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Feature-Based Memory-Driven Attentional Capture: Visual Working Memory Content Affects Visual Attention

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In 7 experiments, the authors explored 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. The presence of singleton distractors interfered more strongly with a visual search task when it was accompanied by an additional memory task. Singleton distractors interfered even more when they were identical or related to the object held in memory, but only when it was difficult to verbalize the memory content. Furthermore, this content-specific interaction occurred for features that were relevant to the memory task but not for irrelevant features of the same object or for once-remembered objects that could be forgotten. Finally, memory-related distractors attracted more eye movements but did not result in longer fixations. The results demonstrate memory-driven attentional capture on the basis of content-specific representations.

Keywords: visual attention, visual working memory, attentional capture, eye movements

Visual attention is the mechanism by which humans *select* relevant and ignore irrelevant visual information for a task. Visual working memory is the mechanism by which humans actively *retain* relevant and prevent interference from irrelevant visual information for a task. This large overlap in definition, together with a large overlap in brain areas involved in attention and working memory (see, e.g., LaBar, Gitelman, Parrish, & Mesulam, 1999), has prompted the hypothesis that the two concepts may reflect one and the same general function, working on the same type of content. Simply put, both visual attention and visual working memory processes selectively activate and prioritize particular visual representations above others; it is just that in the case of working memory, this occurs in the absence of the actual stimulus.

One of the models in which the identity relationship between attention and working memory[1] is made most explicit is the biased competition model of Desimone and Duncan (1995). According to this model, when the observer's task is to select a specific target object from a future stimulus display consisting of multiple competing objects, then, in anticipation of the display's appearance, a representation of the target will be preactivated—activity that reflects the content of working memory. Once the actual display appears, the target object will have a direct advantage in the competition for selective attention, because its features have already been activated through the memory representation. In the extreme case, such a scheme would predict automatic attentional capture, contingent on the mnemonic content: If visually remembering an item unavoidably involves activating its perceptual features, then this should give an automatic advantage to outside world objects carrying those features. The present study was designed to test this prediction of content-based memory-driven attentional capture.

Memory-Driven Attentional Capture

There are now a substantial number of studies pointing toward a content-based relationship between memory and attention. However, so far, none of them have provided conclusive evidence, as alternative explanations have been available.

If one regards *imaging* as a form of visual working memory use, then content-specific interactions between memory and attention can be traced back to Farah's seminal studies on imagery (with related ideas going back as far as Pillsbury, 1908). For instance, Farah (1985) instructed participants to imagine either a *T* or an *H*, after which she faintly presented one of these letters in a two-alternative forced-choice detection task. The letters were better detected when they matched the mental image, a result that implies a common representational structure between perception and imagery. In a follow-up study, Farah (1989) presented participants with a grid of empty squares and asked them to imagine the

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[1] Note that even though we may sometimes omit the adjective *visual*, the discussion is meant to be restricted to *visual* attention and *visual* working memory, because in our experiments stimuli were presented only to the visual modality (as has been the case in most studies on the relationship between attention and memory). Nevertheless, the same principles may apply to other modalities.

presence of either a *T* or an *H* on this grid by "mentally filling in" the corresponding squares. After they had formed the mental picture, the participants were required to detect a probe dot presented in one of the grid's squares. Farah found a greater bias (but not greater sensitivity) toward detecting probe dots for the area "occupied" by the imaged letter. Following Neisser (1976), she interpreted this bias as an "attentional readiness" to perceive the imaged letter. Farah's findings resonate with a more recent study by Downing (2000), who found that probe stimuli were faster detected when presented on a background picture that matched the picture observers had to remember in an accompanying memory task, relative to an unrelated control picture. However, although both Farah's and Downing's studies suggest an interaction between working memory and attention, neither provides a strong test for the automaticity of this interaction. This is because attending to the matching stimulus was never really detrimental to the task—on the contrary, observers may have deliberately chosen to attend more to an object when instructed to imagine or remember that same object, because they thought it might help them.

A more stringent test of memory-driven attentional capture was provided by Downing and Dodds (2004). They asked participants to remember one shape and then search for another shape in a visible display. The to-be-remembered shape could return as a distractor in the visual search display. Because when present it would always be a distractor, paying attention to the memorized item would have been detrimental to the task, and observers should therefore have had no incentive to do so. An increased distractor interference effect would therefore have been a strong indicator of automatic memory-driven attentional capture. However, despite an admirable number of attempts, Downing and Dodds (2004) failed to find such an increased distractor effect and concluded that the to-be-remembered item and the to-be-attended item can be relatively shielded from each other. Recently, Woodman and Luck (in press) also failed to find increased interference from a memorized object that returned as a distractor in a subsequent visual search task. If anything, they found that a memory-matching distractor was less disturbing than unrelated distractors, leading to speeded reaction times (RTs) rather than slowed RTs. Woodman and Luck therefore concluded that working memory content can also be flexibly used to inhibit visual information.

Others have been more successful in finding increased distractor effects in combined attention/working-memory tasks. Pashler and Shiu (1999) asked participants to first form a mental image of an object and then concentrate on the main task of extracting a target digit from a rapid sequence of distractor pictures, one of which was of the imaged object. Pashler and Shiu found that the matching distractor picture affected the detection of a subsequently presented target. However, although this study provides strong evidence for automatic attentional capture, it does not provide unequivocal evidence for a role of visual working memory in inducing this capture. The capture may have been caused by priming, rather than by memory, as the brief activation of an image in itself may be sufficient to induce prioritization of a matching object (cf. Theeuwes, Reimann, & Mortier, 2006). Indeed, Pashler and Shiu (1999) found interference of the imaged object even when observers were instructed to discard rather than remember the initial image.

Moores, Laiti, and Chelazzi (2003) asked participants to search for a particular target object (e.g., a lock) in a briefly presented display containing several other objects. They found that observers were more distracted when one of the nontarget objects was related to the target (e.g., a key), as indicated by both eye movements and RTs. Furthermore, on a free-recall test after the search display, the participants more often reported the related objects than unrelated control objects as present in the displays. Moores et al. concluded that the activation of object representations in working memory primes associated representations, which makes them either receive or attract more attention. However, this study does not provide a strong test for pure memory-driven attentional capture. Note that the Moores et al.'s findings are very much reminiscent of the contingent attentional capture effect reported by Folk, Remington, and Johnston (1992). Folk et al. found that the effectiveness of a cue on the selection of a target depended on the similarity between the cue and the target-defining property. They concluded that observers use a task-specific attentional set and that objects matching this set will automatically capture attention. In the case of Moores et al.'s (2003) study, this means that the target-related objects may have captured attention because they were explicitly related to the observer's attentional set for the task at hand, not because they were related to the working memory content per se. In other words, although the use of an attentional set is likely to involve working memory, this does not necessarily mean that the reverse case—holding an object in working memory automatically creates an attentional set for that object—is also true. To be able to conclude that memory content drives visual attention, one needs to demonstrate the presence of content-based effects when the memory task and the visual attention task are separate.

This was done in a series of experiments by Soto, Heinke, Humphreys, and Blanco (2005). They asked their participants to first remember a particular shape with a particular color (e.g., a red triangle), then to search for a tilted line segment among upright distractor line segments, and finally to perform a memory test. Thus, the memory and search tasks were designed to involve two different task sets. However, in terms of stimulus content, the two tasks could overlap: The line segments of the search task were each placed inside a shape that could match the to-be-remembered item in shape, color, or both. Soto et al. found that search for the tilted line was speeded when it was placed inside a (partially) matching object, whereas it was slowed when one of the distractor lines was placed inside the matching object. This suggests that attention was guided by the memory content. Furthermore, an increased distractor effect occurred even when the memory-matching shape never coincided with the search target, suggesting that attention was captured even though this was detrimental to the task. These effects were not due to mere priming, because no benefits or costs occurred when participants were not required to remember the initial shape. Hence, Soto et al. concluded that visual attention is guided by working memory content in an at least partially automatic fashion.

However, these experiments are not without potential drawbacks. Note that the to-be-memorized item was presented only about 300 ms before the appearance of the search display, leaving observers relatively little time to encode and consolidate the item before they needed to switch tasks. Thus, observers may have attended to the partly matching search object because they were still busy *encoding* the to-be-memorized features, not because they were *retaining* those features. Even if the to-be-memorized object was encoded in time, there may still have been the risk of observers deliberately using the matching item in one task (i.e., the search task) as an aid in performing the other task (i.e., the subsequent memory test). Soto, Humphreys, and Heinke (2006b) argued against this on the basis of the observation that recollection did not improve for to-be-memorized items that had returned in the visual search task. However, memory performance in their task was generally very high, with at least 93% correct, and ceiling effects may therefore have prevented further improvements.

Perhaps the strongest evidence for memory-driven attentional modulation, then, comes from Soto and Humphreys (2006), who tested a group of parietal patients demonstrating visual extinction of contralesional stimuli. They found that the extinction was reduced when the contralesional stimulus matched an earlier presented stimulus that had to be remembered. No such improvements were found when the initial stimulus only needed to be viewed or identified. Note that here the initial stimulus was presented for 1 to 3 s (with the target display following after 200 ms), which may be considered sufficient for encoding and consolidation.

The Present Study

In sum, the evidence so far is mixed and, more often than not, subject to alternative interpretations. In the present study we sought to provide further evidence for the memory-driven attentional capture hypothesis, while circumventing previous caveats. Furthermore, we sought to extend the earlier evidence by answering questions such as, What are the differences between more verbal versus more visual memory representations? What happens when only part of an object needs to be remembered? What happens to stimuli that are allowed to be forgotten? and What is the exact nature of the memory-related interference effects?

Figure 1 illustrates the basic procedure underlying Experiment 1 and, in adapted form, also the subsequent experiments. Trials started with the presentation of a disk, and in the memory conditions, participants were asked to remember its color. After a few seconds, a visual search display was presented consisting of a number of disks and a diamond-shaped target. The target was not always the only unique item in the display, because one of the distractors could carry a unique color. We refer to this item as the *singleton distractor* (after Pashler, 1988a). Previous research has shown that the presence of a singleton distractor leads to increased search RTs, even though it is never the target (Theeuwes, 1991, 1992). This indicates that it involuntarily captures attention. The important manipulation here was that the singleton distractor, when present, could carry the same color as the to-be-remembered item. We hypothesized that if working memory involves the activation of content-specific representations that are shared by the attentional system, then we should find increased interference when the singleton distractor matches the to-be-remembered item as compared with when it is unrelated.

Experiment 1 provided an initial test of such memory-driven attentional capture and also provided a first control for priming by including a viewing-without-remembering condition. However, although Experiment 1 exposed an overall effect of memory load on attentional capture, it failed to reveal any content-specific capture effects. We hypothesized that participants may have used a more verbal type of memory rather than a visual working

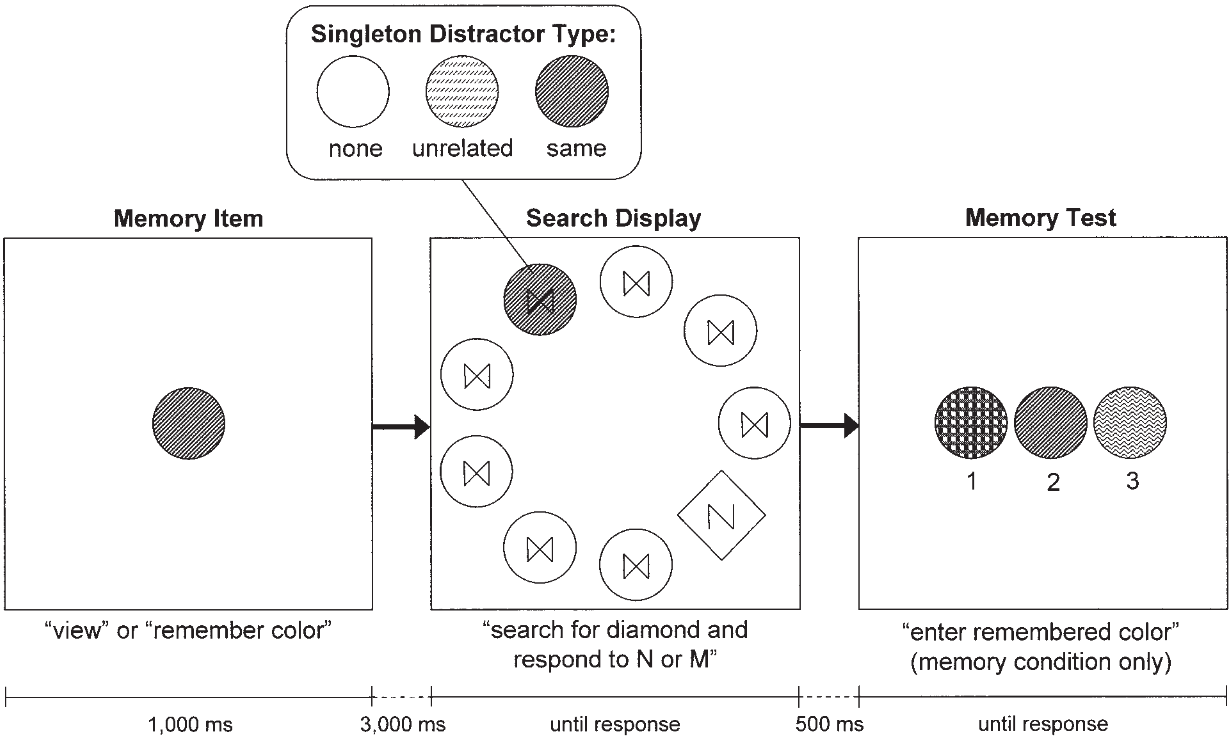

Figure 1. Schematic representation of the stimuli and procedure of Experiment 1. The different patterns correspond to different colors.

memory. This was tested in Experiments 2 and 3, in which observers were encouraged to use a more visual type of memory. This time there was increased singleton distractor interference for matching singletons. These experiments again controlled for priming, now by including the same (more verbal) memory condition as in Experiment 1. Experiment 4 then investigated whether memory-driven attentional capture is restricted to those dimensions that are relevant to the memory task or whether working memory is obliged to represent entire objects. Experiments 5 and 6 looked at forgetting by investigating whether items that were initially memorized but no longer needed still had an effect on singleton interference. Finally, Experiment 7 used eye movement measures to assess the exact nature of the memory-related interference effects, to see whether interference was due to increased attentional capture by, or instead delayed disengagement from, the memory-related stimulus.

Because the target was always defined by a different dimension than the singleton distractor (in this case shape vs. color), any increased distractor effects would be unlikely due to a voluntary attentional set for the distractor properties and more likely due to automatic attentional capture instead. The risk for potential task overlap was minimized in all of these experiments by the relatively long duration between the memory task and the search task (up to 4 s in total), which should have given ample time to encode the initial item and switch to the search task. Moreover, the search target was always the same, making it easy to maintain the basic task descriptions. Nevertheless, there may have been the risk of participants using the matching singleton distractor to refresh their memory of the to-be-remembered item. Experiments 4, 6, and 7 further controlled for this possibility by making the singleton distractor related to the memorized item, but never identical.

Experiment 1: An Initial Test of Content-Based Memory-Driven Attentional Capture

In the *memory* condition of the first experiment, participants were required to remember an easily distinguishable color (red, green, blue, or yellow) and subsequently search for a diamond in a visual search display. The search display could contain a singleton distractor, which, when present, had the same color as the memorized item or an unrelated color. A trial ended with a memory test, in which the participants were asked to choose the remembered color from three presented colors. The memory-driven attentional capture hypothesis predicts increased search RTs when the singleton distractor matches the memory content.

Performance in the memory condition was compared with a *no-memory* condition, in which participants were instructed to simply look at the initial colored disk, without the need to remember it. The no-memory condition had two purposes. First, it served to ensure that any effects of the memorized item in the memory condition were not simply due to priming (i.e., due to just having seen the matching color). Second, it allowed for the assessment of any general effects of working memory load on attentional capture, irrespective of whether the content matched. Using very similar visual search displays, Lavie and De Fockert (2005) found increased distractor interference when participants had to simultaneously rehearse a series of up to six digits. Here we assessed whether having to remember a single color would have a similar effect on attentional capture.

Method

Participants. Twenty university students, aged 16 to 23 years (M = 19.6), participated in exchange for a payment of €7 (approximately $9.00) per hour. All reported having normal or corrected-to-normal acuity and color vision. One participant was left out of the analyses because he made up to 50% errors in the search task, leaving a total of 19 participants.

Stimuli, apparatus, procedure, and design. An HP Compaq d530 CMT Pentium IV computer running E-Prime (Psychology Software Tools, 2003) 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 (0.0 cd/m^2) at a viewing distance of 75 cm.

Each trial started with a brief instruction presented in gray (13 cd/m^2, letter height 0.2°) for 500 ms at the center of the display. The instruction read *watch* in the no-memory condition and *remember* in the memory condition, referring to what the participant should do with the subsequently presented item. This item was a colored disk (radius 1.5°), which was presented for 1,000 ms at the center of the display. It could be any of four main colors (red, green, yellow, or blue, as was randomly determined with the constraint that each color was featured equally often in each condition). Furthermore, the specific hue and chroma of each color 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 kept constant at around 13 cd/m^2, except for yellow, which was brighter (42 cd/m^2) in order to make it appear less brown. The different color combinations used in this and subsequent experiments are listed in Table 1. Note that these were only approximations of Munsell's original colors, owing to screen limitations.

The initial disk was followed by a blank period, which lasted 2,000 ms in the practice blocks and 3,000 ms in the main blocks. In the practice blocks, the blank period was followed for 1 s by another instruction (13 cd/m^2, letter height 0.2°), which read *search*, in order to make participants familiar with the alternation of the tasks. This was followed by a visual search display, consisting of eight gray distractor disks (randomly varying from 11 cd/m^2 to 15 cd/m^2; radius 1.2°) and one gray diamond-shaped target (diagonal 3.0°), placed on the rim of an imaginary circle centered on fixation (radius 5.3°). The search display remained visible until a response was made. 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 (0.32° 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 250 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 three different singleton distractor type conditions: On 50% of the trials there was no singleton distractor. In the *unrelated* condition (25% of the trials), one of the gray disks was replaced with a disk of a color unrelated to the memorized or viewed item (e.g., green when the initial item was red). In the *same* condition (25% of the trials), one of the gray disks was replaced with a disk of the same color as the memorized or viewed item (e.g., the same red as the initial item).

In the memory condition, the visual search display was followed, after 500 ms, by the memory test. This consisted of a central row of three disks of different colors, including the memorized color, in randomized order (e.g., yellow, blue, and red). Below the disks were the numbers 1, 2, and 3. The participants were instructed to indicate the to-be-remembered color by pressing either *1*, *2*, or *3* on the numeric keypad, with the right index, middle, or ring finger, respectively. An incorrect response was again followed by a 250-ms feedback message. In the no-memory condition there was no memory test. The trial ended with a blank screen for 1,500 ms.

All participants first practiced the no-memory condition for 32 trials, then the memory condition for another 32 trials. After practice, four blocks of each condition (no memory vs. memory) were completed in alternating order, counterbalanced across participants. There were breaks in between

Table 1
The Colors Used in Experiments 1, 2, and 3 and Subsequent Experiments

Munsell (as chosen)			CIE (as measured)		
Hue	Value	Chroma	x	y	Luminance (cd/m^2)
			Red		
3R	5	18	0.563	0.314	12.5
3R	5	16	0.544	0.308	11.8
3R	5	14	0.524	0.308	11.6
5R	5	18	0.599	0.335	12.3
5R	5	16	0.585	0.331	11.6
5R	5	14	0.561	0.331	11.5
7R	5	18	0.612	0.346	12.1
7R	5	16	0.604	0.346	11.6
7R	5	14	0.585	0.349	11.4
			Green		
6GY	5	10	0.331	0.582	12.7
6GY	5	8	0.344	0.567	12.5
6GY	5	6	0.348	0.530	12.5
8GY	5	10	0.309	0.598	13.1
8GY	5	8	0.318	0.573	12.6
8GY	5	6	0.319	0.517	12.3
10GY	5	10	0.293	0.600	13.4
10GY	5	8	0.297	0.557	13.0
10GY	5	6	0.294	0.499	12.7
			Blue		
5.5PB	5	16	0.168	0.146	14.8
5.5PB	5	14	0.171	0.153	14.2
5.5PB	5	12	0.176	0.162	13.9
7.5PB	5	16	0.176	0.136	13.3
7.5PB	5	14	0.183	0.146	13.4
7.5PB	5	12	0.189	0.157	13.6
8.5PB	5	16	0.187	0.137	13.5
8.5PB	5	14	0.193	0.148	13.7
8.5PB	5	12	0.199	0.158	13.8
			Yellow		
1Y	8	12	0.445	0.488	41.6
1Y	8	10	0.428	0.478	41.8
1Y	8	8	0.400	0.446	41.9
3Y	8	12	0.436	0.496	41.6
3Y	8	10	0.426	0.490	41.4
3Y	8	8	0.399	0.459	41.9
5Y	8	12	0.431	0.500	40.6
5Y	8	10	0.419	0.503	41.2
5Y	8	8	0.396	0.474	41.5

Note. The Munsell values (R = red; G = green; Y = yellow; P = purple; B = blue) were converted to red, green, and blue (RGB) values by a computer program called Munsell Conversion (Gretagmacbeth, 2004). However, the colors on the screen did not exactly match the original Munsell colors, because computer screens have only a limited color space, and our screens were not calibrated to the Munsell system. CIE = Commission Internationale d'Eclairage values.

blocks, in which participants were notified of their search RTs, search accuracy, and memory accuracy. Each block consisted of 32 trials: 16 no-singleton distractor trials, 8 unrelated singleton distractor trials, and 8 same singleton distractor trials. In total, this resulted in 32 trials for each singleton distractor type and memory type combination (64 trials for the no-singleton distractor condition).

Results and Discussion

Error percentages and mean RTs were entered in an analysis of variance (ANOVA) with memory type (no memory vs. memory) and singleton distractor type (no, unrelated, or same distractor) as factors. Table 2 shows the error percentages in the search and memory tasks. On average, 3.3% search errors and 4.9% memory errors were made. There were no significant effects of memory type or singleton type involving either type of error (all Fs ≤ 1.8, *ns*). Therefore, the remainder of our analyses focused on search RTs. These analyses excluded trials on which a search error was made and trials on which RTs were shorter than 200 ms or longer than 3,000 ms (which constituted less than 1% of the trials in this and subsequent experiments). They included trials on which a memory error was made, however, so as to keep the analyses the same as in later experiments, in which it was important to keep a reasonably high number of trials.

Figure 2 reveals the main RT results. The presence of a singleton distractor led to slower search RTs, as confirmed by a main effect of singleton distractor type, $F(2, 36) = 21.20$, $MSE = 2{,}811.97$, $p < .001$. The presence of an additional memory task also resulted in increased search times, as indicated by a main effect of memory type, $F(1, 18) = 10.77$, $MSE = 14{,}766.92$, $p < .01$. There was also an interaction between memory type and singleton distractor type, $F(2, 36) = 12.86$, $MSE = 1{,}484.91$, $p < .001$. Figure 2 shows that the presence of a singleton distractor led to greater interference in search under conditions of memory load. The important question then was whether this relative increase in distractor interference under memory conditions was at least partially content specific. For this we looked only at the conditions in which a singleton distractor was present. Did the same color distractor result in slower RTs than the unrelated distractor in the memory condition relative to the no-memory condition? Figure 2 suggests not, as was confirmed by the lack of a statistical difference between the two conditions (singleton distractor type, $F < 1$); there was a trend toward a Memory Type × Singleton Distractor Type interaction, $F(1, 18) = 3.64$, $MSE = 2{,}006.32$, $p < .10$, but

Table 2
Error Percentages for the Search and Memory Tasks of Experiment 1

		Singleton distractor type		
Experiment	Task (condition)	None	Unrelated	Same
1	Search (no-memory condition)	3.2	4.0	3.8
	Search (memory condition)	3.2	3.5	2.0
	Memory (memory condition)	4.7	5.6	4.3
2	Search (more verbal condition)	5.2	6.1	6.2
	Search (more visual condition)	5.3	6.1	6.5
	Memory (more verbal condition)	5.3	5.9	4.9
	Memory (more visual condition)	40.1	40.7	40.2
3	Search (more verbal condition)	4.6	3.3	3.7
	Search (more visual condition)	3.9	4.5	3.4
	Memory (more verbal condition)	7.3	9.5	5.8
	Memory (more visual condition)	30.3	28.8	30.3

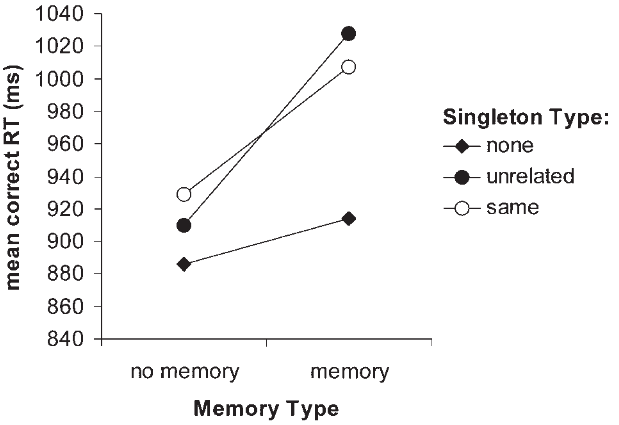

Figure 2. Mean reaction time (RT) results as a function of memory type (no-memory task vs. memory task) and singleton distractor type (no singleton, unrelated singleton, or identical singleton) in Experiment 1.

this went in the opposite direction of that expected on the basis of content-specific memory-driven attentional capture.

Confirming earlier findings, the results show that singleton distractors capture attention (despite being detrimental to the task; cf. Theeuwes, 1991, 1992), but especially so under conditions of memory load (Lavie & De Fockert, 2005). As has been suggested by Lavie and colleagues (e.g., Lavie, Hirst, De Fockert, & Viding, 2004), the additional memory task drains cognitive control mechanisms necessary to reject interfering information.

There was no sign of priming: In the no-memory condition there was no increased distractor effect for matching singletons relative to unrelated singletons. However, nor were there any signs of memory-driven attentional capture: The increased singleton distractor effect was also blind to the specific color held in memory. There may be several reasons for why the present experiment failed to demonstrate memory-driven attentional capture. We propose that the memory representation and the visual input may have been relatively protected from each other (cf. Downing & Dodds, 2004). One reason for this might be that the memory item could easily be remembered verbally rather than visually. Note that there was no real reason for participants to maintain a visual representation of the color, because the color's name would simply suffice to distinguish it from the other colors presented at the memory test. Thus, content-specific interactions between working memory and visual attention may have been absent simply because no visual content was activated. This possibility was addressed in Experiment 2.

Experiment 2: Looking for "More Visual" Working-Memory/Attention Interactions

In Experiment 2 we tried to encourage participants to use a memory that was more visual in nature. We did this by giving instruction to use a more visual type of memory and by changing the memory test at the end of the trial. The procedure is illustrated in Figure 3. Crucially, in the *more visual* condition, the memorized color had to be distinguished from subtle variants of the same color. For instance, it could be that a specific shade of red had to be distinguished from a slightly less saturated red and a slightly more rusty red. These variants of the same color were difficult to remember, presumably because it was difficult to come up with an appropriate verbal label. Hence we hypothesized that participants would use a memory of a more visual character. Performance was compared with a condition that was the same as the memory condition of Experiment 1, in which the memorized color had to be distinguished from other canonical colors (e.g., red among blue and green). We hypothesized that participants could thus use a more verbal description of the color, and hence we labeled this condition the *more verbal* condition. If memory-driven attentional capture depends on the use of a more visual type of working memory, then we should find a content-specific interaction between singleton distractor type and memory type in the more visual condition but not in the more verbal condition.[2]

Method

Participants. Thirty-one university students, aged 15 to 24 years ($M = 18.5$), participated in exchange for a payment of €7 (approximately $9.00) per hour. All reported having normal or corrected-to-normal acuity and color vision. One participant was dropped from the analyses because of exceptionally high RTs (>1,500 ms) in combination with a relatively high percentage of outliers (3%) and memory errors (55%). This left a total of 30 participants.

Stimuli, apparatus, procedure, and design. The method was the same as in Experiment 1, except for the following differences. The intertrial interval was 2,000 ms instead of 1,500 ms. About halfway through the experiment the computers in the lab were replaced. The first part of the experiment (12 participants) was run on Dell Optiplex GX1 Pentium III machines with Dell VGA monitors, the second part (18 participants) on the same HP Compaq machines and monitors as in Experiment 1 (Experiment 2 was run before Experiment 1). Owing to the different monitors, this also meant that the color values for the first group deviated somewhat from those mentioned in Table 1 (which presents the values for the new monitors). However, there was no difference in results between the two groups, and their data were pooled.

The important change in design was that the no-memory condition was dropped. Instead, two variants of the memory task were used. The more verbal condition was the same as the memory condition of Experiment 1. At test, the participant was required to distinguish the memorized color (e.g., red) from among two other main colors (e.g., green and blue). Because the colors were so different, a verbal representation would suffice to do the task (hence the label *more verbal* for this condition). This was also explained to the participants, and they received the instruction to either "remember the global color" (first version of the experiment) or "remember the color verbally" (second version) in this condition. In the more visual condition, everything was the same as in the more verbal condition except the memory test at the end of the trial and the instruction. Now 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 listed in Table 1. The instruction now was to "remember the precise color" (first version) or "remember the color visually" (second version; as with the color differences, the differ-

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[2] Note that we use the stipulation *more* to express the fact that we cannot be sure that observers used only visual working memory and no other types of memory at all. This may even be quite unlikely. The label *more visual* is meant to convey that the type of memory used is probably more visual in character than in the other, more verbal condition.

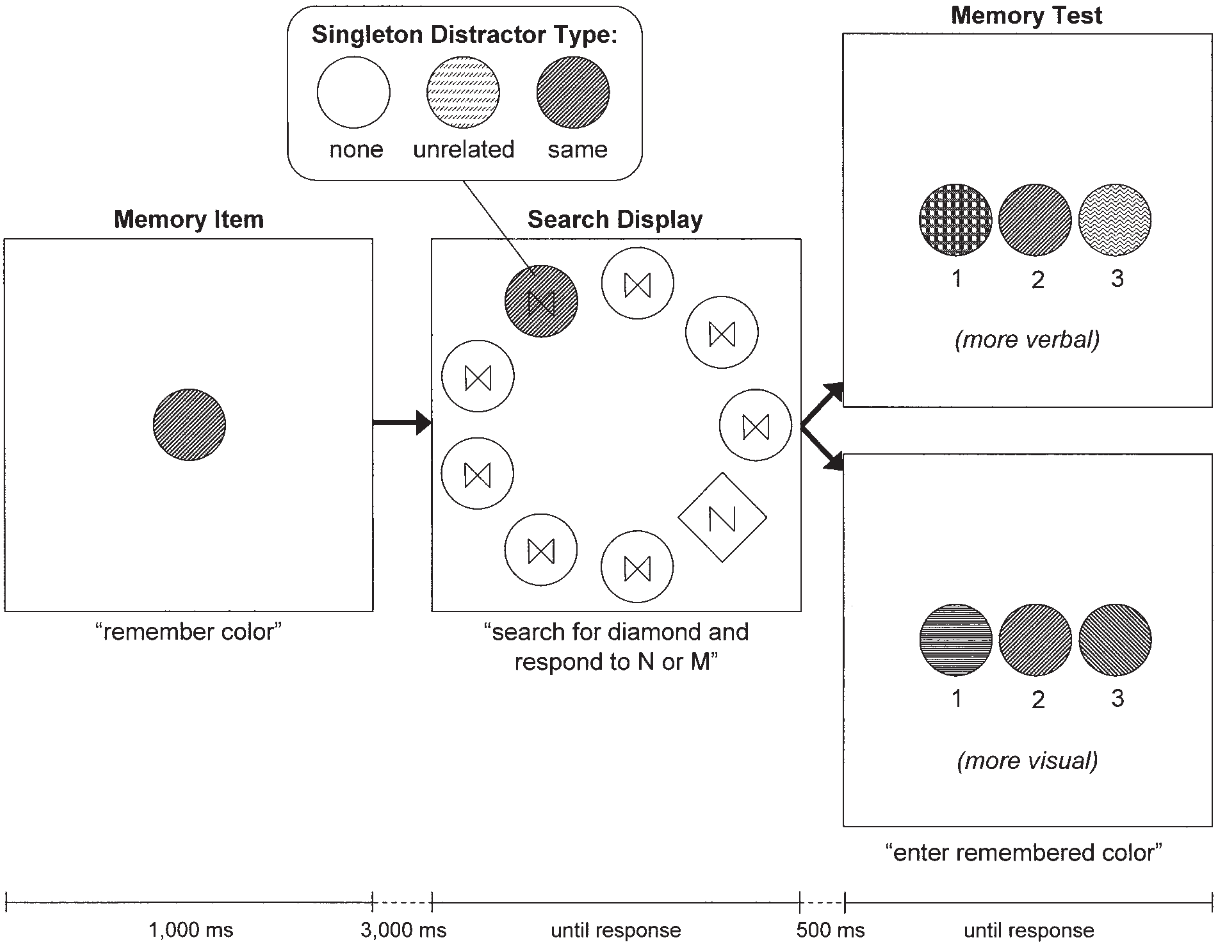

Figure 3. Schematic representation of the stimuli and procedure of Experiment 2. The different patterns correspond to different color categories (red, green, blue, and yellow). Different orientations of a pattern correspond to subtle variants of a color.

ence in instructions between versions appeared to have little effect on the results).

The two different memory types (more verbal vs. more visual) were blocked, with singleton distractor type (none, related, same) randomly mixed within blocks. Participants first practiced the more verbal task for 32 trials and then practiced the more visual task for 32 trials. In the first version of the experiment, participants then received 6 blocks of 32 trials (3 for each memory type); in the second version, participants received 12 blocks of 32 trials (6 for each memory type). The order of nonpractice blocks was counterbalanced across participants.

Results and Discussion

Error percentages and mean RTs were entered in an ANOVA with memory type (more verbal vs. more visual) and singleton distractor type (no, unrelated, or same distractor) as factors. Table 2 shows the error percentages in the search and memory tasks. On average, 5.9% search errors were made, and there were no significant differences between conditions (all Fs ≤ 1.7, *ns*). In the more verbal memory task, on average 5.4% errors were made. In the more visual memory task, the mean error rate was significantly higher, at 40.4%, $F(1, 29) = 669.57$, $MSE = 0.008$, $p < .001$, indicating that this task was indeed more difficult than the more verbal version. There were no effects of, or interactions with, singleton distractor type (all Fs < 1, *ns*).

The RT analyses included the trials on which a memory error was made, to keep the number of trials per cell at a reasonable level. We assumed that many errors in the more visual memory task were due to task difficulty, not due to a failure to comply with task instructions. Figure 4 shows the main results. In general, the presence of a singleton distractor led to slower search RTs: singleton distractor type, $F(2, 58) = 60.86$, $MSE = 2{,}933.48$, $p < .001$. There was no overall effect of memory type ($F < 1.3$, *ns*). However, there was a Memory Type × Singleton Distractor Type interaction, $F(2, 58) = 5.13$, $MSE = 1{,}316.82$, $p < .01$. Figure 4 indicates that singleton distractors matching the memorized color led to an increase in search RTs relative to unrelated singleton distractors (as well as no singleton distractor trials), but only in the more visual condition. A separate analysis on only the unrelated and same singleton distractor conditions again revealed a significant Memory Type × Singleton Distractor Type interaction, $F(1, 29) = 6.34$, $MSE = 1{,}615.02$, $p < .02$, further confirming the content-related interaction.

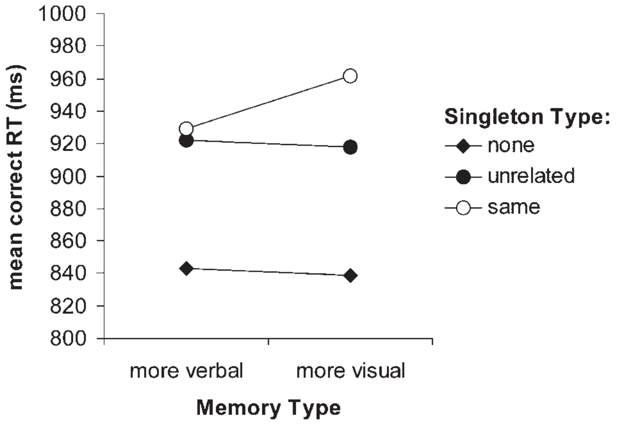

Figure 4. Mean reaction time (RT) results as a function of memory type (more verbal vs. more visual) and singleton distractor type (no singleton, unrelated singleton, or identical singleton) in Experiment 2.

The results provide evidence for memory-driven attentional capture. In the more visual memory condition, interference increased for same singleton distractors relative to unrelated or absent distractors and relative to the more verbal memory condition. These additional costs were not due to a general increase in task difficulty, because this would have predicted additional costs for the unrelated singleton distractors too. Priming can also be largely excluded as a possibility. There was no increased interference for same distractors in the more verbal condition of the current experiment, even though an item had to be attended and remembered. However, priming may still play some role if we assume that the priming strength depends on the amount of attention paid to the prime. Because the more visual memory task was more difficult than the more verbal memory task, participants may have invested more attention in the memory item, which may have resulted in stronger priming in subsequent search displays. We return to this possibility in Experiments 5 and 6.

Another alternative explanation that cannot be excluded at this stage is that observers, realizing that the singleton distractor of the visual search display could be the same as the to-be-remembered item, attended to it in order to use it as a reminder of what the to-be-remembered item looked like—even though this strategy would be detrimental to the search task. We tried to prevent this occurrence by making the singleton distractor the same on only a minority (25%) of trials, but the more visual condition may have been perceived as so difficult that participants believed it would pay off to attend to the singleton distractor. This explanation was controlled for in Experiments 4 and 6. Before that, in Experiment 3 we sought to replicate Experiment 2, but now using shape instead of color as the to-be-memorized dimension.

Experiment 3: Shape-Based Memory-Driven Attentional Capture

In Experiment 3, participants were asked to remember a shape instead of a color. The remembered shape could then return as a singleton distractor in the subsequent search display, in which the target was now the dimmer circle among brighter circle distractors. See Figure 5 for an illustration of the stimuli and procedure. As in Experiment 2, there were two types of memory test: one allowed for more verbal encoding, and the other was assumed to require more visual encoding. In the more verbal condition, the memorized shape (e.g., a star) could be distinguished from other canonical shapes such as a rectangle, triangle, and diamond. In the more visual condition, the memorized shape needed to be distinguished from subtle variants of its own category (in this example, other stars). These variants were created by slightly shifting the position of the apices in a random direction.

Method

Participants. Thirty-two university students, aged 17 to 33 years ($M = 22.4$), participated in exchange for a payment of €7 (approximately $9.00) per hour. All reported having normal or corrected-to-normal acuity and color vision.

Stimuli, apparatus, procedure, and design. The method was the same as in Experiment 2 except for the following changes. The entire experiment was run on the HP/Compaq machines (as were the remainder of the experiments in this article). There were 6 blocks of 64 trials instead of 12 blocks of 32 trials. The greatest change involved the stimuli used. Instead of remembering a color, participants were now required to remember an outline shape (about 3° in diameter), drawn in gray (39 cd/m^2). The shape was randomly selected from four main categories: stars, rectangles, triangles, and diamonds (with the restriction that each category occurred equally often). On each trial, subtle variants were created for each category by randomly displacing the coordinates of the shape's apices by between 0° and 0.15°. One problem with presenting shapes on a computer screen is that the edges often looked jagged ("aliased") because of the limited pixel resolution. Pilot testing revealed that observers could use this jaggedness to recognize the shapes in the memory task. To prevent this problem, the to-be-memorized shape was presented more peripherally, at the same eccentricity as the items in the search display (5.3°), with the restriction that the to-be-memorized item was never presented in the same position as the subsequent singleton distractor or search target. Furthermore, the to-be-memorized item was presented only briefly, for 150 ms, in order to prevent eye movements and the accompanying increase in resolution. Although the presentation was brief, the participants were still allowed ample time to process the shape (4,000 ms), probably using iconic memory (Sperling, 1960).

The target of the visual search display was a relatively dim (16 cd/m^2) outline circle. In the *no singleton distractor* condition, all distractors were 39 cd/m^2 gray outline circles. In the *unrelated singleton distractor* condition, one of the distractor circles was replaced with an outline shape from a different category than the memorized shape, whereas in the *same singleton distractor* condition it was identical to the memorized shape.

Subsequently, at the memory test, the participant was required to choose the remembered shape from three alternatives. In the *more verbal* condition, the alternatives were from different categories. We assumed that observers could use verbal labels to fulfill this task. To promote them doing so, we instructed them to remember the "global shape." Moreover, during the first 16 practice trials, we presented the to-be-memorized shape together with the appropriate verbal label *star*, *rectangle*, *triangle*, or *diamond*. In the *more visual* condition, the alternatives were from the same category, making it more difficult to use verbal labels. In this condition the participants were instructed to remember the "precise shape." We assumed that they would use a more visual memory for this task.

Results and Discussion

The data were analyzed in the same way as in Experiment 2. Table 2 shows the error percentages in the search and memory tasks. On average, 3.9% search errors were made. There were no

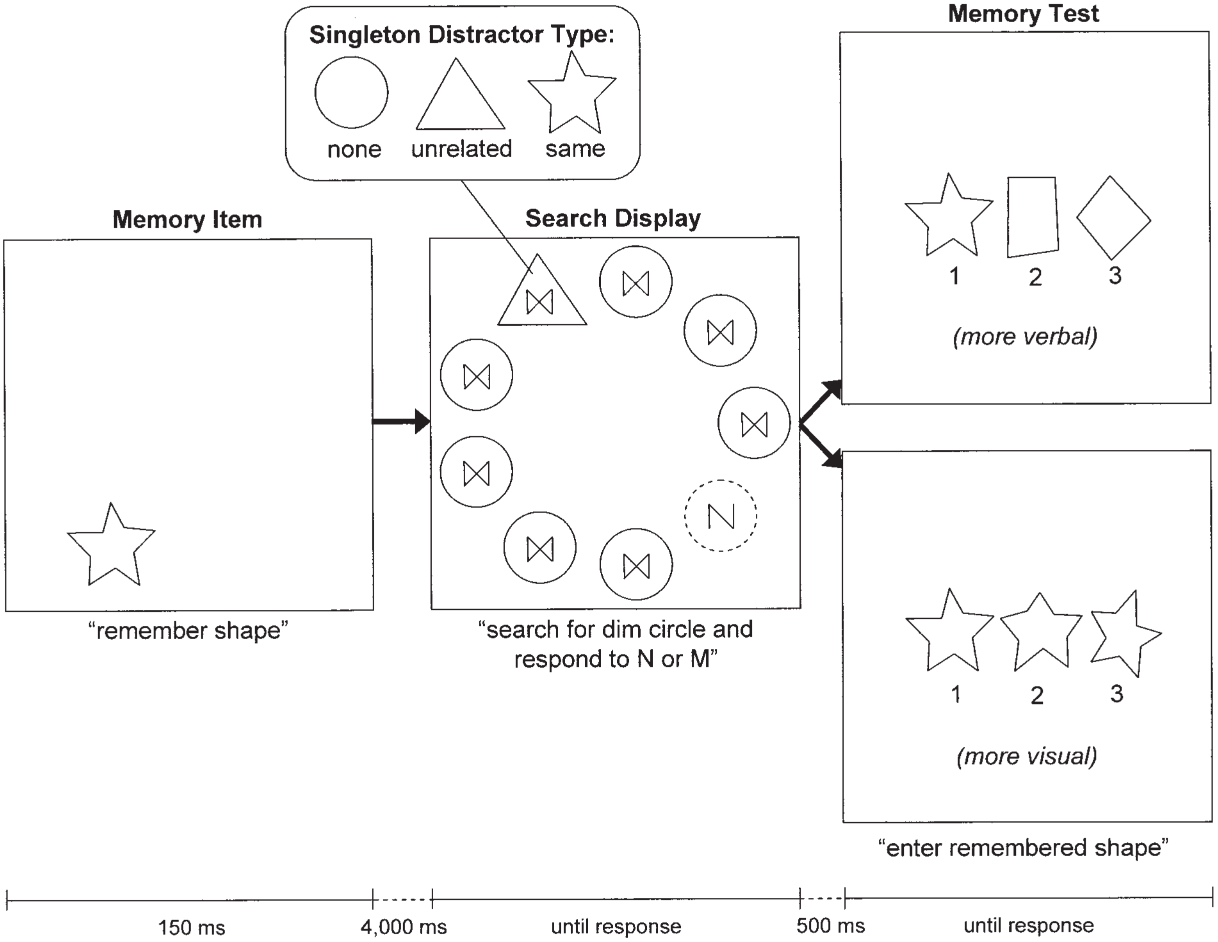

Figure 5. Schematic representation of the stimuli and procedure of Experiment 3.

main effects of memory type and singleton type (*F*s < 1.1, *ns*), but there was a significant interaction, $F(2, 62) = 3.33$, $MSE = 0.001$, $p < .05$. Relative to the more verbal condition, slightly fewer errors were made in the more visual condition for no singleton and same singleton distractor trials, whereas slightly more errors were made for unrelated singleton distractor trials. Even though the differences were only small (see Table 2), this pattern does go against the pattern of RTs, raising the possibility of a speed–accuracy trade-off. However, because we found no evidence for such a trade-off in Experiment 2 and other experiments, and the random mixing of singleton types makes it an unlikely conscious strategy on behalf of the observers, we do not consider this finding as too serious a problem here.

In the more verbal memory task, on average 7.5% errors were made. In the more visual memory task, the mean error rate was significantly higher, at 29.8%, $F(1, 29) = 669.57$, $MSE = 0.008$, $p < .001$. There was also an interaction between memory type and singleton distractor type, $F(2, 62) = 4.71$, $MSE = 0.003$, $p < .05$. This was mainly due to the relatively high number of memory errors made when an unrelated singleton had been present in the more verbal task, followed by the no singleton and the same singleton distractor conditions. It is possible that in memory tests of the more verbal type, participants chose the unrelated singleton's category rather than the memorized item's category. This was not possible in the more visual condition, as there, all test items were of the same category.

Overall, the RTs were about 25% longer than in Experiment 1 and 2, suggesting that the search task used here was more difficult. Because of this, we increased the cutoff limit by 25% to 4,000 ms (which resulted in exclusion of less than 1% of the trials). Figure 6 shows the main results. In general, the presence of a singleton distractor led to slower search RTs: singleton distractor type, $F(2, 62) = 47.53$, $MSE = 7{,}717.60$, $p < .001$. There was no overall effect of memory type ($F < 1$, *ns*). However, there was a Memory Type × Singleton Distractor Type interaction, $F(2, 62) = 3.21$, $MSE = 3{,}048.73$, $p < .05$. Figure 6 indicates that singleton distractors matching the memorized shape led to an increase in search RTs relative to unrelated singleton distractors, but only in the more visual condition. A separate analysis on the unrelated and same singleton distractors again revealed a significant Memory Type × Singleton Distractor Type interaction, $F(1, 31) = 4.88$, $MSE = 3{,}905.06$, $p < .05$, confirming the content-related interaction.

Experiment 2 showed that under visual memory conditions, singletons matching a memorized item in terms of color capture attention. The present experiment shows the same outcome, but

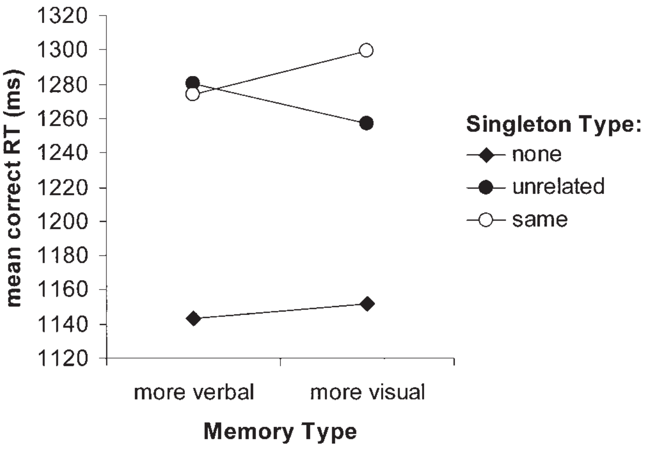

Figure 6. Mean reaction time (RT) results as a function of memory type (more verbal vs. more visual) and singleton distractor type (no singleton, unrelated singleton, or identical singleton) in Experiment 3.

now for shape. We propose that attentional capture can be driven by visual working memory content and that this mechanism generalizes across different visual dimensions. However, the objections against Experiment 2 also hold here. Perhaps the stronger interference in the more visual condition occurs because the more difficult memory task demands more attention, leading to stronger priming effects. Furthermore, the more difficult memory task may entice participants to use the singleton distractor to refresh their memories. We return to these potential problems in the subsequent experiments.

Experiment 4: Remembering Features or Entire Objects?

When, in Experiment 2, participants were asked to remember the color of a disk, did they remember just the color or the entire disk? Likewise, in Experiment 3, when they were asked to remember the shape, did they also remember the shade of gray it was drawn in? In other words, does visual working memory maintain only the feature relevant to the task, or is it obliged to store the entire object—that is, the entire conjunction of features?

Vogel, Woodman, and Luck (2001) estimated that visual working memory capacity is sufficient to hold about four features. Interestingly, they also found that four conjunctions of features could be held without much additional cost, suggesting that visual working memory can store an entire object as a unit. However, the finding that visual working memory can store entire objects just as efficiently as it can store single features does not mean it is obliged to do so. Visual attention studies have suggested that observers can selectively attend to a single feature of an object without the object's other features becoming as activated as the attended attribute (e.g., Corbetta, Miezin, Dobmeyer, Shulman, & Petersen, 1990; Müller, Heller, & Ziegler, 1995). On the basis of our hypothesis that visual attention and visual working memory share the same representations, we might expect that visual working memory can be equally selective.

Experiment 4 tested this prediction by always presenting a to-be-remembered item that carried a specific color (of the kinds used in Experiments 1 and 2), as well as a specific shape (of the kinds used in Experiment 3; see Figure 7 for an illustration). Crucially, in the *color memory* condition, only the color of the initial object would be assessed at the memory test. In the *shape memory* condition, only the shape of the initial object would be tested. These conditions were blocked. Thus, it would be sufficient to remember the relevant property, without the need to remember the entire object. To investigate whether observers indeed prioritize the relevant feature within working memory, we allowed the singleton distractor in the visual search display to be one of four types. The *unrelated* singleton distractor was different from the memorized object in terms of both color and shape and served as a baseline condition. The *color-related* singleton had the same main color as the memorized object but not the same shape. If visual working memory is feature specific, then we would expect increased interference only if color is the relevant dimension. The *shape-related* singleton had a shape of the same category as the memorized object but not the same color. Again, a feature-specific memory would predict increased interference here, but now only when shape was relevant to the memory task. For the *both-related* singleton, both color and shape were of the same categories as for the memorized item. In this condition we would expect increased interference when either dimension was relevant to the memory task.

Experiment 4 also controlled for an alternative explanation of the results so far, namely, that participants may have strategically used (and therefore attended to) the identical singleton distractor in the visual search displays in order to refresh their memories. In the present experiment this was no longer possible. Now, the related singleton was of the same category as the memorized item (e.g., they could both be red and/or both be stars), but it was never identical (i.e., of the same subvariant). Observers were explicitly told that the to-be-memorized item and the singleton distractor were always different and that the latter would therefore not be helpful (and actually be quite obstructive) in remembering the former.

Method

Participants. Twenty-two students, aged 19 to 37 years ($M = 22$ years), participated in exchange for monetary compensation of €7 (approximately $9.00) per hour. They reported having normal or corrected-to-normal vision. One participant was replaced because he performed at chance level in the memory task.

Stimuli, apparatus, procedure, and design. The stimuli and procedure followed those of the more visual memory conditions of Experiments 2 and 3, with the following changes. The target of the visual search display was now defined by size: It was smaller than the distractors (0.8° vs. 1.2° radius). The memory item varied in both shape and color (using the same shapes and colors as in the previous experiments). In the color memory blocks, observers were instructed to remember the color; in the shape memory blocks, they were instructed to remember the shape (and treat the respective other dimension as irrelevant). Within these blocks, only the relevant dimension would be assessed at the memory test. In the color memory condition, the three alternatives of the memory test all had the same shape but varied slightly in color; in the shape memory condition, the alternatives all had the same color but varied slightly in terms of shape. There were two practice blocks of 16 trials for each of the two memory conditions (color and shape). For each memory condition there were two experimental blocks, the order of which was counterbalanced. Within each block there were four singleton distractor conditions, randomly mixed. All singleton distractors deviated in terms of color and shape from the remain-

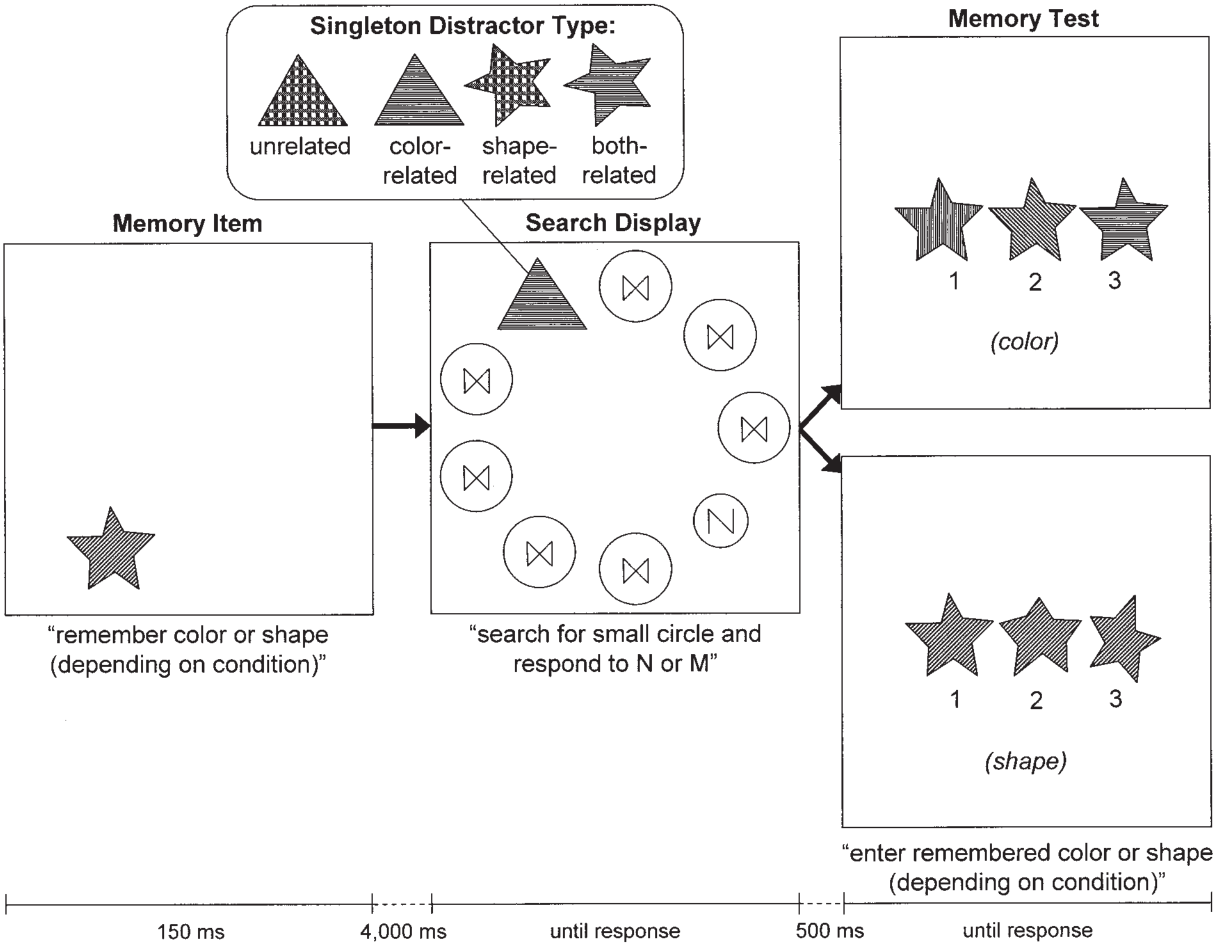

Figure 7. Schematic representation of the stimuli and procedure of Experiment 4. The different patterns correspond to different color categories (red, green, blue, and yellow). Different orientations of a pattern correspond to subtle variants of a color.

ing search elements. In the unrelated condition, the singleton distractor shared neither color nor shape with the to-be-memorized item. In the color-related condition it shared color but not shape, and vice versa in the shape-related condition. Finally, in the both-related condition, the singleton shared both color and shape with the memory item. In contrast to the previous experiments, the singleton was never identical to the memorized item; it could only be related. For instance, if the memorized item was a particular shade of red, then the color-related singleton would be a different shade of red. The same principle held for shape. Participants were notified that the singleton would never be exactly the same as the to-be-memorized item. The related singleton could return as an alternative in the memory test, but this was determined completely randomly (i.e., the related singleton had no more chance of returning as a foil than any of the other color or shape variations). Within each block there were 16 trials per singleton distractor type, except for the unrelated singleton, of which there were 48. Thus, each block contained 96 trials, which resulted in 384 trials in total.

Results and Discussion

The data were entered in an ANOVA with memory type (color vs. shape) and singleton distractor type (unrelated, color-related, shape-related, or both-related) as factors. Table 3 shows the error percentages in the search and memory tasks. On average, 5.0% search errors were made. The analysis revealed a trend toward an interaction, $F(3, 63) = 2.71$, $MSE = 0.001$, $p = .052$. Table 3 indicates a content-specific effect in the color- and shape-related conditions: More search errors were made when the singleton carried a feature that was related to the relevant dimension of the memorized item relative to when it carried a related feature that was irrelevant to the memory task. In the memory task, on average 43.4% errors were made. Overall, more errors were made in the color memory task (52.5%) than in the shape memory task (34.3%), $F(1, 21) = 104.96$, $MSE = 0.014$, $p < .001$, suggesting that the latter task was easier. More errors were made when the singleton was similar in both color and shape to the memorized item, $F(3, 63) = 2.97$, $MSE = 0.006$, $p < .05$. This may suggest that the singleton distractor in the search display interfered with the content of visual working memory. Note further that in the present experiment, the singleton distractor was never identical to the memorized item, to prevent observers from using the distractors as a memory aid. Instead it could be related. However, this raises the possibility that now observers actively used the singleton

Table 3
Error Percentages in the Search and Memory Tasks of Experiment 4

Task (condition)	Singleton distractor type Unrelated	Color-related	Shape-related	Both-related
Search (color memory)	5.2	6.8	5.1	4.8
Search (shape memory)	4.6	3.7	5.8	4.4
Memory (color memory)	52.5	51.8	50.7	54.8
Memory (shape memory)	34.2	32.5	32.9	37.7

distractor as a way to decide *against* one of the alternatives in the subsequent memory test. There were three response alternatives in the memory test, and the singleton may have returned as one of the two foils. As there were 9 color variations and 10 shape variations, the chances of this occurring were 22.2% (i.e., 2 × 11.1%) and 20% (i.e., 2 × 10%), respectively. If participants used the singleton distractor in order to exclude one of the foils, we would expect a bias against the selection of such matching foils. However, no such bias was found: On the trials on which an incorrect probe was selected, in 11.6% of the color memory trials the matching foil was selected, and in the remaining 10.6% the nonmatching foil was chosen. In the shape memory condition these percentages were 11.7% and 8.3%, respectively. So, if anything, there was a bias *toward* the matching foil, not against it (this was not significant, though: overall $p = .30$).

Figure 8 shows the mean RTs. Overall, RTs appeared somewhat faster in the shape memory condition than in the color memory condition, but this was not significant (memory type: $F = 1.0$, *ns*). There was a main effect of singleton distractor type; singletons that shared a feature with the memorized item resulted in increased search RTs, especially when both color and shape were related, $F(3, 63) = 6.56$, $MSE = 1{,}485.42$, $p = .001$. The most interesting effect was a Memory Type × Singleton Type interaction, $F(3, 63) = 3.31$, $MSE = 2{,}385.01$, $p < .05$. As can be seen from Figure 8, whereas both-related singletons were always more disruptive than unrelated singletons, color- and shape-related singletons were only more disruptive if they carried the feature that was relevant to the memory task. An additional ANOVA including only the color- and shape-related singletons confirmed the interaction, $F(1, 21) = 9.13$, $MSE = 2{,}502.02$, $p < .01$; an ANOVA on only the unrelated and both-related singletons showed no interaction ($F < 1$, *ns*).

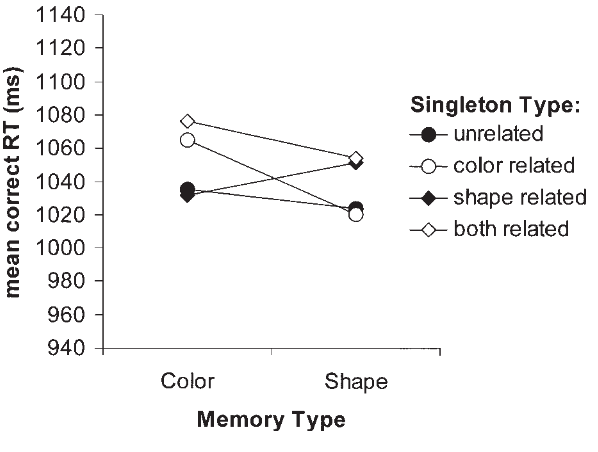

Figure 8. Mean reaction time (RT) results as a function of memory type (color memory vs. shape memory) and singleton distractor type (unrelated, color related, shape related, or both related) in Experiment 4.

Taken together, both the accuracy and the RT data suggest that visual working memory can selectively retain specific features of an attended object. The content-specific interactions indicate that observers retain color when color is important, and shape when shape is important, but that the object's other main attribute can be ignored. Apparently it is not obligatory to fully represent the entire object in visual working memory.

The fact that the relevant feature is more actively represented than the irrelevant feature does not mean that the irrelevant feature is not activated at all. A functional magnetic resonance imaging (fMRI) study by O'Craven, Downing, and Kanwisher (1999) measured the activation of brain areas associated with the different attributes of attended and unattended stimuli. They found that whereas the relevant attribute of the attended object led to the strongest activation, the activation associated with the irrelevant attribute of the attended object was still stronger than the activation associated with the attributes of the unattended object, even though the attended and unattended objects were superimposed on the same position.

A study by Pratt and Hommel (2003) is also relevant here. In their Experiment 4, participants searched an array of items for a target that matched the shape of a preceding cue (either a circle or a square). It was therefore relevant to remember the shape of the cue. The cue also varied in color (between red, green, blue, and white), but this was irrelevant to the task. Between the cue and the target display, a set of colored arrows appeared, one of them pointing toward the subsequent target. Pratt and Hommel found that even though the color of the cue was irrelevant to the task, performance improved when the arrow pointing to the target carried the same color. Contrary to our conclusion, they concluded that participants store an integrated representation of both the relevant and the irrelevant properties in working memory. It is also possible that in our study the irrelevant features were still activated but that our behavioral measures were simply not sensitive enough to pick up on such activation. One difference between our experiment and Experiment 4 of Pratt and Hommel (2003) is that in theirs the memorized object was directly relevant to the search task, whereas in ours it was not. This may mean that their participants much more actively maintained the object's representation, whereas our participants may have put the memory representation on the "back burner" while performing the search task. In any case, Pratt and Hommel's finding does not negate our conclusion that visual working memory can selectively prioritize relevant features.

Experiment 5: Release From Memory

So far we have hypothesized that it is the active maintenance of items (or their features) in visual working memory that affects visual attention. If so, then items that are no longer retained in working memory should lose their effect on search. Experiment 5 explored the fate of once remembered items that were no longer relevant. There were two main conditions, both of which started with the presentation of a to-be-memorized color. Figure 9 illustrates these conditions. The *search before memory* condition was the same as the more visual memory condition of Experiment 2: Following the initial stimulus, participants first performed the search task (in which the color could return as a singleton distractor) and then performed the memory test. Thus, as before, the memory item had to be retained during search. In the *search after memory* condition, the participants first completed the memory test and then performed the search task. In this condition the memory item was no longer relevant by the time the search display appeared. If retention is no longer necessary and the item can be successfully released, the content-related attentional capture should disappear.

Furthermore, this experiment provided another control for priming effects. In the search after memory condition, participants were exposed twice to the memory item before search commenced (once at encoding and once at test). Therefore, contrary to the working memory explanation, we would expect stronger priming effects in this condition than in the search before memory condition, in which observers were exposed only once to the memory item before search started.

Method

Participants. Twenty-four students, aged 17 to 38 years ($M = 21.7$ years), participated in exchange for monetary compensation of €7 (approximately $9.00) per hour. They reported having normal or corrected-to-normal vision. Two participants were dropped from the analyses because they committed more than 25% errors in one of the search conditions, leaving 22 participants in total.

Stimuli, apparatus, procedure, and design. In the search before memory condition, the stimuli and procedure were identical to the more visual memory condition of Experiment 2 except for two changes: The time between the to-be-memorized item and the search display was increased to 5,000 ms, and the time to respond to the memory displays was limited to 3,000 ms. In the search after memory condition, the two tasks were reversed. The initial to-be-memorized item was first followed by a blank for 2,000 ms, after which the memory test appeared for a maximum of 3,000 ms. If participants responded faster than 3,000 ms, the remaining time was filled with a blank, so that altogether, by the time the search display appeared, 5,000 ms had passed (matching the same period in the search before memory condition). The search display appeared until a response was made. The participants first practiced the search before memory condition for 32 trials and then the search after memory condition for 32 trials. They then completed 12 blocks of 32 trials each, 6 for each

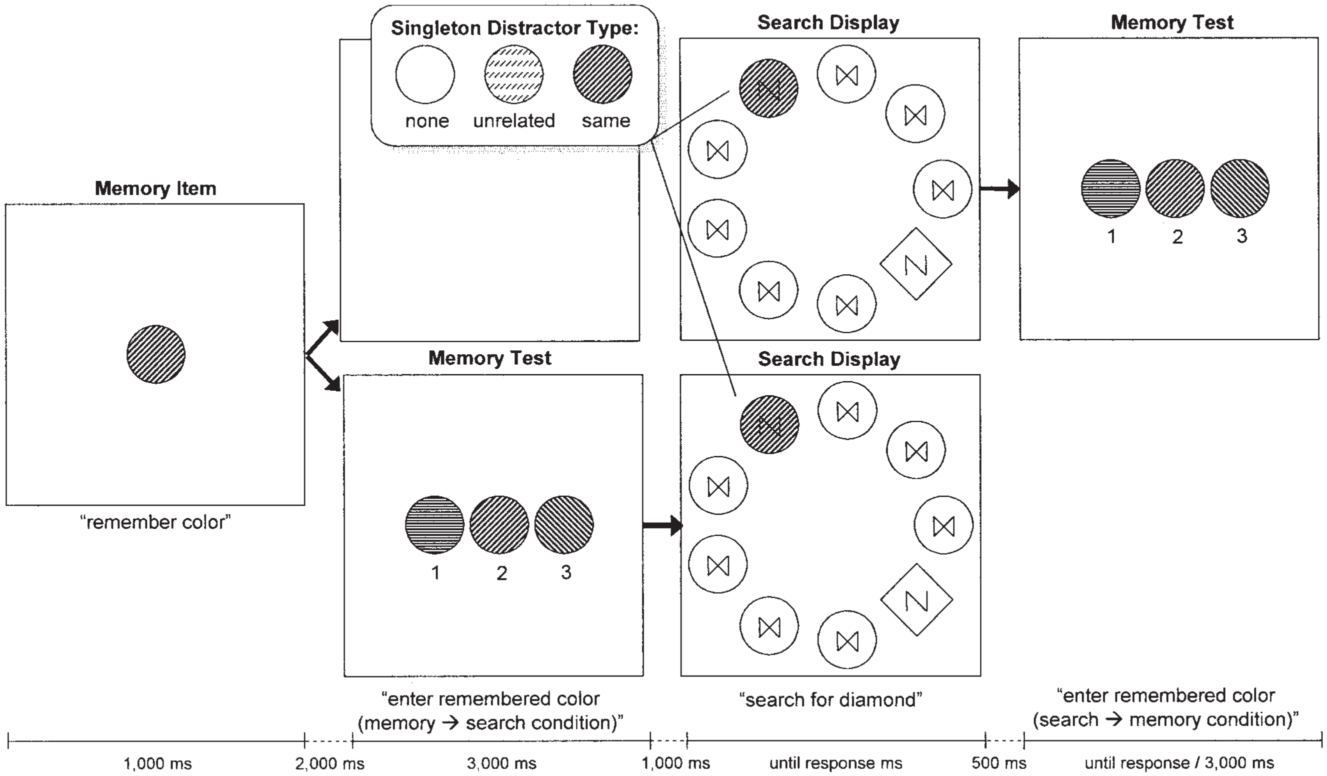

Figure 9. Schematic representation of the stimuli and procedure of Experiment 5. The different patterns correspond to different color categories (red, green, blue, and yellow). Different orientations of a pattern correspond to subtle variants of a color.

condition, in counterbalanced order. Each block contained 8 unrelated, 8 same, and 16 no singleton distractor trials, randomly mixed. In total, this resulted in 48 trials per combination of task order and singleton distractor type (96 for the no singleton distractor condition).

Results and Discussion

The data were analyzed with task order (search after memory, search before memory) and singleton distractor type (none, unrelated, same) as factors. Table 4 shows the error percentages in the search and memory tasks. On average, 3.9% search errors were made. There was a strong trend toward more errors when the memory task was completed first (search after memory condition, 4.4%) than when the search task was completed first (search before memory condition, 3.5%): task order, $F(1, 21) = 4.15$, $MSE = 0.001$, $p = .054$. There were no other main effects or interactions (all Fs < 1, *ns*). On average, 44.5% memory errors were made, with more errors when the search task was completed first (48.7%) than when the memory task was completed first (40.3%), $F(1, 21) = 34.16$, $MSE = 0.007$, $p < .001$. There was a trend toward more memory errors when a singleton distractor was present in the search displays, $F(2, 42) = 2.63$, $MSE = 0.004$, $p = .084$. There was no interaction between task order and singleton distractor type ($F < 1$, *ns*).

Figure 10 shows the mean search RTs. Overall, the presence of a singleton distractor led to slower responses: singleton distractor type, $F(2, 62) = 47.53$, $MSE = 7{,}717.60$, $p < .001$. There was a nonsignificant tendency to respond more slowly when the search task was completed before the memory task than the other way around: task order, $F(1, 21) = 2.45$, $MSE = 2{,}115.76$, $p = .13$. Most important was the Task Order × Singleton Distractor Type interaction, $F(2, 42) = 6.88$, $MSE = 997.75$, $p < .01$. As can be seen from Figure 10, singleton distractors matching the memory content led to increased RTs, but only when the memory task was yet to be completed (search before memory condition). A separate analysis only on the unrelated and same singleton distractors confirmed the interaction, $F(1, 21) = 7.84$, $MSE = 1{,}586.68$, $p < .02$.

The results further confirm the content-based memory-driven attentional capture found in the previous experiments. Here, singleton distractors that matched the memorized items were more disruptive than unrelated singletons, but only when the memorized item had yet to be reported—in other words, when it was presumably still maintained in working memory. No content-based interactions were found when the memory test had just been completed. This means that information that has become irrelevant to the task can be effectively and relatively quickly released from visual working memory and lose its effect on visual attention. It also again means that the results so far have been due not to passive priming effects but to active maintenance of task-relevant information.

Table 4
Error Percentages in the Search and Memory Tasks of Experiment 5

	Singleton distractor type		
Task (order)	None	Unrelated	Same
Search (search before memory)	3.1	3.8	3.6
Search (search after memory)	3.9	4.2	4.9
Memory (search before memory)	46.6	51.0	48.5
Memory (search after memory)	38.8	41.3	40.8

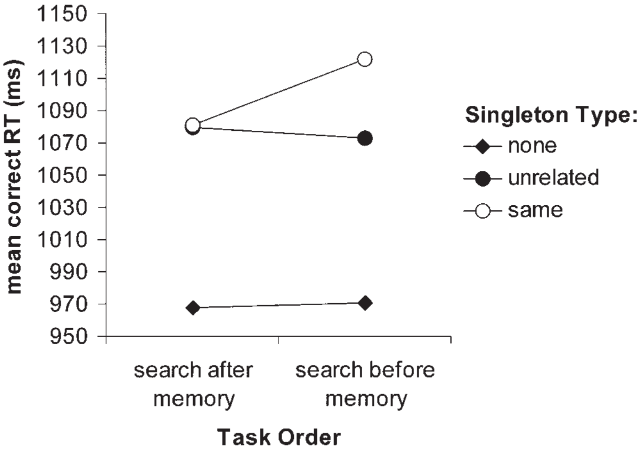

Figure 10. Mean reaction time (RT) results as a function of task order (search completed before or after the memory test) and singleton distractor type (no singleton, unrelated singleton, or identical singleton) in Experiment 5.

Experiment 6: Interference Reduction?

So far we have shown that the active maintenance of features in visual working memory interacts with attending to those same features in the outside world. However, in order to retain information in working memory it is important not only to keep the relevant content active but also to protect it against interference from irrelevant information. It has been proposed that one function of working memory is that such irrelevant stimuli are actively rejected or suppressed while current task goals are maintained (e.g., Lavie, 2000; Miller & Cohen, 2001). If so, then such memory-based rejection or suppression mechanisms may exert their influence on visual attention, in the same way as the active content maintenance mechanisms do.

In this experiment, on every trial, participants were initially required to remember two colors (see Figure 11 for an illustration). After these colors had disappeared, a cue indicated which of the two colors would really be relevant for the remainder of the trial—the color that would be regarded as correct at the later memory test. Because the irrelevant color would also initially have to be remembered, we speculated that after the cue, observers might have to reject or suppress it in order to prevent it from interfering with the relevant memory content. If this rejection or suppression carries over to the visual search display, we may now expect *less* interference from singleton distractors carrying the irrelevant color. The first purpose of Experiment 6 was to test this prediction.

The second purpose of Experiment 6 was to provide a final control for visual priming effects. In the preceding experiments, content-related effects may have been stronger in the more visual memory conditions not because of visual working memory content but because these conditions were simply more difficult, required

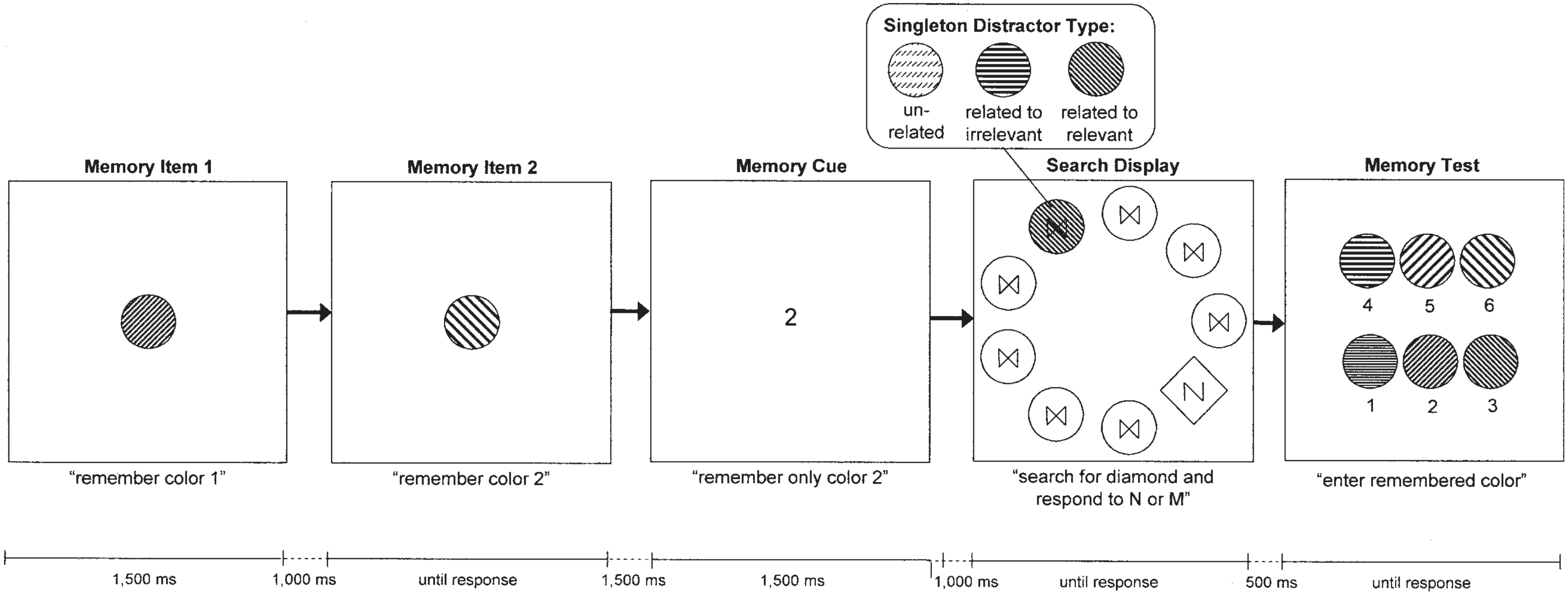

Figure 11. Schematic representation of the stimuli and procedure of Experiment 6. The different patterns correspond to different color categories (red, green, blue, and yellow). Different orientations of a pattern correspond to subtle variants of a color.

more attention, and therefore resulted in stronger visual priming (if we assume that priming strength depends on attention). Experiment 5 already provided results that go against this argument. It showed that content-related effects occurred only when the item was still actively maintained, suggesting that it is not some passive, lower level visual process. In the present experiment, priming was further controlled for in that both the relevant and the irrelevant color initially had to be equally attended (because at the time of presentation it was not yet known which was which). Thus, on the basis of the attention-modulated priming hypothesis, equal effects are expected for singleton distractors regardless of whether they are related to the relevant or to the irrelevant color.

The third purpose of Experiment 6 was to again control for the possibility that observers use the singleton distractor in the search display as an aid in the memory task (i.e., they deliberately attend to the singleton to refresh their memory). As in Experiment 4, the singleton distractor was never identical to the memorized item; it could only be related in color.

Method

Participants. Forty-one students participated in exchange for monetary compensation of €7 (approximately $9.00) per hour. They were 18 to 35 years old ($M = 22.2$), and they reported normal or corrected-to-normal vision. Three participants were dropped from the analyses. Two of these had performed virtually at chance level in the memory task ($< 20\%$ correct; one of them also made more than 32% search errors), and the third produced average RTs of over 2,000 ms in all cells. Their removal left 38 participants in total.

Stimuli, apparatus, procedure, and design. The method was again the same as in the previous experiments, with the following changes. Each trial started with the successive presentation of two colored disks (instead of one), which were presented in the center of the display for 1,500 ms each with an interval of 1,000 ms in between. The participants were instructed to remember the colors of both disks. When the disks had disappeared, after 1,500 ms a gray cue ($x = .30$, $y = .31$; 13 cd/m^2 and height 0.19^o) appeared for 1,500 ms, indicating the to-be-memorized item (*1* for the first color, *2* for the second color, randomly determined).[3] Consequently the indicated color became *relevant* whereas the other color became *irrelevant* for the memory task. After a 1,000-ms blank screen, the visual search display appeared, always containing a color-defined singleton distractor, which could be *related to the relevant* color, *related to the irrelevant* color, or *unrelated* to either. (It was still always irrelevant to the search task.) To avoid the possibility that the participant would attend to the singleton distractor item to aid in the memory task, the singleton was made related in color but never identical. At the memory test at the end of the trial, six disks (instead of three) were presented in two rows centered on the screen. The related singleton distractor could, at chance level, return as a foil in the memory test. One row showed three alternatives of the relevant color category (including the exact to-be-memorized color); the other row showed three alternatives of the irrelevant color category (including the exact to-be-ignored color). The participant had to decide which color was the to-be-memorized one and responded with the ring, middle, and index fingers of the right hand by pressing one of the keys *1* to *6* on the numeric keypad. There were four blocks of 48 trials each, containing 12 related to relevant, 12 related to irrelevant, and 24 unrelated trials each, randomly mixed, resulting in a total of 48 trials per singleton distractor type in total (96 for the unrelated condition). Participants received 24 practice trials before the experiment started.

Results and Discussion

The data were analyzed with singleton distractor type (unrelated, related to relevant, related to irrelevant) as a single factor. On average, 4.0% errors were made in the search task, with no significant differences between the different types of singleton distractor (3.9%, 3.9%, and 4.4% for unrelated, related to irrelevant, and related to relevant singletons, respectively; $Fs < 1$, *ns*). In the memory task, 48.7% errors were made, again without significant differences between conditions (47.6%, 48.5%, and 50.0% for unrelated, related to irrelevant, and related to relevant singletons, respectively; $F = 1.9$, *ns*). These included 5.4% (of the total number of trials) on which the irrelevant color category was chosen (of which 5.8% were in the related to irrelevant condition, 4.8% were in the related to relevant condition, and 5.5% were in the unrelated condition; again, a nonsignificant difference, $F = 1.44$, *ns*). Furthermore, there was no sign of an active bias against memory test alternatives that coincidentally matched the related singleton distractors. Matching probes were selected on average on 11% of the trials, which is exactly the expected value if there is no bias whatsoever (see Experiment 4 for further details).

The analyses of RTs revealed a significant main effect of singleton distractor type, $F(2, 74) = 6.28$, $MSE = 1{,}557.58$, $p < .01$. The direction of this effect is revealed in Figure 12. Participants tended to respond slowest in the related to the relevant color condition (981 ms), followed by the unrelated condition (959 ms) and the related to the irrelevant color condition (950 ms). Additional pairwise comparisons showed that the difference between the related to relevant and the unrelated conditions was significant (981 vs. 959 ms), $t(37) = 2.77$, $p < .01$, as was the difference between the related to relevant and the related to irrelevant conditions (981 vs. 950 ms), $t(31) = 3.07$, $p < .01$. The related to irrelevant and unrelated conditions were not significantly different (950 vs. 959; $t < 1$, *ns*).

The results again revealed memory-driven attentional capture on the basis of the contents of working memory. Singleton distractors related to the memory content were more disruptive than unrelated distractors. No such increased distractor effect was found for singletons related to the irrelevant item—that is, the item that had initially been attended and remembered but could subsequently be ignored. Like Experiment 5, then, this experiment shows that memory-driven attentional capture occurs only when the item is indeed actively maintained in memory. The experiment provides another argument against an explanation in terms of attention-modulated priming. Because initially both the relevant and the irrelevant color had to be remembered, the amount of attention paid to each should have been equal. Yet they resulted in quite different distractor effects. The results also once more argue

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[3] After 20 participants, it turned out that the cue was not generated completely randomly owing to a programming error. In the *related to the relevant* color condition the cue always indicated the first colored disk as the to-be-memorized item. In the *related to the irrelevant* color and the *unrelated* conditions the cue always indicated the second disk as the to-be-memorized item. At debriefing, participants did not indicate having noticed any abnormalities. The fact that trial types were randomized also makes it unlikely that participants noticed the relationship. Note that because the cue and singleton always came after the to-be-memorized items, they had no predictive value for the memory task. After having restored the error, we determined that there was no difference in the pattern of results between the participants who received a randomly generated cue and those who did not. We therefore pooled the data together to create maximum statistical power.

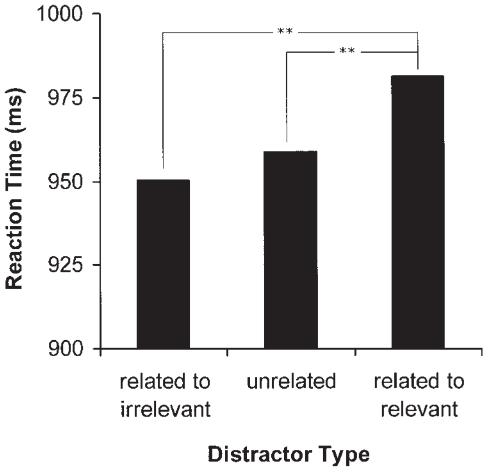

Figure 12. Mean reaction time results as a function of singleton distractor type (related to the irrelevant memory item, related to the relevant memory item, or unrelated) in Experiment 6. $^{**}p < .01$.

against the singleton being used as a deliberate memory aid. Here the singleton color was never identical to the to-be-memorized item, and attending to it should, if anything, only have harmed memory performance.

There was no real sign of active suppression of the irrelevant memory item. Our original hypothesis was that in order to prevent the irrelevant color from interfering with the memory for the relevant color, the irrelevant color might have to be inhibited. We speculated that such inhibition might then carry over to the search display, resulting in reduced interference from a related singleton. However, the singleton related to the irrelevant color was just as disruptive as the unrelated singleton.

Experiment 7: Attentional Capture or Delayed Disengagement? An Eye Movement Study

So far, we have interpreted the memory-related effects as evidence for stronger attentional capture on the basis of memory content. However, at this stage we are still agnostic as to what exactly this "stronger attentional capture" means. One possibility is that observers direct their attention to the related singleton more often than to the unrelated singleton. Stronger capture would thus be equivalent to more frequent attentional engagement. The second possibility is that observers do not attend to the related singleton more frequently but that when they do attend to it they have more trouble moving their attention away. In this case, stronger capture would be equivalent to delayed attentional disengagement, or increased attentional dwell time (Posner, Walker, Friedrich, & Rafal, 1984; see also Theeuwes, Atchley, & Kramer, 1998). Of course, a combination of these processes is also possible. Some evidence for the first option (more frequent engagement) comes from Soto et al. (2005; see also Moores et al., 2003), who found that the first saccade was more often made to a memory-related object than to an unrelated object. They concluded that the memory-based guidance of attention occurs rather early, that is, shortly after the onset of the display. Soto et al. did not look at the second possibility, namely, that attention may dwell on memorized objects for longer than on unrelated objects.

To assess whether the memory-based interference effects found in the present study were due to more frequent engagement, delayed disengagement, or both, we compared eye movement behavior in a condition in which the singleton distractor was related to the content of memory with behavior in a condition in which the singleton was unrelated. If memory-related singletons result in more frequent capture, then we should see more eye movements directed toward the singleton distractor than in the unrelated condition. If related singletons are more difficult to disengage from, then we should find longer fixation times on related than on unrelated singletons.

Method

Participants. Thirteen students participated in exchange for monetary compensation of €7 (approximately $9.00) per hour. They were 18 to 34 years old ($M = 21.9$), and they reported normal or corrected-to-normal vision. One participant was removed from the analyses because her eye movement pattern showed extremely slow and serial search, as she was inspecting the search items one by one.

Stimuli, apparatus, procedure, and design. The method was again the same as in the previous experiments, except that there were now only two conditions. A singleton distractor was always present, and it could either be *related* or *unrelated* to the memory item (which was a single item). The singleton distractor was never the same as the memory item, but it could return (at random) as one of the alternatives in the memory probe. The singleton distractor never appeared in the position next to the target. As before, the visual search set size was nine items in total. Apart from RTs and response accuracy, eye movements were measured during the search displays, using a 500-Hz EyeLink II infrared head-mounted eye tracker (SR Research Ltd., Mississauga, Ontario, Canada; claimed spatial resolution 0.01°), in combination with a chin rest. To make sure that participants really had to make an eye movement to the target, the *M* or *N* printed inside it was reduced from 0.32° to 0.19°. Participants performed 16 blocks of 16 trials each (8 related and 8 unrelated, randomly mixed) with breaks in between. These breaks were also used to recalibrate the eye tracker. The experimental session was preceded by a 16-trial practice session without eye tracking.

Results and Discussion

The data were analyzed with singleton distractor type (unrelated, related) as a single factor.

Response data. On average, 3.5% errors were made in the search task, in both the unrelated and related singleton condition (no significant difference, $t = 0.1$). In the memory task, error rates across the two conditions were also identical, at 37% (no significant difference, $t = 0.25$). Furthermore, there was again no sign of a bias against related singletons at the memory test: Matching probes were selected on average on 14.1% of the trials, which is slightly but not significantly ($p = .17$) more than the expected value of 11.1% (on the basis of nine possible color alternatives; see also Experiment 4). The RTs for correct responses were analyzed for valid eye movement trials only (discussed below), but the results also held when invalid eye movement trials were included. The RT data are shown in Figure 13A. RTs were 32 ms slower when the singleton distractor was related (1,003 ms) than when it was unrelated (971 ms), $t(11) = 3.52$, $p < .01$.

Eye movement data. Eye movement samples were parsed into saccades and fixations using EyeLink II's standard parser configuration, with thresholds set at 30°/s for saccade velocity, 8,000°/s^2

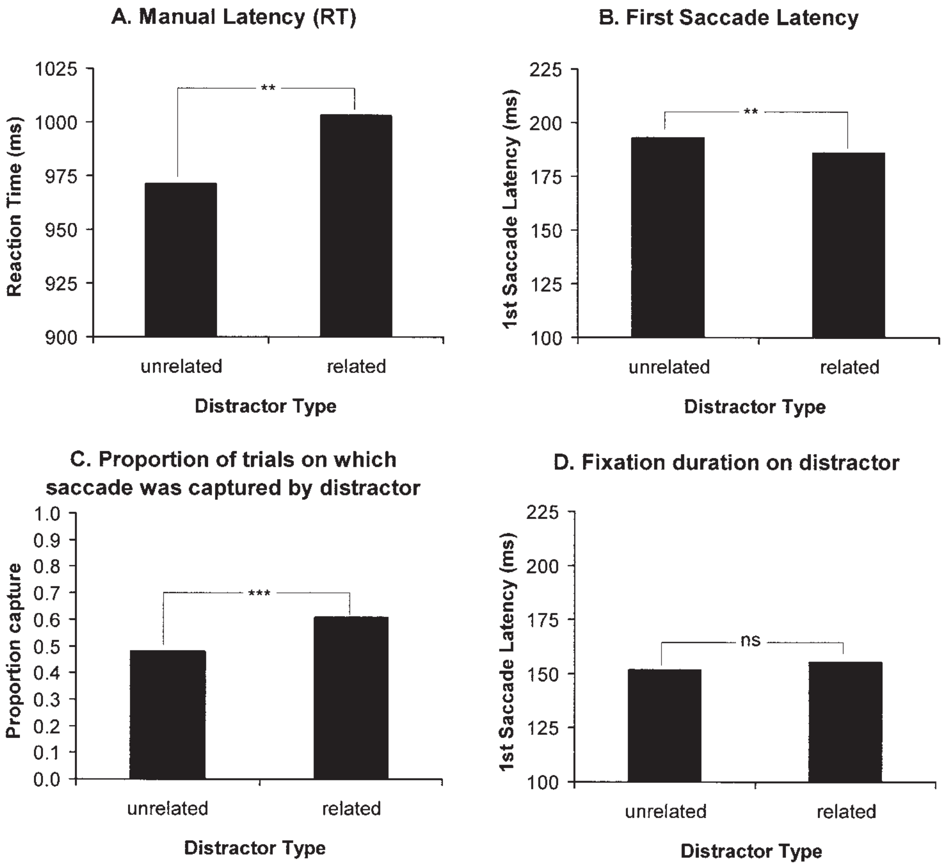

Figure 13. The most relevant data of Experiment 7, as a function of singleton distractor type (unrelated or related). Panel A shows the average manual reaction times (RTs). Panel B shows the average saccadic latency for the first saccade. Panel C shows the proportion of trials on which the eyes went in the direction of the singleton distractor (before going to the target). Panel D shows the average fixation duration on the singleton distractor only for those trials on which attention was captured by it. $^{**}p < .01$. $^{***}p < .001$.

for saccade acceleration, and a minimum of 0.1° initial displacement. Fixations were then classified as *initial fixation* (the very first fixation, falling within approximately 4° from the center of the display),[4] *on target* (the first fixation that was not the initial fixation and that fell on or within one item from the target), *toward the singleton distractor* (any fixation that was not the initial fixation and that fell within a "pie slice" of 40° to either side of the straight line from the center of the display toward the singleton), or *other fixations* (fixations on or toward items other than the target or singleton distractor that occurred before the target fixation). Trials on which no proper initial or target fixations were made or on which eye movement data were (partly) lost owing to blinks or technical problems were marked as invalid. In total, 5.35% of the trials were lost this way, with no difference between related and unrelated singleton conditions (5.3% and 5.4%, respectively). An example trial is shown in Figure 14.

The most important eye movement results are summarized in Figure 13B, 13C, and 13D. On average, the latency of the first saccade (as indicated by the initial fixation duration after display onset; Figure 13B) was 186 ms in the related condition and 193 ms in the unrelated condition—a difference that was small (7 ms) but significant, $t(11) = 3.67, p < .01$. In other words, at the start of the search, the eyes left the initial fixation spot a little sooner when there was a related singleton compared with when there was an unrelated singleton. In contrast, on average the eyes were somewhat slower to arrive at the target when the singleton was related (460 ms) than when it was not (439 ms; a significant difference of 21 ms), $t(11) = 3.01, p = .01$. The most important result was that in the related singleton condition, on a larger proportion of the trials an eye movement was made in the direction of the singleton distractor than in the unrelated singleton condition (63% vs. 48%, respectively), $t(11) = 5.44, p < .001$ (Figure 13C). On about 22% of the trials, other types of eye movements were made (not directed toward target or singleton distractor), with no significant difference between related and unrelated singleton conditions (21% and 23%, respectively; $t = 1.5$, *ns*).

We then analyzed the data separately for trials on which capture did and did not occur. On average, manual response times were slower (1,060 ms) when the eyes were captured by the singleton as

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[4] Participants occasionally failed to fixate on the exact center of the display at the start of the trial. However, the pattern of results did not deviate for these trials, and we decided to regard these trials as valid as long as the initial fixation fell inside the empty inner area of the search display and did not fall within the target or singleton distractor areas.

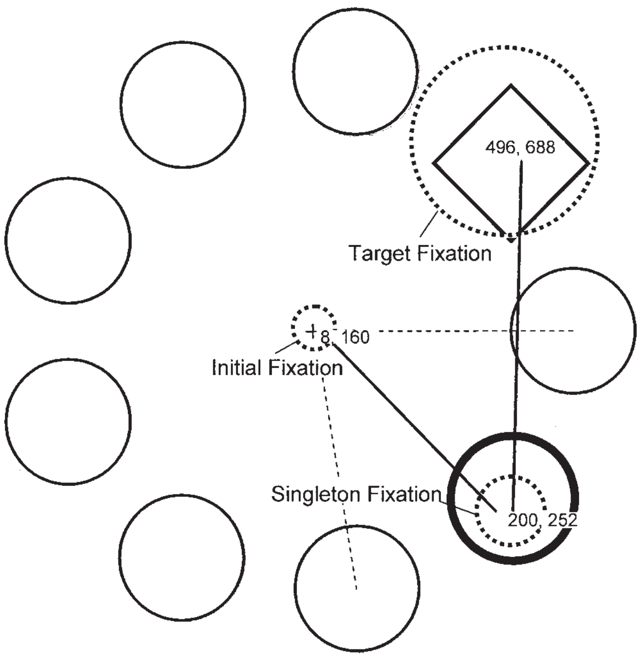

Figure 14. Example eye movement pattern from Experiment 7 (Participant 4, Block 1, Trial 18). The diamond was the target, and the bold disk represents the uniquely colored distractor (which on this trial was related to the memory content). The dashed lines represent the area within which an eye movement was regarded as directed to the singleton distractor (if it was not the initial fixation). The dashed and solid lines represent fixations and eye movements, respectively, with larger circles representing longer fixation durations. The pair of numbers corresponds to the start time (relative to the start of the trial) and duration of the fixation. On this trial the eyes left central fixation after 160 ms ("first saccade latency"), arrived at the singleton distractor 200 ms after display onset, remained fixated on the singleton for another 252 ms, and then arrived at the target location at 496 ms after display onset. The manual reaction time on this trial was 977 ms.

compared with when they were not captured (900 ms), $t(11) = 7.38$, $p < .001$. Initial fixation durations (i.e., saccadic latencies) were shorter when the eyes were captured (177 ms) than when they were not (197 ms), but this effect failed to reach significance, despite 10 out of 12 participants showing it to a smaller or larger extent, $t(11) = 1.64$, $p = .126$. However, eye movements did arrive significantly later at the target after capture as compared with when no capture occurred (511 ms vs. 374 ms), $t(11) = 7.38$, $p < .001$. On trials on which the eyes were directed toward the singleton distractor, the only difference was in the duration of the initial fixation: The eyes left the initial fixation location after 174 ms after display onset when the singleton was related and after 180 ms when it was unrelated (a 6-ms difference), $t(11) = 3.79$, $p < .01$. The eyes also arrived 6 ms earlier at the related singleton distractor (237 ms vs. 244 ms after display onset; not significant, however: $t = 1.02$). It is important to note that on these capture trials, there were no significant differences in fixation duration on the singleton itself, as related singletons were on average fixated for 155 ms and unrelated singletons for 152 ms (Figure 13D). Furthermore, on capture trials, arrival at the target was no later when the singleton had been related (510 ms) than when it had been unrelated (513 ms; $t < 1$, *ns*). Finally, on capture trials, manual RTs were not significantly slower when the singleton had been related (1,067 ms) than when it had not (1,054 ms), $t(11) = 1.34$, $p = .20$.

The results are clear: Once more, manual RTs were found to be slower when the singleton distractor was related to the contents of working memory, demonstrating a memory-driven interference effect. The eye movement data show that this slowing of RTs occurred because related singletons captured attention on an increased proportion of trials relative to unrelated singletons. Furthermore, the saccadic latency for the initial saccade was slightly but significantly speeded when the singleton was related, suggesting that it more strongly attracted attentional orienting than an unrelated singleton. The alternative hypothesis that the slowing of RTs would be due to delayed disengagement from the related singleton was not supported. When the eyes were captured, they did not linger longer at related singletons than at unrelated singletons, and after singleton fixation, they did not take longer to move toward the target. The results therefore point toward increased frequency of engagement, and not delayed disengagement, as the cause of the memory-driven interference.

Again, there was no sign of participants using the related singleton distractor in the search display as an aid to select against response alternatives in the memory test. This conclusion was further corroborated by the eye movement data: If observers had deliberately studied the related singleton distractor to aid their memory, then we would have expected longer fixation times on related singletons than on unrelated singletons. This was not the case.

It is interesting to compare the present study with a recent patient study by Soto, Humphreys, and Heinke (2006a). They compared patients with frontal lobe damage with age-matched controls on a combined working-memory/visual-search task in which the to-be-memorized item could return in the search display, either on the target location (valid trials) or on a distractor location (invalid trials). Relatively more saccades were directed to the target on valid trials than on invalid trials, but this effect was the same for the patients as for the controls, suggesting that the initial capture effect was the same for the two groups. The main difference was on invalid trials, when the first fixation was not necessarily made to the target. Under those conditions, the time to arrive at the target was disproportionately high in the frontal patient group as compared with the controls. This suggests that the patients may have had trouble disengaging from a distractor matching the content of memory. As suggested by Soto et al., frontal damage may lead to deficits in maintaining separate templates for each of the tasks (i.e., the memory item and the search target). Combining Soto et al.'s results (no effects on capture but effects on disengagement) with ours (effects on capture but no effects on disengagement) provides further support for the idea that attentional engagement and disengagement processes can be dissociated (Posner et al., 1984).

Of further interest is the fact that the proportion of trials on which the eyes were captured by the singleton was generally quite high, at 48% even in the unrelated singleton condition. Compare this with a very similar study by Theeuwes, De Vries, and Godijn (2003, Experiment 2), in which participants were also asked to search for a specific target shape and ignore a salient color singleton. Although Theeuwes et al. found signs of attentional capture (i.e., increased manual RTs when a color singleton was present), the singleton distractor hardly ever captured the eyes (only 1.5% of the trials; see also Wu & Remington, 2003). We believe the crucial difference lies in the additional working memory load in the present experiment. In line with previous findings (Lavie & De Fockert, 2005), we speculate that the increased working memory requirements make it more difficult to maintain goal-directed control of attention, resulting in stronger interference from task-irrelevant distractors and therefore more frequent oculomotor capture. Indeed, Experiment 1 provided direct evidence for this by showing increased singleton distractor costs under dual task conditions.

General Discussion

The reported experiments demonstrate the following:

1. Working memory load leads to overall increased interference from singleton distractors in a visual search task (Experiment 1).

2. Visual working memory and visual attention share representations of task-relevant stimuli, as interference is further increased when the distractor matches the content of working memory (Experiments 2–7).

3. However, content-specific interference occurs only when observers are discouraged from using verbal codes and forced to use a (presumably) more visual kind of memory (Experiments 1–3).

4. Just like visual attention, visual working memory can prioritize one feature over the other (Experiment 4).

5. Only those items that are actively maintained in memory drive visual attention. Items that are no longer relevant can be selectively dropped from memory and do not result in increased interference (while relevant items are maintained; Experiments 5 and 6).

6. Increased interference effects occur because attention (and the eyes) goes to the memory-related distractor more often, not because attention dwells on it for longer (Experiment 7).

The present study corroborates and extends earlier findings, while controlling for factors such as low-level perceptual priming by the matching item, the absence of penalties associated with attending to the memorized item, confounding attentional sets for the memorized property, and strategic use of the item in the attention task to improve performance on the memory task, by (a) always making the singleton distractor irrelevant, and in fact harmful, to the task, so that costs would be due to automatic attentional capture and not to implicit or explicit attentional sets (Experiments 1–7); (b) including conditions that controlled for priming, such as the no-memory condition of Experiment 1, the verbal memory conditions of Experiments 2 and 3, the reversed task order of Experiment 5, and the irrelevant but attended color of Experiment 6; (c) including singleton distractors that were related but not identical to the memorized item, so that attending to the singleton distractor was of no use for the memory task (Experiments 4, 6, and 7). Taken together, our results provide evidence for content-based, memory-driven attentional capture, as predicted by the shared representation hypothesis.

Working Memory = Attention?

Our study appears to further fuel the idea that attention and visual working memory should, in essence, be regarded as one and the same concept. They appear to share not only representations (i.e., content) but also the same maximum capacity, the same resources, and the same control processes. In terms of capacity, it has been proposed that observers can typically attend to, track, tag, enumerate, and retain a maximum of around four items simultaneously in both attention and working memory tasks (Alvarez & Cavanagh, 2004; Burkell & Pylyshyn, 1997; Cowan, 2000; Luck & Vogel, 1997; Mandler & Shebo, 1982; Pashler, 1988b; Phillips, 1974; Pylyshyn & Storm, 1988; Sperling, 1960; Trick & Pylyshyn, 1994; Yantis & Johnson, 1990). If they share the same capacity, then filling working memory to the brim should affect attention. To test this, Woodman, Vogel, and Luck (2001) assessed visual search performance when observers had to simultaneously remember a set of up to four objects. They found an overall effect on search RTs, regardless of the number of to-be-searched items. Note, however, that this overall effect is somewhat difficult to explain from a shared capacity perspective, because if memory load results in reduced search capacity, one would expect an increase in search slope rather than just in the intercept. In a follow-up study, Woodman and Luck (2004) found such slope effects when observers were given a spatial memory task instead of an object memory task. Woodman and Luck interpreted this as a content-specific effect: Because visual search is a spatial process, it is affected only by spatial memory. This may be the case, but the alternative explanation is that the spatial memory task was more taxing on general control processes than the object memory task, therefore leaving fewer resources to reject the distractors.

The case for shared resources and control mechanisms is further boosted by the earlier mentioned study by Lavie and De Fockert (2005), demonstrating increased visual distractor interference under conditions of high memory load. It suggests that the maintenance of working memory demands resources or control mechanisms that are otherwise used to bar irrelevant visual information. This result was replicated here in Experiment 1. However, note that this general load effect presents somewhat of a puzzle with regard to our findings in Experiments 2 to 7. There we found increased interference for memory-related singleton distractors in the more visual memory conditions relative to the more verbal memory conditions. However, note that the visual memory conditions were also overall more difficult, as participants made substantially more errors on the visual memory test than on the verbal memory test. We may assume that visual memory load was therefore generally higher than verbal memory load. Yet this did not lead to overall stronger distractor interference in the more visual conditions (i.e., also for unrelated distractors), as would be expected on the basis of the general load effect. We believe the answer lies in another series of experiments by Lavie et al. (2004; especially their Experiments 4 and 5) showing that it is not so much (or not only) the amount of memory load that causes increased interference but the fact that the observer needs to maintain and coordinate two task sets (i.e., dual task coordination load).

In our experiments the bulk of the increased interference may be due to the fact that participants need to coordinate a search task as well as a memory task, regardless of whether the latter was verbal or visual in nature. Important in this respect is that Lavie et al. (2004; Experiment 5) showed that these dual task coordination costs remain the same regardless of whether the secondary task has a high or low load. Furthermore, they found that the same dual task costs occurred even when one task could be finished before the other. This is important in relation to our Experiment 5, where we found no overall difference in capture whether the memory task was completed before or after the search task (there were only content-based effects). Apparently, just having to coordinate two tasks puts a strain on visual attentional control processes, regardless of whether these tasks are high or low in memory load and regardless of whether they overlap.

Another series of studies suggesting shared control mechanisms has looked at the process of maintenance in visuospatial working memory (see Awh & Jonides, 2001, for a review). The idea is that the retention of information occurs through attention-based rehearsal (Smyth & Scholey, 1994). For instance, a series of locations is being remembered by continuously or repeatedly attending to those locations. In support of this idea, Awh and colleagues found that probes presented during the retention interval were better perceived, and resulted in stronger fMRI and event-related potential signals, when occurring at remembered locations as compared with irrelevant locations (Awh & Jonides, 2000; Awh, Jonides, & Reuter-Lorenz, 1998; Awh et al., 1999). Recently, Theeuwes, Olivers, and Chizk (2005) showed that remembering a location affects not only attention but also the oculomotor system, as eye movement trajectories curved away from the memorized location. Furthermore, Awh et al. (1998) found that spatial memory was impaired when observers were given a spatial attention task during the retention interval but not when they were given a nonspatial attention task. This latter finding indicates that not only does the content of working memory affect attention, but the reverse case—attention affecting working memory content—also holds. In the present experiments there were some hints of the singleton distractor influencing memory performance (notably in Experiment 4; see also Schmidt, Vogel, Woodman, & Luck, 2002).

Working Memory Versus Attentional Set

In the introduction we argued that the interference caused by irrelevant singletons reflects involuntary, automatic capture. In the past, such automatic capture effects have been interpreted as evidence for pure bottom-up processing (Theeuwes, 1991, 1992). The fact that in the present study the interference was modulated by working memory content indicates that there is some cognitive penetrability to singleton capture. The effects are reminiscent of the contingent attentional capture by certain features when observers actually adopt an attentional set for that feature (Folk et al., 1992) and what has been termed *conditional automaticity* by Bargh (1992). They clearly suggest top-down influences. Nevertheless, the bulk of the attentional capture effect in our study was still blind to working memory content, and the safest conclusion is probably that both bottom-up and top-down mechanisms affect attentional priority.

Note that we do not want to suggest that the concepts of working memory and attentional set should be treated as one and the same. Although the merging of attention and working memory into a single model sounds attractive to us, we do have reservations. First of all, note that the content-related effects reported here, although reliable and replicable, were relatively small (around 30 to 40 ms). Other studies even failed to find a content-related effect of working memory on attention (Downing & Dodds, 2004; Woodman & Luck, in press; Woodman et al., 2001). This appears to stand in contrast to the rather strong attentional engagement effects found when observers are actually looking for a related object, rather than just remembering it. For instance, Folk, Leber, and Egeth (2002) found that when their participants were looking for a target presented at fixation, the appearance of peripheral distractors that matched the target-defining property caused a drop in accuracy of between 30% and 40%, suggesting that attention was captured on at least those proportions of trials. Similarly strong contingent capture effects have been found on RTs (Folk et al., 1992). Others have suggested that once engaged onto a related object, attention may dwell on it for periods of 200 to 300 ms or longer despite the presentation of subsequent targets (Duncan, Ward, & Shapiro, 1994; Ward, 2001). If both memorizing and looking out for an object involve attending to an internal representation of that object—as is implicitly or explicitly assumed in various attention theories—then what makes the one more effective than the other in driving attention?

There could be several reasons. A rather mundane one is that our tests were simply not sensitive enough to yield strong effects. Participants may have attempted to use verbal codes even in the conditions we assumed to be more visual. This may also partly explain why others failed to find effects at all. For example, Woodman and colleagues used an articulatory suppression task to prevent verbal coding (Woodman & Luck, in press; Woodman et al., 2001), but even this method may not be watertight, allowing for relatively simple color names to be accessed. A second possibility is that the bulk of the singleton distractor interference is caused by the more general load effect, as is suggested by Experiment 1. This may leave little room for additional content-specific effects (i.e., interference is already at ceiling). Indeed, relative to the no singleton distractor conditions, the content-related distractor resulted in costs in the order of 120 to 150 ms, which comes closer to the attentional dwell time effects estimated in other studies.

However, we cannot exclude a more fundamental reason for why pure memory-based attentional capture may be relatively rare or weak. Here we return to the point we alluded to in the introduction: Working memory and attentional set are not necessarily one and the same thing (see Downing & Dodds, 2004, and Woodman & Luck, in press, for similar arguments). Traditionally, working memory and attention have been regarded as two different constructs, one selecting relevant information (i.e., perception) and the other remembering relevant information (i.e., memory). To be able to answer the question of whether these constructs should be better treated as one and the same, one needs to at least give them the chance to behave as two different constructs. In other words, one needs to devise two different tasks: one typical memory task ("now *remember* this green thing here") and one typical attention task ("now *look* for a diamond there"). If we then still find interference between the two tasks, then we can conclude that our constructs should perhaps not be so separate. In typical attentional set studies, however, the to-be-memorized and to-be-looked for stimulus are one and the same.

A study by Chelazzi, Miller, Duncan, and Desimone (1993) may be illustrative here. In this study, trained monkeys were first presented with a single object, which they were required to remember. The initial object disappeared and, after about 3 s, was followed by the presentation of a search display containing multiple objects, one of which could be the same as the remembered object. The monkey's task was to make an eye movement to the matching object. Cells in the inferior temporal cortex that were sensitive to the target object's properties revealed relative increases in activity to the presentation of the target in both the initial memory display and the subsequent selection display. Important here, though, is that the same cells also responded with increased activity during the interval between the memory and the selection display, which likely reflected the maintenance of a target representation until the selection task was finished. This finding has often been taken as evidence for the involvement of working memory in maintaining a target-defining template for selection (e.g., Chelazzi et al., 1993; Desimone & Duncan, 1995). We agree that this task involves a good deal of working memory and that target activity in the absence of the actual stimulus indeed provides evidence for this. However, this does not mean that the activity in these cells in particular directly reflects working memory per se. Note that not only was the monkey required to *remember* the object, it was also required to almost immediately apply the same information to a visual selection task. This means that on top of a memory representation, the monkey may have formed an *attentional set* for the appearance of the same object. Such an additional attentional representation is what may have been measured by Chelazzi and colleagues. If the memorized item had been necessary for some purpose other than an immediately following external visual task (e.g., for internal use or later use), activity in some cells may have been absent or reduced. Our point is that attentional sets may require working memory but that the reverse case is not incontrovertibly true: Working memory does not necessarily result in an attentional set for stimuli for the outside world.

The consequence may have been that in our experiments, the memory and visual search tasks were relatively shielded from each other (Downing & Dodds, 2004). Memory representations may have been protected while the search task received priority, and vice versa (although the fact that the search target always remained the same probably meant that the search task demanded little working memory). Only when the stimulus becomes directly relevant to the task will the additional level of attentional priority be switched on. Under certain circumstances, the memorized item may even be visually suppressed, leading to less rather than more interference in the visual task (Woodman & Luck, in press). Future research will need to address when memorized items are prioritized (as in the present case) and when they can be actively deprioritized (as in Woodman & Luck's case). The point here is that working memory and attention share visual representations (as shown by both the present study and Woodman & Luck's study) but that this does not necessarily mean that priorities are also shared.

Of course, one might argue that the managing of such task priorities should be regarded as an integral part of working memory (Baddeley, 2003; Lavie, 2000). One might even argue that there is no such thing as "pure" working memory, in that a memorized item that is not immediately relevant to the task at hand is by definition not represented in working memory but perhaps either stored in long-term memory or merely lingering as fleeting activation (cf. Potter, 1993). We suspect that in the end, whether or not we will regard working memory and attention as one and the same will depend on such issues of definition. Whether they should be regarded as separate constructs or not, from the present work we can at least conclude that at some level they make use of the same visual representations.

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