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RESEARCH REPORT

Incidental Biasing of Attention From Visual Long-Term Memory

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Holding recently experienced information in mind can help us achieve our current goals. However, such immediate and direct forms of guidance from working memory are less helpful over extended delays or when other related information in long-term memory is useful for reaching these goals. Here we show that information that was encoded in the past but is no longer present or relevant to the task also guides attention. We examined this by associating multiple unique features with novel shapes in visual long-term memory (VLTM), and subsequently testing how memories for these objects biased the deployment of attention. In Experiment 1, VLTM for associated features guided visual search for the shapes, even when these features had never been task-relevant. In Experiment 2, associated features captured attention when presented in isolation during a secondary task that was completely unrelated to the shapes. These findings suggest that long-term memory enables a durable and automatic type of memory-based attentional control.

Keywords: attentional capture, features and objects, episodic memory, memory-guided attention, working memory

Much of the visual information we encounter is highly familiar. We inhabit the same places over time, such as our homes and offices, and these environments are populated by the same people and things. Because of this stability, memory for prior experiences can help us achieve our behavioral goals, such as finding lost keys or a particular spice in the cupboard. This influence of memory on behavior has been construed as a form of top-down attention (Awh & Jonides, 2001), whereby actively maintaining information in working memory increases the priority of matching information in the world, even when task-irrelevant (Soto, Hodsoll, Rotshtein, & Humphreys, 2008). For example, when holding a colored shape in mind for a secondary delayed match to sample task, the appearance of that shape as a distractor during a primary orientation-discrimination task impairs performance (Soto, Humphreys, & Rotshtein, 2007; see also Carlisle & Woodman, 2011; Downing, 2000; Olivers, Meijer, & Theeuwes, 2006).

This prior work shows that recently experienced information, when actively maintained in working memory, gets prioritized if it appears again in the world. However, this mechanism for memory-guided attention has two limitations. First, there are often gaps in time longer than the span of working memory between repeated encounters with the same information (e.g., leaving home in the morning and returning in the evening). Second, when pursuing the goal of finding a target, other information associated with the target but not directly held in working memory might be useful (e.g., looking for a spice based on its label but also knowing its color and texture). In both cases, what influences attention is information from long-term memory retrieved coincidentally with the goal.

Here we characterize the influence of visual long-term memory (VLTM) on the guidance of attention. We show that information that was encoded in the past, but that is no longer present or relevant to the task, nevertheless influences visual search (Experiment 1) and captures attention (Experiment 2) by way of learned associations with the contents of working memory. This contrasts with previous studies showing biases in attention when information in long-term memory is directly presented again (Christie & Klein, 1995), or when explicitly searching for information in working memory is the goal of the task (Stokes, Atherton, Patai, & Nobre, 2012; Summerfield, Lepsien, Gitelman, Mesulam, & Nobre, 2006). In addition, our study complements a growing literature on attentional guidance from long-term memory that has focused on how visual search is biased by preexisting associations in semantic memory (Moores, Laiti, & Chelazzi, 2003; Olivers, 2011; Rappaport, Humphreys, & Riddoch, 2013). By training novel and arbitrary visual feature associations within an experimental session, our study seeks to link episodic memory to attention.

Experiment 1

The goal of this experiment was to investigate how VLTM for features associated with a target influences visual search. We

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tested this by manipulating whether the target appeared with or without those features. We also examined whether such guidance results from automatic reactivation or explicit retrieval of associated features by manipulating their conscious accessibility in VLTM.

Method

Participants. Thirty naïve observers (18 women, mean age = 22.1 years) participated. In this and the next experiment, observers provided informed consent to a protocol approved by the Princeton Institutional Review Board, reported normal or corrected-to-normal visual acuity and color vision, and received course credit or $12 per hour as compensation.

Stimuli. Eight "alphabets" of eight shapes each were used (from Fan & Turk-Browne, 2013). To create novel objects, each shape was assigned a unique angular location (radial eccentricity = 8°) and color (CIE $L^*a^*b^*$ space centered at $L = 54/a = 18/b = -8$; radius = 59°). Stimuli were presented on a CRT monitor 70 cm from the observer, controlled by MATLAB and the Psychophysics Toolbox (http://psychtoolbox.org).

Procedure. The experiment contained eight blocks, each employing one alphabet. Within each block, observers completed three phases: encoding, search, and recall.

In the encoding phase, each object was presented three times in a randomized order, with the constraint that every object appeared once before any object repeated. On every trial (see Figure 1), an object was presented for 500 ms, followed by a 1,500-ms retention interval. Observers were then postcued to report the object's color or location. We previously showed that this form of retrieval practice robustly affects the conscious accessibility of features in VLTM, both enhancing the accessibility of practiced features and reducing the accessibility of unpracticed features (Fan & Turk-Browne, 2013). Observers continuously adjusted a memory probe until it matched the original object on the postcued feature; the shape and uncued feature were presented veridically (e.g., if cued to report the color of a shape, it was shown in the correct location and vice versa). Each object was assigned to either the color-practice or location-practice condition; these assignments were randomized over objects and observers. Because the influence of VLTM on search was of primary interest, only objects whose features were successfully reported during the encoding phase were retained for analysis. This was defined as report error within 1.5× the interquartile range beyond the 1st and 3rd quartiles (Fan & Turk-Browne, 2013; Frigge, Hoaglin, & Iglewicz, 1989; Tukey, 1977). On average, 3.43 of the 64 objects were excluded per observer. This rate did not differ between color-practice and location-practice items ($t < 1$).

In the search phase, observers searched for a cued target shape in cluttered arrays of colorful distractors generated from fragments of novel shapes. The cue consisted of a monochromatic, centrally presented version of the shape. Each shape was cued twice, once present and once absent. The assignment of objects to target conditions was counterbalanced (Figure 2A). This resulted in four conditions for present trials (location match/color match): target matched original object's color and location (+/+); target matched original object's location but appeared in a novel color (+/–); target matched original object's color but appeared in a novel location (–/+); target appeared in a novel color and location (–/–). Novel features were randomly selected >90° from the original value in feature space. Observers were instructed to determine as quickly and accurately as possible whether the *shape* was present or absent—that is, regardless of its color or location. The array remained onscreen until response. We tested two hypotheses: First, if VLTM for associated features guides search for the target shape, response times (RTs) should be faster when there is a location and/or color match. Second, if these features are reactivated automatically, RT effects should not only be present when a matching feature was practiced, and thus more consciously accessible (Fan & Turk-Browne, 2013), but also

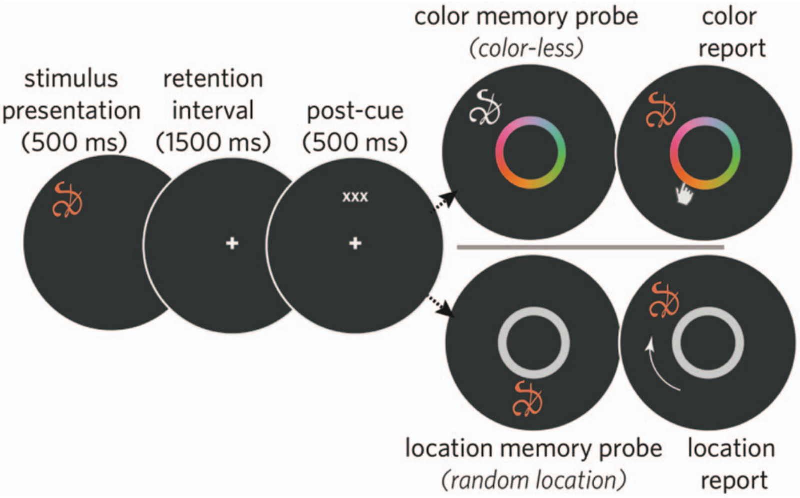

Figure 1. Encoding task. On each trial, one shape was presented in a unique color and location. After offset, a postcue ("xxx" replaced by "color" or "location") prompted observers to report one of these two features by continuously adjusting a memory probe until it matched the original stimulus. Objects were viewed multiple times and the same feature was postcued each time. See the online article for the color version of this figure.

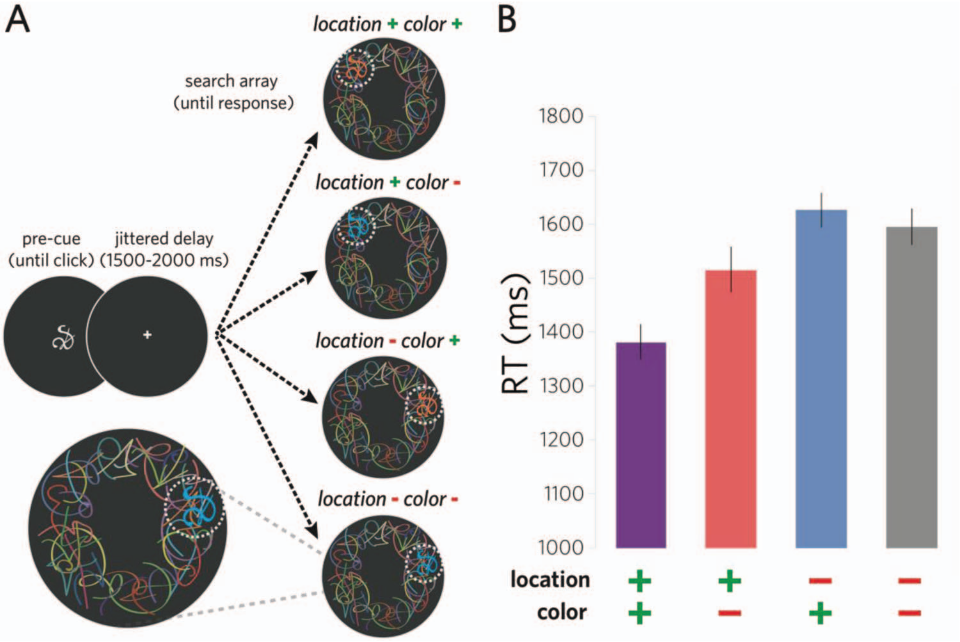

Figure 2. Search phase of Experiment 1. Observers determined whether a cued shape was present or absent within a cluttered display, regardless of its color or location (A). Enlarged version of sample search array also provided for greater legibility (left-bottom). Mean log-transformed search response times (RTs) for correctly detected targets, as a function of whether the target matched the color and/or location of the cued shape from encoding (B). Error bars reflect ±1 SEM. See the online article for the color version of this figure.

when a matching feature was not practiced (e.g., location match for color-practiced objects).

In the recall phase, observers were prompted to report the practiced feature of each shape, as verification that VLTM had been formed.

Results and Discussion

Encoding phase. Accuracy exceeded chance (root mean squared error, RMSE, = 103.9°) for all three presentations of a shape for both color (RMSE $< 12.7°$; $t(29) > 139.2$, $p \ll 0.001$) and location (RMSE $< 3.61°$; $t(29) > 711.8$, $p \ll 0.001$). We analyzed errors using a 2 (Dimension: color, location) × 3 (Presentation number: first, second, third) repeated-measures analysis of variance (ANOVA; see Table 1). There was a main effect of feature dimension, $F(1, 29) = 269.0$, $p \ll 0.001$, $\eta^2 = 0.903$, with higher accuracy for location than color. There was no main effect of presentation number, $F(2, 58) = 0.677$, $p = .512$, $\eta^2 = 0.023$, or interaction, $F(2, 58) = 0.769$, $p = .468$, $\eta^2 = 0.023$, suggesting that repeated practice did not boost the fidelity of observers' already accurate reports.

Table 1
Encoding Phase Accuracy. Root Mean Squared Error (RMSE) in Degrees (and Standard Error of the Mean) for the Report Task, by Practiced Dimension and Presentation Number

Practiced dimension	Presentation number		
	1	2	3
Color	12.7° (.59°)	12.3° (.51°)	12.2° (.66°)
Location	3.21° (.14°)	2.76° (.14°)	3.61° (.14°)

Search phase. The primary dependent measure of interest was RT. As in other visual search tasks, RTs were slower for target-absent trials ($M = 3.33$ s, $SD = 1.88$ s) than target-present trials ($M = 1.51$ s, $SD = 0.35$ s; $t(29) = 6.03$, $p < .001$, $d = 1.10$). Because conditions were defined by the color and location of the target, only correct target-present trials were included in subsequent RT analyses. RTs greater than 3 *SD*s from the mean in each condition or longer than 10 s were trimmed (0.26% of trials). To mitigate the influence of extreme values, single-trial RTs were also log-transformed prior to computation of the mean, and the mean was then transformed back using the exponential function. None of these steps affected the overall pattern of results.

To test our first hypothesis that feature associations in VLTM guide search, we analyzed RTs using a 2 (Location match) × 2 (Color match) repeated-measures ANOVA (Figure 2B). There was a main effect of location match, $F(1, 29) = 12.8$, $p = .001$, $\eta^2 = 0.306$, but no main effect of color, $F(1, 29) = 1.31$, $p = .262$, $\eta^2 = 0.043$. This suggests that VLTM specifically guided spatial attention to the search target, perhaps reflecting the spatial demands of the visual search task or the more precise encoding and better recall of location associations. However, a reliable interaction, $F(1, 29) = 4.19$, $p < .05$, $\eta^2 = 0.126$, combined with a significant ordinal interaction, $t(29) = 3.69$, $p < .001$, $d = 0.674$; see Strube & Bobko, 1989, revealed a superadditive benefit of matching colors for the location effect. This provides tentative evidence that color associations in VLTM may have partially guided attention, in conjunction with location associations.

To test our second hypothesis that feature associations in VLTM can guide visual search automatically, we compared the location match effect in RT between location- and color-practice items, finding no difference as a function of practice, $F(1, 29) = 0.216$, $p = .646$, $\eta^2 = 0.007$. Indeed, the location match effect was reliable for color-practice items when analyzed separately, $F(1, 29) = 13.0$, $p = .001$, $\eta^2 = 0.310$, suggesting that conscious accessibility of features in VLTM did not modulate the degree to which VLTM influences spatial attention during visual search.

In order to examine how location and color associations influence search, the target shape appeared in its original location half of the time and in its original color half of the time. Therefore, although observers were instructed to search for the shape itself, it could have been beneficial to strategically retrieve and search for these features. To test this possibility, we examined the prevalence of this strategy and its effect on the results. During debriefing, 6 out of 30 observers (20%) reported using a strategy of retrieving and searching for associated locations and/or colors. When these observers were excluded from analysis, however, we obtained the same pattern of results, including: the main effect of location, $F(1, 23) = 12.2$, $p = .002$, $\eta^2 = 0.347$, the significant ordinal interaction with color, $t(23) = 3.19$, $p = 0.004$, $d = 0.652$, and no modulation of the location effect by practiced feature, $F(1, 23) = 0.001$, $p = .979$, $\eta^2 < 0.001$. These results lend further support to the idea that attentional guidance by VLTM can occur automatically.

For completeness, we also analyzed the accuracy data from the search phase (see Table 2). We quantified accuracy with A', a nonparametric measure of sensitivity (Grier, 1971). A 2 (Location match) × 2 (Color match) repeated-measures ANOVA revealed no main effects of location match, $F(1, 29) = 0.644$, $p = .423$, $\eta^2 = 0.022$, or color match, $F(1, 29) = 0.687$, $p = .414$, $\eta^2 = 0.023$, and no interaction, $F(1, 29) = 0.878$, $p = .356$, $\eta^2 = 0.029$. These results argue against the possibility that the RT effects reflected a speed–accuracy trade-off.

Recall phase. During the recall phase, accuracy exceeded chance for both color (RMSE = 61.4°; $t(29) = 11.4$, $p \ll 0.001$, $d = 2.08$) and location (RMSE = 45.5°; $t(29) = 21.0$, $p \ll 0.001$, $d = 3.84$), with better memory for location than color, $t(29) = 5.82$, $p < 0.001$, $d = 1.06$. These results verify that observers encoded the shapes and their practiced features into VLTM.

Table 2
Search Phase Accuracy. Mean A', Hit Rate, and False Alarm Rate by Condition (with SEM)

		Accuracy		
Location	Color	A'	Hit rate (%)	False alarm rate (%)
+	+	.956 (.010)	88.3 (2.24)	4.0 (1.60)
+	−	.943 (.019)	86.7 (2.84)	4.8 (2.48)
−	+	.944 (.019)	87.1 (2.43)	4.4 (2.34)
−	−	.946 (.016)	86.3 (2.19)	4.2 (1.73)

Experiment 2

Experiment 1 suggested that VLTM for the location of an object is reactivated during visual search for the object. Experiment 2 sought to expand these findings in three ways.

First, we wanted to better assess VLTM guidance for color. In Experiment 1, the presence of a matching color from VLTM only influenced visual search insofar as the location also matched VLTM. Here we use a simpler paradigm that has previously revealed attentional capture for colors and shapes in working memory (Soto et al., 2007).

Second, we aimed to further test the automaticity of such guidance by making VLTM associations entirely task-irrelevant. In Experiment 1, associated locations and colors could be construed as task-relevant because they were each useful on half of trials for finding the target. Observers were not informed about this, and debriefing data suggested that strategic use of these relationships was uncommon, as well as unnecessary to observe guidance. Nevertheless, to more definitively rule out such a strategy, we employ a dual-task paradigm in which associated colors serve as task-irrelevant distractors.

Third, we sought to verify that our practice manipulation affected the conscious accessibility of features in VLTM. In Experiment 1, the location guidance effect was observed for color-practice objects, which we interpreted as support for automaticity because the unpracticed locations underlying this guidance were assumed to be less consciously accessible. This assumption was based on our prior work (Fan & Turk-Browne, 2013), and we were unable to independently verify it because the final recall phase only tested practiced features. Here, we test recall of both practiced and unpracticed features in a subset of observers to replicate this prior work and support the claim that unpracticed features were less accessible.

Method

Participants. Sixty naïve observers (34 women, mean age 19.2 years) participated.

Procedure. For each observer, six alphabets each containing 10 shapes were used, for a total of six blocks. Within each block, a similar three-phase design was used: encoding, dual-task, and recall. There were three differences in this experiment: First, each object was presented five versus three times during encoding, which we thought might benefit learning of feature associations, without extending the duration of the experimental session beyond 1 hr. Each object was assigned to either location- or color-practice. Again, only objects whose practiced features were successfully reported during encoding were retained for analysis (2.9 of the 60 objects excluded per observer).

Second, the search task was replaced by a dual-task consisting of an outer-loop delayed match to sample task and an inner-loop orientation-discrimination task (Figure 3A). The delayed match to sample task required that a monochromatic, centrally presented version of a shape be maintained in working memory (cue = 2,000 ms, delay = 700 ms + orientation discrimination RT; modeled on Soto & Humphreys, 2007) and compared with a test shape (50% match). During the delay, two horizontally offset Gabor patches were presented (frequency = 2 cpd; eccentricity = 6.8°) for the orientation-discrimination task. One (target) patch was randomly tilted 26° (clockwise/counterclockwise) from vertical, and the

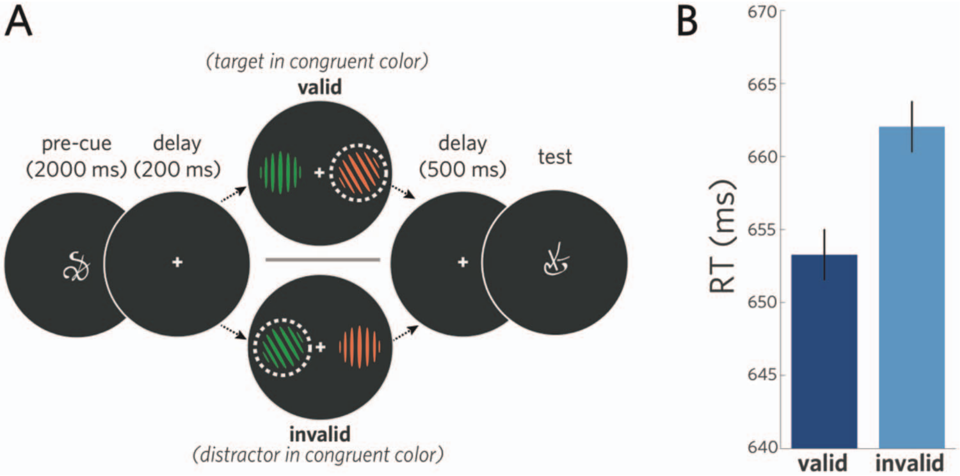

Figure 3. Dual-task phase of Experiment 2. While maintaining a (monochromatic) shape in working memory, observers discriminated the orientation (clockwise/counterclockwise) of the tilted Gabor (target; A). The color of this patch was associated with the shape on 50% of trials (valid). On the remaining trials, the vertical Gabor (distractor) appeared in this color (invalid). Mean orientation-discrimination response times (RTs) as a function of validity (B). Error bars reflect ±1 SEM. See the online article for the color version of this figure.

other (distractor) patch was vertical. The location of the target was randomized, and observers judged its tilt direction. Additionally, one of the patches appeared in the color associated with the delayed match to sample target in VLTM and the other in a different color (>90° away). Each shape served as the delayed match to sample target twice: once where the target patch in the orientation-discrimination task matched the associated color (valid), the other where the distractor patch matched the associated color (invalid). Thus, the associated color predicted neither the location nor orientation of the target and was therefore completely task-irrelevant. Before the experiment, observers were trained on both tasks to the same performance criterion: 90% correct with RTs $< 1{,}000$ ms (from Soto et al., 2007).

This phase allowed us to test a key hypothesis—that VLTM for the associated color is reactivated during the delayed match to sample task, drawing attention to the matching patch in the orientation-discrimination task, and speeding RTs for valid versus invalid trials. Such a result would license strong claims about the automaticity of guidance: not only was the color association irrelevant to the delayed match to sample task, the shape cue was irrelevant to the orientation-discrimination task.

Third, to verify that our manipulation of conscious accessibility of features in VLTM was successful, we ran two cohorts of observers in this experiment (each with $N = 30$, equal in size to Experiment 1). The first cohort was tested on either the practiced or unpracticed feature of each object (counterbalanced across objects) during the recall phase. Comparing recall performance as a function of practice allowed us to verify that unpracticed features were less consciously accessible. The second cohort was always tested on the practiced feature of each object in the recall phase to mirror Experiment 1. The two cohorts only differed in the recall phase (after the critical dual-task phase), and thus, we did not expect this between-subjects manipulation to influence the critical dual-task results. Therefore, we pooled observers from both cohorts into the final sample, though we also verified with an ANOVA that the amount of guidance did not differ between groups.

To compare recall performance for practiced and unpracticed features in the first cohort, we used an approach from Fan and Turk-Browne (2013), who found that unpracticed features were less accessible (the basis for our assumption in Experiment 1). Specifically, we fit a model to the distribution of errors that observers made when reporting one or the other feature in the recall phase (cf. Zhang & Luck, 2008; Wilken & Ma, 2004). Maximum likelihood estimation was used to partition errors into two component distributions (Equation 1): (1) a uniform distribution reflecting the probability of guessing (i.e., 1 – probability of successful retrieval from memory) and (2) a von Mises distribution (an approximation to a wrapped normal distribution) centered on the actual feature value whose variance provides a measure of the precision of memory for the feature.

$$p(\hat{\theta}) = \beta\phi_{\sigma}(\hat{\theta} - \theta) + (1 - \beta)\frac{1}{360} \qquad (1)$$

Here, β represents the probability of successful retrieval from memory, and φ_{σ} represents the von Mises distribution centered on the actual feature value θ with standard deviation σ. Because of the small number of recall phase trials collected per test condition per observer (30 trials each), errors were pooled across observers within each condition for subsequent analysis, providing sufficient statistical power to derive robust model estimates. Random-effects reliability was established across observers by iteratively resampling observers with replacement 2,500 times to derive 95% confidence intervals for each model parameter in each condition (Efron & Tibshirani, 1986).

Results and Discussion

Encoding phase. During the encoding phase, performance was better than chance at all five-item presentations for both color

(RMSE $< 15.7°$; all $t(59) > 77$, $p < 0.001$) and location-practiced items (RMSE $< 10.8°$; all $t(59) > 169$, $p < 0.001$). We analyzed encoding phase errors using a 2 (Dimension: color, location) × 5 (Presentation number) repeated-measures ANOVA (see Table 3). Accuracy was again higher for the location versus color dimension, $F(1, 59) = 40.2$, $p < .001$, $\eta^2 = 0.405$, and there was no effect of presentation number, $F(4, 236) = 1.06$, $p = .378$, $\eta^2 = 0.018$.

Dual-task phase. Only trials where responses to both the orientation discrimination and delayed match to sample tasks were correct (93.3%) and less than 1,000 ms (93.9%) were included in RT analyses (from Soto et al., 2007). The delayed match to sample task served to induce maintenance of a shape with color associations, so beyond showing that participants were highly accurate in this task overall (Table 4; vs. chance of 50%, $t(59) = 87.2$, $p \ll 0.001$, $d = 11.3$), it is not analyzed further and we focus analysis on the orientation-discrimination task.

Consistent with our hypothesis, orientation discrimination was slower for invalid (662 ms) versus valid trials (653 ms; $t(59) = 2.57$, $p = .023$, $d = 0.332$), suggesting that the color associated with the shape in working memory captured attention (Figure 3B). The color validity effect did not differ between location and color-practice items, $F(1, 59) = 1.10$, $p = .298$, $\eta^2 = 0.018$, similar to what was found in Experiment 1. The two observer cohorts did not differ in overall RT, $F(1, 58) = 0.061$, $p = .805$, $\eta^2 = 0.001$, nor did the color validity effect differ across cohorts, $F(1, 58) = 0.029$, $p = .864$, $\eta^2 < 0.001$. Moreover, accuracy did not differ between valid and invalid trials, $t(59) = 0.051$, $p = .959$, $d = 0.007$, inconsistent with a speed–accuracy trade-off (see Table 4).

We interpret these findings as reflecting attentional capture from the memory-matching color on invalid trials (consistent with Soto et al., 2007). However, another possibility is that the memory-matching color facilitated attention to the target on valid trials. Future experiments could disentangle these processes with a neutral condition (i.e., search arrays without the memory-matching color). Nevertheless, the key goal of this experiment was to show that, beyond the salience of the current display and the identity of cues being maintained in working memory, information from VLTM can also influence attention. The RT difference between valid and invalid trials, whether driven by capture or facilitation, helps achieve that goal.

Recall phase. During the recall phase, both color (RMSE = 51.9°; $t(59) = 20.3$, $p \ll 0.001$) and location (RMSE = 51.5°; $t(59) = 18.4$, $p \ll 0.001$) accuracy exceeded chance performance, and they were not different from one another, $t(59) = 0.167$, $p = .867$, $d = 0.022$, demonstrating successful encoding of practiced features into VLTM.

Confirming that our practice manipulation influenced recall (without affecting guidance), the probability of retrieval (β) was lower for the unpracticed feature than for the practiced feature in the cohort who was tested on both ($p = .003$; Table 5). There was no such difference in precision (inversely related to σ), however ($p = .223$), suggesting that practice affected the conscious accessibility of memories but not their fidelity.

General Discussion

This study aimed to elucidate some ways in which long-term memory influences visual selection. To accomplish this, we associated multiple features with novel shapes in VLTM, and then tested how these associations subsequently biased attention when this information was no longer task-relevant. Experiment 1 showed that VLTM for the associated location of a target guided spatial attention during visual search for the target, even when this location was task-irrelevant. Experiment 2 extended these findings by showing that VLTM for the associated color of a target induced attentional capture in a different task.

These results build on previous work that examined the relationship between memory and attention (see Awh, Belopolsky, & Theeuwes, 2012; Hutchinson & Turk-Browne, 2012). For example, there are many compelling examples of attentional guidance by task-irrelevant information in working memory (e.g., Soto et al., 2007; see also, Carlisle & Woodman, 2011; Downing, 2000; Olivers et al., 2006), but these typically depend on memory for recently viewed features rather than automatic reactivation of features in VLTM. Perhaps the closest analogues to our findings come from the growing literature on attentional guidance from long-term memory. These effects range from more implicit in the case of interference from semantic memory during search (Moores et al., 2003; Olivers, 2011; Rappaport et al., 2013), to more explicit in terms of the influence of episodic memory on search within scenes (Stokes et al., 2012; Summerfield et al., 2006; West Chanon & Hopfinger, 2008).

Our findings complement this prior work, but are distinct in multiple important ways: First, we show that such memories can guide attention toward associated features even when these features were encoded incidentally and were never relevant to any task. In studies of contextual cueing, for example, repeated pairings of a spatial context with a target location can speed visual search (e.g., Chun & Jiang, 1998; Endo & Takeda, 2004), even in the absence of explicit awareness of these repetitions. These spatial associations are encoded and tested in the same task, cued by the same visual information across encounters, and always relevant to the task of searching for the target. By contrast, we demonstrated (in Experiment 1) that exposure to objects in particular colors and

Table 3
Encoding Phase Accuracy. Root Mean Squared Error (and SEM) in the Report Task by Practiced Dimension and Presentation Number

Practiced dimension	Presentation number				
	1	2	3	4	5
Color	15.5° (1.15°)	15.6° (.83°)	15.1° (.96°)	15.2° (1.03°)	14.4° (.80°)
Location	10.2° (.40°)	10.8° (.51°)	10.6° (.55°)	10.4° (.51°)	10.2° (.46°)

Table 4
Dual-Task Phase Accuracy. Orientation-Discrimination and Delayed Match to Sample Task Performance (% Correct) by Condition

			Accuracy	
			Orientation discrimination (%)	Delayed match to sample (%)
Condition	Color-practiced	Valid	96.6 (.67)	95.9 (.66)
		Invalid	97.0 (.54)	96.1 (.57)
	Location-practiced	Valid	97.1 (.48)	96.4 (.62)
		Invalid	96.5 (.58)	96.3 (.75)

locations in a short-term recall task (i.e., not a search task) established associations in long-term memory that guided attention in a later visual search task. These findings show that such associations can be abstracted away from the encoding context, and that this generalization allows the associations to transfer flexibly and automatically to a novel context at test. This is especially true in Experiment 2, in which memories guided attention toward associated features even when these features were completely irrelevant to the current task—not only omitted from the task instructions, but in fact orthogonal to the relevant aspects of the task.

Second, rather than relying upon preexisting semantic associations (as in Olivers, 2011), we show that VLTM for experimentally induced, arbitrary feature associations can also bias attention, providing evidence of a more causal link between long-term memory and the automatic deployment of attention. This distinction is meaningful, given that semantic memories derived from experience have been encountered dozens to hundreds of times over many weeks or years, and via consolidation have been embedded in neocortical areas such as the anterior temporal lobe (Binney, Embleton, Jefferies, Parker, & Lambon Ralph, 2010; Mummery et al., 2000). By contrast, the associations acquired in our study are episodic, in the sense that they are arbitrary with respect to existing knowledge, have only been experienced a handful of times, and have not benefitted from sleep consolidation outside the hippocampus and integration with cortical schemas (Lewis & Durrant, 2011; McClelland, McNaughton, & O'Reilly, 1995; Vargha-Khadem et al., 1997).

The present findings are consistent with a common mechanism for these diverse examples of memory-guided attention, whereby an object's features are automatically retrieved from long-term memory based on environmental cues, encoded into working memory, and these working memory representations (as in Soto et al., 2008) bias selection toward items in the world that at least partially match reactivated features. This interpretation has origins in modal models of memory (Shiffrin & Atkinson, 1969), in which working memory serves as the juncture between long-term representations and ongoing sensory processing. Moreover, it makes novel predictions about the scope of VLTM guidance of attention, insofar as capacity limitations in working memory should create a bottleneck for reactivation and guidance.

Table 5
Recall Phase Performance. Model Parameter Estimates for Responses When Tested on the Practiced Feature vs. Unpracticed Feature

	Probability of retrieval (β)		Precision of memory (σ)	
	MLE	95% CI	*MLE*	95% CI
Practiced feature	.699	[.613, .779]	14.3°	[12.6°, 16.0°]
Unpracticed feature	.626	[.540, .714]	15.7°	[14.0°, 17.5°]

Note. *MLE* = maximum likelihood estimation; CI = confidence interval.

Another potential theoretical account is that associations retrieved automatically from VLTM may directly influence attention without needing to be temporarily encoded into working memory. This view has been supported recently, including the finding that visual search can be efficient even when the number of potential targets, sampled from a large set of previously studied items, exceeds limits on working memory (Wolfe, 2012). Moreover, stimulation of a frontal brain region thought to index the accumulation of traces in long-term memory can directly induce changes in perceptual attention without affecting neural correlates of working memory load (Reinhart & Woodman, 2015). Although our findings do not adjudicate between these accounts, a fruitful avenue for future research is to elucidate the shared and distinct mechanisms by which representations in working memory and long-term memory guide attention.

Interestingly, our manipulation of the conscious accessibility of features in long-term memory did not modulate the degree of attentional guidance. This suggests that although selective attention during encoding constrains subsequent explicit recall of object features (Fan & Turk-Browne, 2013), unselected features are encoded at some level and can still influence behavior. Because we used a postcue to manipulate attention, all features may have received similar "external" attention, with cued features receiving additional "internal" attention (Chun, Golomb, & Turk-Browne, 2011). Less overall attention during encoding may impair later controlled retrieval but not automatic reactivation from long-term memory. Moreover, controlled retrieval may specifically benefit from the more elaborated internal attention during encoding, whereas automatic reactivation may only require external attention.

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