .8$.

It appears that explicitly instructing observers to ignore the matching distractors did not reduce attentional capture by those distractors. On the contrary, one could argue for the opposite: Now a strong memory-based interference effect was found in a condition that previously yielded no such effects (see the more verbal memory conditions of Experiments 1, 2, and 3 of Olivers et al., 2006). It seems that the instructions caused observers to attend to the distractor rather than ignore it, as might indeed be predicted from Tsal and Makovski's (2006) study. A skeptic could argue that participants did not quite trust the instructions and actually expected the target to carry the to-be-ignored color at least occasionally. If so, one might expect such trust to build up during the course of the experiment. However, the memory-related interference actually turned out to be largest and most reliable for the last part of the experiment (76 ms, $p < .01$, vs. 66 ms and 36 ms for the first and middle parts, respectively, $ps > 0.1$). This goes against an explanation based on mistrust.

General Discussion

The underlying theoretical issue at stake here is to what extent the concepts of visual working memory and visual attention should be regarded as representing one and the same function. Ever since their development, these concepts have been increasingly rubbing against each other. Attention has achieved a more and more central role in controlling the information flow into, within, and from working memory, as well as the maintenance of this information; (Awh & Jonides, 2001; Baddeley, 1986). Conversely, working memory has become an increasingly important theoretical factor in the biasing and control of attention (e.g., Desimone & Duncan, 1995; Engle, Kane, & Tuholski, 1999; Lavie, Hirst, de Fockert, & Viding, 2004). Parallel to this, it has been found that working memory and attention tasks activate the same brain regions (Cabeza & Nyberg, 1997, 2000; Corbetta & Shulman, 2001; D'Esposito, 2001; Fuster, 1997; Handy et al., 2001; Kanwisher & Wojciulik, 2000; Kastner & Ungerleider, 2000). The fourth cornerstone would be the demonstration that attention and working memory share content, in that they cannot work on separate representations. If so, then working memory content should automatically bias selection. It is exactly with regard to this latter claim that controversy has recently risen: A number of studies reported evidence that working memory content affects visual selection (and claimed at least partial unison of working memory and perceptual content), whereas at least an equal number of studies, using very similar paradigms, failed to find such effects (and claimed the separation of working memory and perceptual content). The present study partially succeeded in resolving this controversy by showing which factors do and which factors do not contribute to the discrepant findings.

Experiment 1 showed that the discrepancy is not due to the different ways of inducing the use of visual working memory (rather than verbal working memory). It is also not due to search display heterogeneity (Experiment 2) or search difficulty (Experiments 3 and 4). A change in instructions also did little to explain the different findings (Experiment 7). Experiment 5 identified the first factor affecting memory-based attentional capture: The to-be-memorized item lost its effect on visual search when observers also had to actively remember the search target on each trial (varied mapping vs. consistent mapping). Experiment 6 provided evidence that the surface energy of the display items may also play a role in the strength of the memory-based interference by showing that very thin stimuli fail to induce memory-driven attentional capture.

A Single Focus of Mnemonic Attention?

The finding in Experiment 5 that the object of visual working memory interacts with visual search only when observers are not also required to memorize a new search target on each trial suggests that visual working memory does not actively maintain multiple objects at the same time. One reason for this may be limited capacity: Working memory can really maintain only one object at a time. When the search target template remains identical from trial to trial (and thus the burden on working memory is minimal), there is sufficient capacity to maintain another object, which, rather ironically, is then sufficiently activated to interfere with search. However, the idea of a single object capacity goes against current estimates of at least three to four items on average (Cowan, 2001). Furthermore, a recent study by Soto and Humphreys (2008) showed that having to remember two colored objects (instead of only one) did not diminish the effects that either of these items had on a subsequent visual search task (see also Woodman & Luck, 2007). This suggests that the number of items in memory per se is not the crucial factor here. It is interesting though, that a reduced influence of the memory content on the visual search task was found when observers had to perform the additional task of rehearsing two random numbers (to induce articulatory suppression). This suggests that the additional task may diminish the priority assigned to the task of remembering the colored shapes in favor of the search target template, thus reducing their influence on the subsequent search task.

The relative priority of tasks may also explain why in Experiment 5 there was no effect of the to-be-memorized item. This explanation emphasizes functionality rather than limitations: Since in the paradigm at hand observers largely perform the tasks in sequence (first memory encoding, then visual search, then memory test), working memory may actively juggle the different representations necessary for the different tasks, such that the visual search target is prioritized over, or shielded from, the to-be-remembered object when the visual search task is at hand (and vice versa at the memory test). When no visual search target needs to be remembered (as it remains constant throughout the experiment), the to-be-memorized object is the only object present in working memory and therefore automatically gains priority. Thus, active prioritization or separation of representations may occur only when this is necessary for the task.

Evidence for separate functionality comes from a neuropsychological study on patients with damage to the inferior frontal cortex (Soto et al., 2006a). Just as for normal observers (Soto et al., 2005, 2006b), search times were modulated by the match between objects in the search display and the to-be-remembered object. However, the important finding here was that in the frontal patient group, search was much more affected by the memory content than in the age-matched control group, suggesting the patients had more trouble separating the working memory and search tasks. Conversely then, this implies that under normal functioning, working memory and attentional representations can be kept relatively shielded from each other. This relative flexibility of working memory representations is further underlined by the findings of Woodman and Luck (2007), which suggest that the contents of working memory can be strategically used to inhibit (rather than automatically enhance) irrelevant information in the attention task (see also Downing & Dodds, 2004).

One may then argue that the conclusion that visual working memory is fractionated, allowing for multiple representations to coexist and to be selectively (de)prioritized according to task demands, jeopardizes the idea that attention and working memory are one and the same process, working on the same type of content. After all, if one type of representation is prioritized to guide search, whereas the other types of representation are either kept active but shielded from the search template, or even deprioritized, we might as well grant the first type a special status and call it "attention," while the other representations belong to the realms of "working memory." Although this is probably largely a question of semantics (Houtkamp & Roelfsema, 2006), the unison between working memory and attention may be saved if we assume that, whatever selection or prioritization mechanisms occur within working memory, they are the same as those that operate on real, "outside" stimuli. Thus, just as attention may be focused on a single object in the outside world, attention can also be focused on a single object within our mnemonic world, in the absence of visual stimulation. In both cases, this grants a special status to the object (it is attended), at the expense of other objects, and the separate functionality is then an emergent feature of the prioritization of one object over the others.

The idea of such a "focus of mnemonic attention" is not new. Cowan (1995) proposed that working memory representations are in fact long-term memory representations kept active by the focus of attention. Representations outside the focus of attention are more prone to decay and interference than items inside the focus. Given that the capacity of working memory appears to be close to four units (Cowan, 2001), this means that the focus of mnemonic attention should span about four units. Note, however, that in the present paradigm, this would still imply more than sufficient capacity for both the search target template and the to-be-memorized object to be maintained—contrary to what was found. A narrower focus appears to be required to account for the present data. Such a narrow focus of attention *within* working memory was proposed by Oberauer (2002; see also Garavan, 1998, and McElree, 2001). Consistent with Cowan (1995), Oberauer proposed that a limited number of long-term memory representations are activated to make them, in principle, available for direct access. However, of this subset, only one object at a time *is* directly accessed—the current object of attention. Such a scheme would fit with the present findings: When each trial requires a new search target to be remembered, the attention will be focused on its representation to try to keep it active in memory. This will be at the expense of the to-be-memorized object, which is removed from the focus of attention but is still available for direct access. This explains why memory performance does not suffer too much in the varied mapping conditions of Experiment 5. When the search target remains the same from trial to trial (as in the consistent mapping conditions), it is probably sufficient to degrade the target representation to the activated, potentially accessible subset of long-term memory, outside the focus of mnemonic attention. The focus is then fully available for the to-be-memorized object, causing it to be directly accessible and to interfere with search.

Another way of looking at this, but keeping the nomenclature of working memory and attention, is that working memory is there to maintain *templates*, whereas attention is there to maintain *goals*. We use the storage capacity of our working memory to set up the different templates belonging to the different tasks (e.g., one template for the search target, another template for the memory object, yet another one for the response feature). Attention then serves as a pointer to the template that is currently relevant and that needs to be additionally activated over the other templates (depending on which of the three aspects of the task currently needs to be performed), thus instantiating the current goal of behavior. This would imply that memory regains its original role as the store while attention becomes the goalkeeper.

When Does Capture Turn Into Inhibition?

Although the present work can explain why Downing and Dodds (2004) and Houtkamp and Roelfsema (2006) failed to find memory-driven attentional capture, it cannot explain why Woodman and Luck (2007) regularly found exactly the opposite of capture, namely memory-driven inhibition (see also the target-present condition of Experiment 2 of Downing & Dodds, 2004; and Experiment 1 of Olivers et al., 2006, for similar findings). These are not stand-alone effects. Recently, Nieuwenstein, Johnson, Kanai, and Martens (2007) asked observers to detect two letter targets in a rapid stream of digit distractors. Prior to the stream, an array of three to-be-memorized letters was presented. Each target letter in the stream could match one of the memorized letters. The surprising result was that targets (whether the first or the second) were more often missed when they matched the memory content. Nieuwenstein et al. proposed that a particular instantiation (or "tokenization") of an object (Kahneman, Treisman, & Gibbs, 1992; Kanwisher, 1987) within a certain task may be impaired when the same object is already bound to another task. A recent follow-up by Koelewijn, Van der Burg, Bronkhorst, and Theeuwes (2008) showed that this impairment occurs even when observers are not required to memorize the object shown prior to the stream. Merely showing an object makes that same object more difficult to extract from a subsequent stream. Koelewijn et al. suggested that objects that are irrelevant to the current task are inhibited, resulting in impaired detection when the same object happens to return as a target (comparable to the negative priming phenomenon; Tipper, 1985).

There are several implications. First, at the most general level, we can conclude that working memory content interacts with (the selection of) perceptual content. The effects may be opposite in sign (i.e., some studies find enhancement, others inhibition), but the position that working memory and perceptual representations are completely separated does not appear tenable. Second, there is the distinct possibility that the inhibitory effects found by Woodman and Luck (2007) are not strategic but automatic, like in the Nieuwenstein et al. (2007) and Koelewijn et al. (2008) studies. Third, there is the distinct possibility that both inhibitory and excitatory effects of memory on selection occur in a given task, but that for some reason, one of the effects is stronger than, or outlives, the other. For example, a recent study by Sreenivasan and Jha (2007) suggested that distractors matching memory content are behaviorally more intrusive but at the same time perceptually less salient (as measured through the N1 ERP component). One candidate factor here is timing, most notably the interval between the memory object and the search display. The present experiments (as well as Olivers et al., 2006) used intervals in the order of several seconds and found robust memory-based interference. Woodman and Luck (2007) employed much shorter intervals (in the order of 500 ms) and found inhibition. The inhibitory effect potentially occurs before the enhancing effect. On the other hand, Soto et al. (2005) inserted only 188 ms between the memory item and the search display and found clear enhancement effects, which goes against timing as the important factor.

Conclusion

This study shows that the content of visual working memory has robust and replicable effects on the deployment of visual attention. This does not mean that studies that failed to find such effects in the past did just that: fail. When all studies investigating the issue are taken together, a pattern is emerging from which important new insights on the nature of the memory representations and the mechanisms operating on them can be derived. The present study has pinpointed two such mechanisms as important (while excluding a series of others): (a) Task requirements determine the number of objects to be held in memory and the relative priority of each; and (b) sufficient energy from the stimulus input is required for interactions between memory and attention to become measurable. Nevertheless, detailed models are required to explain exactly when memory content leads to attentional bias and when it leads to inhibition.

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