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Task-Irrelevant Memories Rapidly Gain Attentional Control With Learning

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Although many of our perceptual biases stem from long-term, repeated exposure, current theories of visual search assume a central role for visual working memory (VWM) in guiding attention to target information. Crucially, whether a VWM representation guides attention depends on the relative priority that the memory has within VWM. Here, in a combined visual search/VWM task, we used attentional guidance by irrelevant memories to measure how long a target representation remains prioritized in VWM when observers repeatedly search for the same target. Irrelevant memories started guiding attention already when the target was repeated once, indicating that the target representation rapidly lost priority within VWM as it moved to long-term memory. By showing that training can lead to interference from irrelevant memories, the findings resolve a long-standing paradox on why VWM appears central to, yet at the same time not sufficient nor necessary for attentional guidance.

Keywords: working memory, involuntary attentional guidance, learning, long-term memory, cognitive control

We often search for visual objects such as a friend, a tennis ball, or a particular key on a keyboard. Most theories of attention claim that visual search requires a visual working memory (VWM) representation that acts like a "search template" or "attentional template" by specifying the target (Bundesen, Habekost, & Kyllingsbaek, 2005; Chelazzi, Miller, Duncan, & Desimone, 1993; Desimone & Duncan, 1995; Wolfe, Cave, & Franzel, 1989). Consistent with this, some studies have found that maintaining a VWM is *sufficient* for guiding attention (Olivers, Meijer, & Theeuwes, 2006; Soto, Heinke, Humphreys, & Blanco, 2005). In these studies, participants performed a visual search task while also maintaining a VWM representation that was only relevant for a later task—the *accessory* memory item. Distractor objects that matched the accessory memory item interfered more with the search than distractors unrelated to the memory, even though both the distractor object and the accessory memory item were irrelevant to the search. However, other studies using variants of this paradigm failed to find interference from memory-matching distractors (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, 2009; Woodman & Luck, 2007), suggesting that maintaining a VWM is actually not sufficient for guiding attention.

Moreover, recent electroencephalography (EEG) studies have provided evidence that VWM may not even be *necessary* for visual search (Carlisle, Arita, Pardo, & Woodman, 2011; Gunseli, Meeter, & Olivers, 2014; Gunseli, Olivers, & Meeter, 2014; Reinhart, Carlisle, & Woodman, 2014). These studies have shown a marked and rapid reduction in VWM related event-related potential (ERP) components when the search target is repeated, which suggests a hand off of the template from VWM to long-term memory (LTM), consistent with theories of learning and automaticity (Anderson, 2000; Logan, 1988; Shiffrin & Schneider, 1977) and previous studies that have observed a role of LTM in guiding attention (Hutchinson & Turk-Browne, 2012; Olivers, 2011). In fact, one may argue that most of our everyday attentional biases stem from repeated exposure, and are engrained in LTM. The evidence that VWM is neither always necessary, nor always sufficient to guide attention is puzzling for theories that put VWM at the heart of attentional guidance.

One piece of this puzzle may be the current understanding that not all VWM representations are equal. There is converging evidence for a functional dissociation between a most relevant, prioritized, item and (at least momentarily) less relevant, nonprioritized items in VWM (LaRocque, Lewis-Peacock, & Postle, 2014; Lewis-Peacock, Drysdale, Oberauer, & Postle, 2012; Lewis-Peacock & Postle, 2012; McElree, 1998; Oberauer, 2002; Zokaei, Manohar, Husain, & Feredoes, 2014). Specifically, attention has been suggested to be guided by the prioritized item in VWM, but not by nonprioritized items, which appear to be kept in a more passive state (Carlisle & Woodman, 2011a; Olivers & Eimer, 2011; for a review, see Olivers, Peters, Houtkamp, & Roelfsema, 2011; Peters, Goebel, & Roelfsema, 2009; Peters, Roelfsema, & Goebel, 2012). In line with this, previous studies observed involuntary attentional guidance by task-irrelevant VWM representations only when it was the single VWM representation, but not when there were more than one VWM representations (Soto, Greene, Chaudhary, & Rotshtein, 2012; Soto & Humphreys, 2008;

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van Moorselaar, Theeuwes, & Olivers, 2014). Accordingly, it seems sensible to assume that when a template is represented in VWM, it will typically be in a prioritized state, reducing accessory items in VWM to the nonprioritized state in which they do not guide attention. Conversely, when the template is no longer that strongly represented in VWM, the accessory item gains priority, and as a result acquires an influence on attention. We hypothesize that this occurs when the target template is learned, and its representation is handed off to LTM.

Initial evidence for the role of learning in VWM-based guidance comes from the division between studies that did (Olivers, 2009; Olivers et al., 2006; Soto et al., 2005) and those that did not observe an influence of accessory memories on attention (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006). In the first set of studies, the target remained the same throughout the experiment, probably causing it to be well-learned. Assuming such a well-learned template is no longer present in VWM, accessory items could gain prioritized status (but see Woodman & Luck, 2007). In contrast, in the second set of studies, the search target was always new, probably resulting in a strong VWM presence that would prevent the accessory item from being prioritized. Consistent with this, Woodman, Luck, and Schall (2007) showed that visual search efficiency suffers from additional VWM load, but only for variable targets. When the target template remains constant, and thus presumably does not reside in VWM, search efficiency is not affected by other VWM items. Furthermore, Olivers (2009) found evidence for guidance from accessory items when the target was constant, but not when it was variable. However, in Olivers (2009), memory load was a potential confound across the two conditions: The consistent target condition contained only a single memory item—the accessory item—whereas the variable target condition had two memory items. Previous studies have shown that VWM-based guidance is compromised for two versus a single item in memory (Soto et al., 2012; Soto & Humphreys, 2008; van Moorselaar et al., 2014). Therefore, the lack of guidance from accessory items in the variable target condition of Olivers (2009) may have been due to the higher memory load in this condition instead of the target learning.

Here we provide direct evidence for the hypothesis that learning a template leads to its deprioritization in VWM, allowing the task-irrelevant accessory item to become prioritized within VWM. Moreover, we provide evidence that this deprioritization of a learned template occurs very rapidly, within just a couple of trials. We used the search task illustrated in Figure 1. On each trial, participants were presented with two items to remember: a search target (a particular shape) and a color. The color became only relevant after the search (or in Experiment 2, was relevant on only 20% of the trials) when participants were asked to report the memorized color, and during search it was thus an accessory memory. The search display contained the target and a colored distractor that matched the accessory memory item on 50% of the trials. Importantly, the search target was then repeated for a number of consecutive trials, which has been suggested to result in the hand off of its representation from VWM (Carlisle et al., 2011; Gunseli, Meeter et al., 2014; Gunseli, Olivers et al., 2014; Reinhart et al., 2014; Reinhart & Woodman, 2014). If this indeed causes the template to be handed off from VWM, this should inadvertently lead to the prioritization of the accessory item (i.e., the color representation) within VWM, as it is no longer competing with the target representation. This in turn should lead to a stronger interference from a memory matching distractor in the search display, leading to slower responses. Thus, our framework makes the counterintuitive but crucial prediction that learning the task-*relevant* item causes increasing interference from task-*irrelevant* (accessory) items. In other words, where previous studies have observed *improved* search performance as the target template is handed off from VWM to LTM (e.g., Carlisle et al., 2011), our hypothesis predicts that repeating targets leads to a *worsening* of performance when there is a distractor that matches the accessory memory, as the transition from VWM to LTM results in a change in attentional priorities within VWM. Moreover, our method provides a behavioral measure for how rapidly this change in VWM occurs.

Such a result would be of significant theoretical importance. First, it would demonstrate that the problems of necessity and sufficiency regarding the role of VWM in attentional guidance are actually related: A task-irrelevant VWM becomes sufficient for driving attention when VWM is no longer necessary for the task-relevant item. This further bridges conflicting findings in the literature. Second, it provides further support for the idea that there are multiple states within VWM, as the accessory item changes from being deprioritized to being prioritized. Third, such a result would be in line with a distinction between at least two partly independent, parallel routes of attentional guidance, both operational at the same time. One is based on LTM and is expressed by improved search for repeated targets when no memory-matching distractor is present. The other is VWM based, and in the present experimental design leads to a worse search performance when there is a memory-matching distractor. Where previous studies have faced the difficulty that VWM-based guidance and LTM-based guidance worked in the same direction, making it difficult to dissociate them, our design can tear them apart exactly because they result in opposite effects. Because of this, our design may yield a clear indication of when, over the course of a set of repetitions, a transition from VWM-based guidance to LTM-based guidance occurs.

Method

Participants

A total of 33 (age between 18 and 28, mean 20.9; 26 female) and 31 (age between 17 and 29, mean 21.1; 24 female) healthy volunteers participated in Experiment 1 and 2, respectively, for course credit or for monetary compensation, after informed consent. The study was reviewed by the faculty's Ethical Committee and conducted in accordance with the Declaration of Helsinki. Thirty participants were planned for each experiment, and extra participants, with some reserve, were run in order to replace outliers. Two participants in Experiment 1 were excluded from analysis, one due to low performance (mean search reaction time, RT, = 1,503 ms, and memory deviation = 28.6 degrees, both beyond 2.5 standard deviations from the grand average RT of 1,025 ms, and deviation of 15.8 degrees), while the other was listening to music during the experiment, contrary to instructions. One participant in Experiment 2 was excluded due to low performance (i.e., chance level—50%—search accuracy, a mean search RT of 1,661 ms, and a memory deviation of 42.9 degrees, both beyond 2.5 standard deviations from the grand average RT of 977 ms, and deviation, 17.6 degrees).

Stimuli

All stimuli were presented on an liquid crystal display (LCD) screen in a darkened cubicle. Viewing distance was approximately

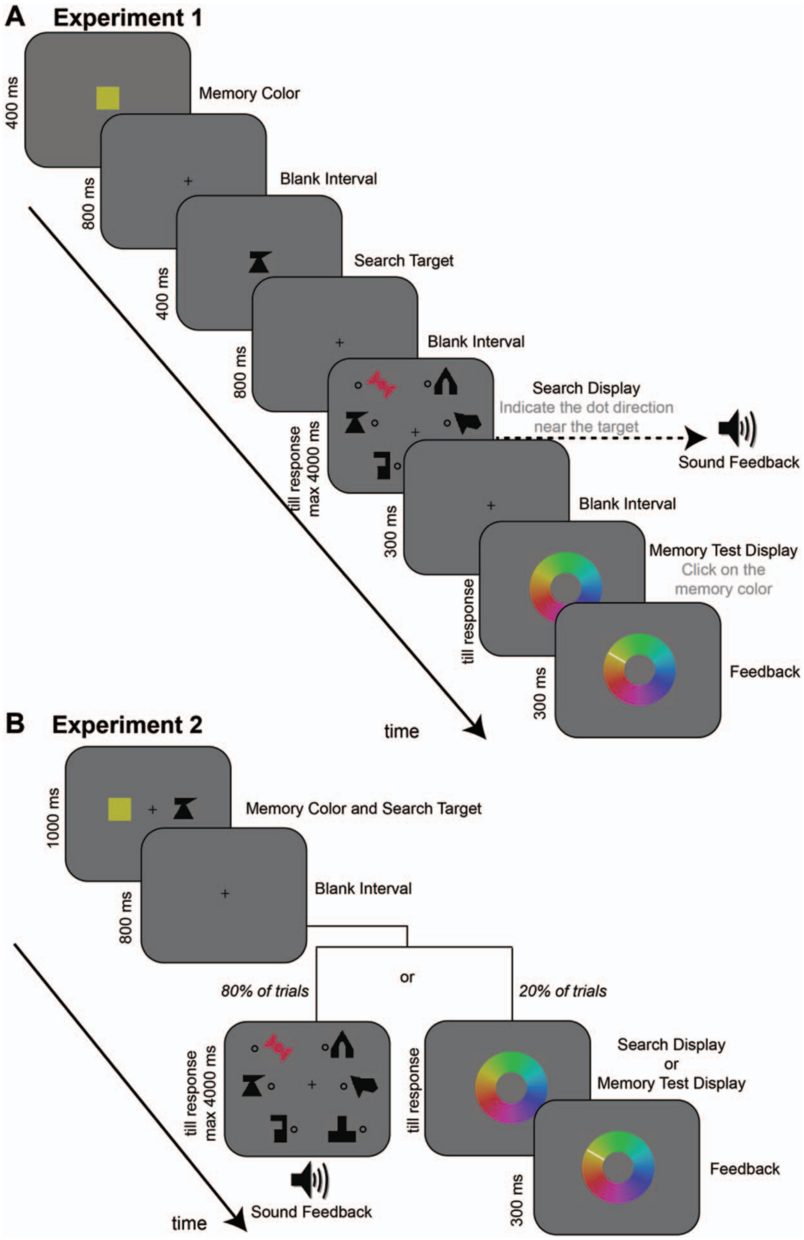

Figure 1. The experimental procedure in Experiment 1 (a). Participants were presented first with a memory color and then with a search target. After a blank period, they were presented with the search display. The task was to indicate the direction of the dot next to the target shape by pressing arrow keys (left vs. right). In this example, the correct response is "right." There was a colored distractor in the search display that matched the memory color on 50% of trials. In this example, it is a memory-mismatching distractor color. After another blank interval, they received the memory test display. The task was to click on the memory color using the mouse. After the click, the position of the real memory color was shown with a white line. The experimental procedure in Experiment 2 was the same except for the following (b). The memory color and the search target were presented simultaneously. After a blank interval, participants were presented either with the search display (80% of the trials) or the memory test display (20% of the trials). See the online article for the color version of this figure.

75 cm. Figure 1 shows the sequence of events for both experiments. The background color was gray (15.64 Cd/m2). The fixation cross was a black plus sign (.20° of line length, .05°of line thickness) and was centrally presented (throughout the method section, we use "°" to refer to the degrees of visual angle, and "degrees" to refer to the circular distance on the color wheel). In Experiment 1, the search target and the memory color were presented sequentially at the center of the screen. In Experiment 2, they were simultaneously presented 1.02° of visual angle to the right and left of the center of the screen. The search target shape

was always presented in black. The memory color was presented as a square (.50° × .50°). The search display consisted of multiple shapes (six or nine in Experiment 1, and always six in Experiment 2) presented on an imaginary circle with a radius of 3.82° in Experiment 1 and 3.18° in Experiment 2. In the search display, one shape was colored, and the rest were black. There was also a dot (a small circle .08° of radius, .05° of line thickness) presented .13° to the left or right of each shape. The shapes were selected from a pool of 100 different shapes (1.42° × 1.42°) generated by Downing and Dodds (2004). The memory color was selected from a pool of 360 different color values that varied in hue, but had the same saturation (.7) and luminance (.7) values based on the hue, saturation, and lightness (HSL) model. These color values were used to generate a ring (i.e., the color wheel) that was centrally presented during the memory test display, adopted from Hollingworth and Hwang (2013). The inner and outer radii of the color wheel were 3.82° and 8.89°, respectively. The feedback for the search task was provided by two different tones indicating accuracy. The feedback for the memory task was a white line (.05° line thickness) extending from the inner radius to the outer radius of the color wheel overlaying the memory color.

Design and Procedure

Each trial started with the presentation of the fixation cross for a randomly jittered duration of 800–1,000 ms. Then, in Experiment 1, the memory color was presented for 400 ms, followed by a blank interval of 800 ms, and the presentation of the search target for 400 ms. After a second blank interval of 800 ms, the search display was presented until response or a maximum of 4,000 ms. The task was to indicate the side of the dot next to the target shape using the arrow keys (i.e., left or right). Auditory feedback on accuracy was provided. Following another blank interval of 300 ms, the memory test display (i.e., the color wheel) was presented until participants mouse-clicked on the color wheel at the location of the memory color. Following a mouse response, the feedback line was presented for 300 ms.

The sequence of events in Experiment 2 was the same as Experiment 1 except for the following. The memory color and search target were presented simultaneously for 1,000 ms. The side of the presentation of the search target and the memory color (i.e., left or right) was constant thorough the experimental session and was counterbalanced across participants. Following a blank interval of 800 ms, either a search display or the color wheel was presented. Task type was randomly distributed across trials with the constraint that 80% of trials per block would be a search task, and 20% a memory task. For both experiments, during the practice session, the search target and the memory color were presented 1,000-ms longer than during the real session (in total, 1,400 ms each in Experiment 1, and 2,000 ms of simultaneous presentation in Experiment 2).

Participants were told that each target was going to be repeated 20 (Experiment 1) or 6 (Experiment 2) times in a row, and were also told that the colored shape in the search display was irrelevant for the task. They were asked to aim for speed without risking accuracy in the search task, and for precision (but not speed) in the memory task.

Experiment 1 employed a factorial design with 2 singleton types (memory-match; memory-mismatch), 2 set sizes (6; 9) and 20 repetitions. Singleton type, set size, and dot sides on the search display varied randomly. Experiment 2 employed a factorial design with 2 task types (search task; memory task), 2 singleton types (memory-match; memory-mismatch), and 6 repetitions; set size was constant (it was six) and the singleton type varied equally and randomly across trials per block. Note that, in Experiment 2, the target repetition indicated the repetition of the same search target as it was presented at the beginning of the trial. Participants did not necessarily repeat the search for this target as many times, as in 20% of the trials there was no search task.

At the beginning of each experimental session, participants performed a practice session of 16 trials in which they were required to achieve a search task accuracy of minimum 75% (80% for Experiment 2), and a memory task deviation of maximum 40 degrees (30 degrees for Experiment 2). Practice session was repeated until these requirements were achieved (1.4 and 1.8 blocks on average in Experiment 1 and Experiment 2, respectively).

Each experimental block contained 36 trials (× 10 blocks) in Experiment 1, and 40 trials (× 14 blocks) in Experiment 2. After each block, there was a self-paced break in which participants were presented with their cumulative average and block average search accuracy, search RT, and deviation. To not confound the distance from the last break with target repetition number, we spaced brakes so that they did not consistently coincide with a first target repetition. However, since there may have been startup costs in the first trial after a break, these trials were excluded from analysis.

For both experiments, a search target shape was not repeated as a target again during the experimental session once its repetition run was over, during a next repetition run, a search target shape from the previous repetition run was not used as a distractor shape, the target color in two consecutive trials were at least 45 degrees away on the color wheel, target color and the distractor color on every trial were at least 45 degrees away on the color wheel, on two consecutive trials, the location of the target (and also the distractor) on the search display was different, and the color wheel was randomly rotated 0, 60, 120, 180, 240, or 300 degrees on every trial.

Data Analysis

Where necessary, *p* values were adjusted based on the Greenhouse–Geisser epsilon correction on degrees of freedom for sphericity violations (Jennings & Wood, 1976). The first trial after each break was excluded from the analysis (see method section). Results of statistical tests in terms of reaching significance were the same without this exclusion. In Experiment 1, consecutive repetitions were binned together to increase power (e.g., 1 and 2, 3 and 4, etc.).

Search Task

The mean RT for each condition was calculated after the exclusion of the trials with incorrect responses in the search task, trials with a deviation larger than or equal to 45 degrees on the memory task (for Experiment 1 only), and outlier trials. Outlier trial removal was performed in two steps. First, trials with a search RT below 350 ms were rejected (0.24% and 0.14% of all trials for Experiment 1 and 2). The second step was a so-called nonrecursive moving criterion procedure, in which trials were removed if the search RTs were beyond *s* standard deviations from the mean per condition, with *s* varying according to the number of data points in that condition (Van Selst & Jolicoeur, 1994). This procedure was preferred over a fixed cutoff point procedure because of the low number of trials per repetition condition in Experiment 1. This two-step trimming led to rejection of 2.82% and 3.01% of all trials in Experiment 1 and 2. Accuracy analysis were performed on the trials that were trimmed based on search RT and memory deviation as described above.

Accuracy and RT were entered in separate repeated measures analyses of variance (ANOVAs) with the factors singleton type, target repetition, and set size.[1] In order to test whether there is an involuntary attentional guidance by the memory color on each repetition, following a significant Singleton type × Repetition interaction, paired-sample *t* tests were used to compare RTs across singleton types on each repetition. In order to test whether the size of involuntary attentional guidance by the memory color was different in early repetitions relative to the later repetitions, paired-sample *t* tests were used to compare the *memory-driven interference* (i.e., the RT difference between memory-match and memory-mismatch trials) for each repetition against the mean of all further repetitions (i.e., 1 against the average of repetitions 2, 3, 4 . . .).

Memory Task

For each condition, the mean deviation score on the color memory test was calculated as the average deviation (i.e., error) of the color selected by the participant from the original memory color, in terms of angular degrees on the color wheel. In Experiment 1, the deviation analysis included trials with a correct search response only. Deviation scores were entered in a repeated measures ANOVA with the factors singleton type (only in Experiment 1), and target repetition (for both experiments). Singleton type was not defined for memory task trials in Experiment 2, because in this experiment a memory task never followed a search task. In Experiment 1, following a significant Singleton type × Repetition interaction, separate repeated measures ANOVAs were used for each singleton type with the target repetition. In order to infer whether the deviation decreased across target repetitions (i.e., memory performance increased), the effect of repetition was treated as a linear contrast (Rosenthal & Rosnow, 1985), but the results of the standard omnibus tests were the same (in terms of reaching significance).

Results: Experiment 1

Search RT

The mean RT in each condition is shown in Figure 2 (collapsed across set size). Responses were overall faster in memory-mismatch than on the memory-match trials, $F(1, 30) = 45.92$, $p < .001$, $\eta_p^2 = .60$ (main effect of singleton type), and they were also different across repetition bins, $F(5.45, 166.38) = 2.12$, $p = .058$, $\eta_p^2 = .07$. Importantly, these two factors interacted, $F(6.19, 185.77) = 2.16$, $p = .047$, $\eta_p^2 = .07$. RT on memory-match trials was larger than on memory-mismatch trials for each repetition bin, *t* values > 2.14, *p* values $< .041$, except bin 1, $t(30) = .63$, $p = .533$. Set size had a main effect on RT, $F(1, 29) = 256.62$, $p < .001$, $\eta_p^2 = .90$. Responses were overall slower for set size 9 ($M = 1{,}093.7$ ms, $SD = 182.0$) compared with set size 6 ($M = 905.7$ ms, $SD = 147.6$). As it did not interact with other factors (*F* values < 1.68, $p > .205$), it is not reported on further.

Memory-driven interference, measured as the RT difference between memory-match and memory-mismatch distractor trials, is presented below the main panels of Figure 2. Interference was smaller in repetition bin 1 relative to the average of any of the other repetition bins (i.e., 2 to 10), $t(30) = 3.14$, $p = .004$; no further increase was seen from the second bin onward (i.e., interference on bin 2 was not different from the mean of bins 3 to 10 etc.), *t* values $< .86$, *p* values $> .394$.

Search Accuracy

The mean accuracy for each condition is shown in Table 1. There was no main effect of singleton type, $F(1, 30) = .10$, $p = .748$, $\eta_p^2 = .01$, nor repetition bin on accuracy, $F(9, 270) = .691$, $p = .717$, $\eta_p^2 = .02$. There was a marginal Singleton type × Repetition bin interaction, $F(5.44, 163.09) = 1.86$, $p = .099$, $\eta_p^2 = .06$, which was not analyzed further as the pattern was not indicative of a speed–accuracy tradeoff. Set size had no effects on accuracy, *F* values < 2.76, *p* values $> .107$.

Memory Deviation

The mean deviation in each condition is shown in Figure 3. Deviation was smaller after memory-matching distractors than after memory-mismatching distractors (main effect of singleton type), $F(1, 30) = 14.95$, $p < .001$, $\eta_p^2 = .33$, and there was a main effect of repetition bin on deviation $(1, 30) = 6.08$, $p = .020$, $\eta_p^2 = .17$, and an interaction between these two factors $(1, 30) = 6.25$, $p = .018$, $\eta_p^2 = .17$. Separate ANOVAs for each singleton type with bin as a linear factor showed that the deviation decreased with increasing repetitions for memory-match trials $(1, 30) = 17.04$, $p < .001$, $\eta_p^2 = .36$, but not for memory-mismatch trials $(1, 30) = .66$, $p = .799$, $\eta_p^2 = .01$.

Results: Experiment 2

Experiment 1 showed that the size of involuntary guidance toward the memory-matching color increased with repeated search for the same search target. This result suggests that learning a template leads to its deprioritization in VWM and consequently the prioritization of the accessory item. However, there is an alternative explanation. Participants might be voluntarily attending to the memory-matching color during search in order to refresh its memory representation for the upcoming memory task. In order to eliminate this alternative explanation, in Experiment 2 a memory task never followed a search task. Instead, at a given trial, participants either received the search or the memory task. Therefore, there was no benefit of deliberately attending to the distractor in the visual search task. Furthermore in Experiment 2, the memory task was not susceptible to any potential confounding effects of an intervening search task such as interference from a colored distractor or the reprioritization of the target shape upon its detection. Lastly, in Experiment 2, the memory color and the

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[1] Data was collapsed across set size (except for set size analysis) because there was 1 participant who had no trials with a correct response in one bin in one condition.

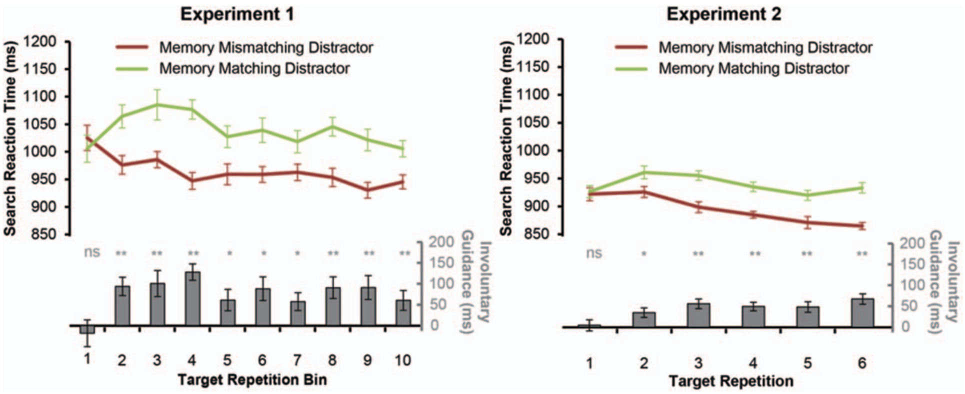

Figure 2. Search RT results from both experiments. Memory-mismatching and memory-matching distractor trials are shown in different colors, given in the legend. The column bars in the bottom panels show the RT difference between memory-match and memory-mismatch distractor trials (i.e., the memory-driven interference). The error bars represent standard mean errors for standardized data (i.e., corrected for between-subjects variance; Cousineau, 2005). The ns, "*" and "**" represent $p > .05$, $p < .05$, and $p < .005$, respectively, for t tests comparing RT in memory-match and memory-mismatch trials (two-tailed). See the online article for the color version of this figure.

search target were presented simultaneously to eliminate any potential effect of the order of their presentation on VWM, because previous research have demonstrated that the item presented last is often prioritized within VWM (Zokaei et al., 2014), and recalled better than items presented earlier (Gorgoraptis, Catalao, Bays, & Husain, 2011; McElree & Dosher, 1989, 1993; Neath, 1993).

Search RT

The average RT in each condition is shown in Figure 2. Responses were overall faster in memory-mismatch than in memory-match trials, $F(1, 28) = 43.36$, $p < .001$, $\eta_p^2 = .61$, and were different across repetitions, $F(5, 140) = 6.76$, $p < .001$, $\eta_p^2 = .20$. As in Experiment 1, there was a Singleton type × Repetition interaction, $F(5, 140) = 2.76$, $p = .021$, $\eta_p^2 = .09$: The RT on memory-match trials was larger than on memory-mismatch for each repetition (t values > 2.53, p values $< .017$), except the first one, $t(28) = .30$, $p = .766$.

Memory-driven interference, measured as the RT difference between memory-match and memory-mismatch distractor trials, is also presented in Figure 2. Interference was smaller in repetition 1 relative to the average of any of the other repetitions (i.e., 2 to 6), $t(28) = 2.93$, $p = .007$, no further difference was seen from repetition 2 to 6 (i.e., interference on repetition 2 was not different from the mean of repetition 3 to 6, etc.; t values < 1.43, p values $> .163$).

Search Accuracy

Mean accuracy in each condition is reported in Table 1. There was a main effect of repetition bin on accuracy that was not further explored, $F(2.80, 78.31) = 5.86$, $p = .001$, $\eta_p^2 = .17$, but none of singleton type, $F(1, 28) = .58$, $p = .452$, $\eta_p^2 = .02$, and no Singleton type × Repetition interaction, $F(5, 140) = 1.43$, $p = .217$, $\eta_p^2 = .05$.

Memory Deviation

The average deviation across repetitions is shown in Figure 3. There was a main effect of repetition on deviation, $F(1, 28) = 18.95$, $p < .001$, $\eta_p^2 = .40$, suggesting that the deviation decreased across target repetitions.

Discussion

Both experiments showed that repeating the search target led to improved search performance (expressed in decreasing RTs) as

Table 1
Search Accuracies for Both Experiments Given Separately for Each Condition

	Accuracy (%)									
Experiment 1										
Target repetition bin	1	2	3	4	5	6	7	8	9	10
Memory-match	98.5	97.3	97.1	97.4	97.0	97.4	96.7	97.2	97.4	97.9
Memory-mismatch	96.2	96.6	97.3	98.1	96.3	97.6	98.9	98.1	98.4	98.1
Experiment 2										
Target repetition	1	2	3	4	5	6				
Memory-match	95.1	97.5	96.7	96.8	97.3	96.2				
Memory-mismatch	93.8	95.9	96.8	96.9	97.7	97.1				

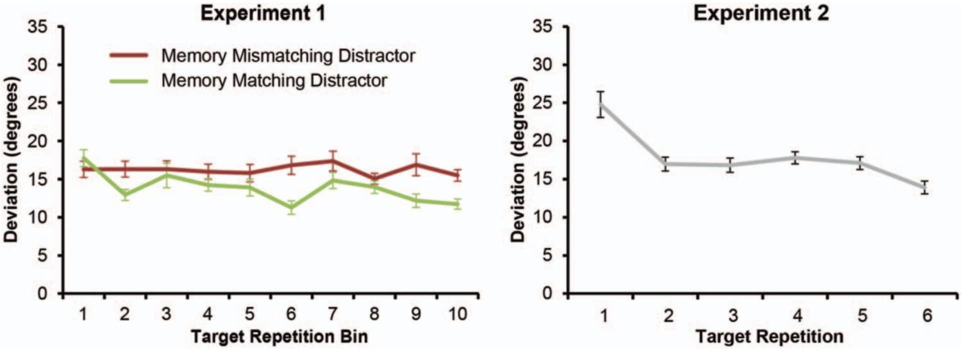

Figure 3. Memory deviation results from both experiments. Lower deviation values indicate better memory. Memory-mismatching and memory-matching distractor trials are shown in different colors, given in the legend. Note that in Experiment 2, the memory task never followed the search task, thus singleton type was thus not defined for memory task trials in Experiment 2. The error bars represent standard mean errors for standardized data (i.e., corrected for between-subjects variance; Cousineau, 2005). See the online article for the color version of this figure.

long as there was no memory-matching distractor present. Consistent with earlier work (e.g., Carlisle et al., 2011), this suggests that the search target was effectively learned within a few trials. Importantly, both experiments showed that learning the search target additionally makes *other* VWM representations, though irrelevant for the search task, guide attention. Whenever observers encountered a new search target, memory-matching distractors did not interfere with search. However, interference rapidly emerged when participants searched for the same target again on subsequent trials. Moreover, recall performance for the memory item improved with repetition of the search target. Together these results suggest that, with learning the task-relevant stimulus, the relative attentional priorities within VWM rapidly change: As the VWM involvement for maintaining a search template reduces, an irrelevant VWM representation gains priority. Furthermore, the results suggest that this occurs already after one or two repetitions, suggesting that a single experience with a search target is sufficient for at least a partial hand off to other memory systems.

The results bridge the divide between studies that had a new target defined on every trial and failed to find attentional guidance from additional VWM content, and those that had a consistent target definition throughout the experiment and did find guidance from VWM (Downing & Dodds, 2004; Houtkamp & Roelfsema, 2006; Olivers, 2009; Olivers et al., 2006; Soto et al., 2005). Our data reveal that concurrently (a) the task-relevant item is learned, and (b) a task-irrelevant item is transferred from a nonprioritized state (in which it does not guide attention) to a prioritized state (in which it does guide attention). Thus, our results show how learning a target unites the different claims in the literature regarding memory-driven interference. Our results also support the claim that multiple representations active in VWM influence attention less than a single active VWM representation (Olivers et al., 2011; van Moorselaar et al., 2014) by showing an increased VWM-based guidance as one of the two VWM representations is transferred to LTM.

Although our results provide an explanation for many inconsistent findings in the literature, there are some studies whose findings cannot be explained by target repetition alone (e.g., Carlisle & Woodman, 2011b; Woodman & Luck, 2007). These studies have used consistent targets yet failed to observe VWM driven involuntary attentional guidance. This suggests that there may be other constraints on guidance by VWM representations that contribute to the inconsistent findings, such as perceptual difficulty of the search display (Han & Kim, 2009). However, our results clearly show that, when these constraints are met, learning the task-relevant VWM representation makes a task-irrelevant VWM representation involuntarily guide attention.

Our results are consistent with the idea that VWM comprises multiple states, such that only currently task-relevant items are maintained in a prioritized state characterized by neural activation, while currently irrelevant items are maintained in a more passive state (LaRocque et al., 2014; Lewis-Peacock et al., 2012; Lewis-Peacock & Postle, 2012; McElree, 1998; Oberauer, 2002; Olivers et al., 2011; Peters et al., 2012; Zokaei et al., 2014). Our data show that a VWM can be prioritized in two ways: Either when it is a new template for the current task, or when it is an accessory item, but the current task-relevant template is no longer represented in VWM (but presumably stored in LTM). In the latter case, the accessory item, as the only one remaining, automatically gains priority. The finding that the prioritization of the accessory VWM item occurs even though it is detrimental for the task suggests that people may have imperfect control over the state of VWM items. Note the similarity to Lavie's perceptual load theory of attention, which states that available attentional resources for perception must be spent even if this leads to attending to distractors (e.g., Lavie, 1995). Here we suggest that this idea may generalize to the VWM domain by showing that resources available for mnemonic prioritization (or internal attention as some refer to it; Chun, 2011; Chun, Golomb, & Turk-Browne, 2011) are spent on the single item in VWM even if that item is task-irrelevant. In other words, if representations are being held in VWM, one of them will be in the prioritized state.

This prioritization of the memory color within VWM may have been an inadvertent consequence of the search template being handed off from VWM due to its repetition across trials. Alternatively, participants may have strategically prioritized the memory color as the search target was learned in order to improve their memory performance. Indeed, memory performance for the color improved over the course of target repetitions in both Experiment 2 and in the memory-match condition of Experiment 1 (though not in that experiment's memory-mismatch condition; it may have been that having to search for the template interrupted the prioritized status of the color memory in both conditions, but that in the memory-match condition the perception of the colored distractor reactivated the color representation within VWM). Whether it was strategic or inadvertent, our results show that the task-irrelevant item (i.e., the memory color) was only prioritized after learning the task-relevant item (i.e., the search template).

The results are in line with the growing evidence in the literature that suggests there are two at least partly independent routes of top-down guidance of attention (Hutchinson & Turk-Browne, 2012). One route operates through prioritized VWM representations that guide attention (which may occur even when these are not task-relevant), while the other route goes via LTM representations of the search target. Because these two routes had opposite effects in our experiments, with repeated targets leading to faster baseline search but more VWM-based interference, our results provide particularly strong evidence for such dual routes to guidance. Interestingly, while normally VWM is seen as the gatekeeper for currently task-relevant activity protecting it against interference from task-irrelevant events (Corbetta & Shulman, 2002; Luck & Vogel, 2013; Schwager & Hagendorf, 2009; Zelinsky & Bisley, 2015), here we report the reverse case: The task-relevant representation drives attention from LTM, whereas the task-irrelevant representation stored in VWM causes interference. Thus, this finding argues against the assumption that VWM content implements current task goals.

The emergence of involuntary guidance from VWM was surprisingly rapid. Within two repetitions of the same search target, the memory item started to cause interference. This is consistent with electrophysiological studies that investigated the markers of VWM maintenance of a template and observed the largest reduction in VWM involvement at the second target repetition (Carlisle et al., 2011; Gunseli, Meeter et al., 2014; Gunseli, Olivers et al., 2014; Reinhart et al., 2014). However, although the decline was rapid, such electrophysiological markers of VWM did not completely disappear, and certainly not already at the second repetition, while in our studies involuntary guidance emerged with the second repetition and remained rather constant from thereon. There are two possible explanations. First, a complete hand off of the template from VWM may not be necessary for accessory items to start guiding attention. Instead, a mere reduction in VWM involvement for maintaining the template may be sufficient for accessory items to gain influence. Second, the hand off might be faster when there are competing demands on VWM (i.e., multiple representations for multiple tasks), as in the present study, than when compared with the electrophysiological studies in which there was less of a demand on VWM (i.e., a single representation for a single task). In any case, our results show that within a few trials observers go on autopilot, where their search is presumably driven by LTM, but becomes susceptible to interference from an irrelevant VWM.

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