AMERICAN PSYCHOLOGICAL ASSOCIATION

Journal of Experimental Psychology:
Human Perception and Performance

ISSN: 0096-1523

2023, Vol. 49, No. 6, 907–922
https://doi.org/10.1037/xhp0001098

Category-Specific Learning of Color, Orientation, and Position Regularities Guide Visual Search

Ariel M. Kershner and Andrew Hollingworth
Department of Psychological and Brain Sciences, The University of Iowa

In six experiments, we examined how object categories structure the learning of environmental regularities to guide visual search. Participants searched for pictures of exemplars from a set of real-world categories in a repeated search task modeled on the contextual cuing literature. Each trial began with a category label cue, followed by a search array of natural object photographs, with one target object matching the category label. Participants completed a series of search blocks, each containing one search trial per category. Individual categories were assigned either to the Repeated condition or to the Novel condition. For Repeated categories, a perceptual feature value of target objects remained constant across each search for that category: color (Experiments 1 and 3), orientation (Experiment 2), and position (Experiment 4). For Novel categories, the relevant feature value varied randomly for each search for that category. We observed a *categorical cuing* effect, with faster improvement in reaction time across blocks for Repeated compared with Novel categories. This effect reflected both the episodic retrieval of the immediately preceding search episode in that category and cumulative learning across multiple searches within a category. The cuing effect was observed from the very first repetition, a point in the experiment where the learning effect was not plausibly strategic. Finally, participants could reliably retrieve and report the repeated values in memory tests administered either at the end of the experiment or when the effect first emerged (Experiments 5 and 6), demonstrating that nonstrategic guidance of attention can be driven by explicitly available memory.

Public Significance Statement
In six experiments, we examined how object categories structure the acquisition and expression of statistical regularities guiding visual search for different perceptual feature values. Search templates were biased toward categorical regularities, and nonstrategic guidance of attention was driven by explicitly available memory.

Keywords: visual search, contextual cuing, categorical cuing

Every day, we search for objects from familiar real-world categories, such as searching for a pen in a crowded kitchen drawer. How might attention be guided efficiently in this case? First, attention might be guided to the pen because it is physically salient, although this is unlikely in a kitchen drawer containing a heterogeneous collection of objects. In addition, attention might be guided in a goal-driven manner based on a template specifying the perceptual properties of the target, such as a search for a favorite blue pen. Finally, attention might be guided through the nonstrategic influence of selection history, as environmental regularities (such as the frequent location of the pen) are learned from previous searches and other encounters.

Selection history has come to play a major role in theories of visual search, since it has become clear that such effects account for a substantial proportion of the variance in attention guidance (Anderson et al., 2021; Awh et al., 2012; Failing & Theeuwes, 2018). However, to be of any functional utility in real-world search, the learning that supports guidance by selection history must be *structured*, reflecting how the visual world is structured. For example, learning that search targets have been found most frequently in the front-left corner of the kitchen drawer does not provide much information about where targets are likely to appear in a car or in a handbag. And learning the probable location of pens does not provide much information about the probable locations of cats or shoes. That is, learning during visual search needs to be structured, at a minimum, both by the scene context in which it occurs and the category of the target object.

Researchers have made substantial theoretical and empirical progress toward understanding how scene context structures the acquisition of environmental regularities guiding visual search, collected under the term *contextual cuing* (for a review, see Sisk et al., 2019). In the original contextual cuing experiments, participants searched for a T among Ls in Repeated and Novel search arrays (Chun,

This material is based on work supported by the National Science Foundation Graduate Research Fellowship Program (Grant DGE-1945994).

The data and materials for the experiments reported here are available upon request. None of the experiments were preregistered.

Correspondence concerning this article should be addressed to Ariel M. Kershner, Department of Psychological and Brain Sciences, The University of Iowa, Psychological and Brain Sciences Building, 340 Iowa Avenue, Iowa City, IA 52242, United States. Email: ariel-kershner@uiowa.edu

2000; Chun & Jiang, 1998). In Repeated search arrays, the spatial configuration of distractors and the target location remained constant. For Novel search arrays, the configuration of distractors was randomized on each trial. Search reaction times (RTs) became faster for Repeated arrays than for Novel arrays as the experiment progressed, demonstrating that the learning of target position was structured by array context.

Contextual cuing has been observed across a variety of contextual structures and features, including the original abstract spatial arrays, natural scenes (Brockmole et al., 2006; Brockmole & Henderson, 2006), and object shapes (Chun & Jiang, 1999). In most examples of contextual cuing, learning emerges relatively quickly: after as few as three repetitions using abstract arrays (e.g., Zellin et al., 2014) and even earlier using natural scenes (Brockmole & Henderson, 2006). Contextual cuing reflects cumulative learning that extends beyond the immediate repetition of location from one trial to the next (Kabata & Matsumoto, 2012). Mechanistically, it is currently best understood as reflecting episodic retrieval of previous searches and is well explained by instance-based models of learning (Chun & Jiang, 2003). Finally, the effects in contextual cuing studies are likely to be nonstrategic, as participants typically perform poorly on end-of-experiment tests probing retrieval and explicit report of array-to-target-location associations (e.g., Chun & Jiang, 1998, 2003; Jiang et al., 2014). Thus, contextual cuing constitutes one of the primary phenomena of "selection history" effects on attention guidance, lying outside the traditional dichotomy of stimulus-driven and goal-directed control (Awh et al., 2012).

Although there has been extensive work into how scene and spatial contexts structure learning in search, there has been little work examining how target object category fulfills this role. The statistical learning literature has shown that participants can form temporal associations among categories of objects and scenes that have appeared in the same sequence (Brady & Oliva, 2008; Otsuka et al., 2014), but this does not reveal how categories structure learning about consistencies within the category (e.g., that pen targets have tended to be blue) or how such learned regularities can be used during visual search. Work on contextual cuing has shown that the category of contextual words can structure learning of target location regularities (Goujon et al., 2009). However, in these experiments, semantics was a property of the context; the work did not concern category-specific learning of target attributes, as here. Moreover, the effects observed by Goujon et al. (2009) have not generalized to natural object stimuli (Makovski, 2016), potentially limiting their relevance to real-world search.

Recently, Bahle et al. (2021) conducted the first investigation into *categorical cuing*: how real-world categories structure the learning of object regularities, guiding visual search. The experiments were divided into an exposure session and a search session. During the exposure session, participants viewed centrally presented photographs of real-world objects and classified each object as "natural" or "man-made." They viewed six exemplars from each of 40 familiar, real-world categories (e.g., cat, laptop), with the exemplars from a category always presented in a similar color (e.g., all cats were black, and all laptops were silver). Following the exposure session, participants completed a categorical search task (Alexander & Zelinsky, 2011, 2012; Yang & Zelinsky, 2009). On each trial, they were first shown a category label cue (e.g., "laptop") and then searched through an object array for any category member. Critically, the color of the category member in the search array could either match (e.g., a silver laptop) or mismatch (e.g., a black laptop) the color of the exemplars from that category in the exposure phase. Visual search was reliably faster in the match condition than in the mismatch condition, indicating that participants had acquired target regularities during exposure, that these regularities were organized by object category, and that category-specific learning influenced the formation of the visual template guiding search. Importantly, these effects were driven by differences in the guidance of attention to the target, rather than by post-selective decision processes: the bulk of the difference between match and mismatch conditions was accounted for by the amount of time required to orient gaze to the target, rather than by the amount of time between target fixation and the response.

The division of the experiments by Bahle et al. (2021) into an exposure phase and a search phase was important to demonstrate the cross-task transfer of learning (cf. Jiang et al., 2015). However, the structure of those experiments limited comparison with the existing literature on related learning effects, such as contextual cuing (Chun & Jiang, 1998) and probability cuing (Geng & Behrmann, 2005; Jiang et al., 2013), which have tended to introduce position regularities in the same visual search task in which the effects of those regularities are observed. In the present study, we examined *categorical* cuing by manipulating the consistency of within-category target attributes across blocks of a single search task. In the basic method, participants searched for categorically defined object targets, with one exemplar from each of a set of categories serving as the target within each block of the experiment. For Repeated categories, an attribute of the target remained constant across blocks (color, orientation, or location). For Novel categories, this attribute varied randomly. Categorical cuing was defined as faster improvement in search RT across blocks for Repeated categories compared with Novel categories, an empirical pattern analogous to that observed in contextual cuing. This method allowed us to examine key theoretical and empirical issues of relevance to the larger literature on learning in visual search.

Our first goal was to test whether target properties observed during previous searches in a category would lead to modification of the categorical search template guiding attention. Although several studies have demonstrated that the visual properties of natural object search targets are reliably encoded into memory (Hollingworth, 2012; Võ & Wolfe, 2012; Williams et al., 2005), it is unknown whether these are retrieved to influence the guidance of attention when searching again for an object belonging to that category. Having observed reliable categorical cuing, our second goal was to expand the set of learned regularities to include color, orientation, and location. The third goal was to examine whether the categorical cuing effect is driven by retrieval of the immediately preceding search episode in that category or whether it additionally reflects cumulative learning that spans multiple search episodes. To this end, we examined whether searches after multiple property repetitions in the Repeated conditions were more efficient than searches after a single, incidental repetition in the Novel condition. The fourth goal was to assess whether participants could explicitly retrieve and report the repeated attributes in memory tests administered either at the end of the experiment or at the point in the experiment where the cuing effect was first observed. Given that participants can reliably retrieve and report the perceptual properties of many hundreds of briefly observed objects (Brady et al., 2008; Hollingworth, 2004), we predicted that memory for the object properties guiding search would be explicitly available. Having observed that the learning was indeed explicitly available, the final goal was to determine whether the application of explicit learning was strategic or nonstrategic. To this end, we examined whether there was a categorical cuing effect for the very first repetition, before participants could have developed a strategy based on observation of the repeated value in each category.

Experiment 1

Experiment 1 implemented a color consistency manipulation similar to that of Bahle et al. (2021) but using a multi-block search design modeled on the contextual cuing literature. We characterized the rate of search improvement across blocks as a function of the within-category color consistency of target objects. The method is presented in Figure 1. The basic task was categorical visual search (Yang & Zelinsky, 2009). Each search trial began with a category label cue (e.g., "cat"), which required participants to retrieve a representation of the category from long-term memory to guide attention to the target. They searched for the target item in an array of eight object photographs and reported the orientation of a superimposed letter "F." In each block of the experiment, participants searched once for an exemplar in each of 20 different categories. Half of the categories were assigned to the *Repeated* condition, in which the color of exemplars within a category was consistent across blocks, and half were assigned to the *Novel* condition, in which the color of exemplars within a category varied across blocks. The RT data across blocks were fit with a power function (Chun & Jiang, 2003), allowing us to characterize the rate of improvement in search time as a function of condition. We hypothesized that category-specific templates would reflect the recently observed properties of exemplars in each category (Bahle et al., 2021), producing a more accurate template and a more efficient guidance process in the Repeated condition than in the Novel condition. Specifically, we predicted a higher learning rate in the Repeated condition than in the Novel condition, a data pattern analogous to that found for contextual cuing (Chun & Jiang, 2003; D. I. Brooks et al., 2010).

In the Novel condition, the color of the target within a category varied randomly between two possible colors in Experiment 1. The use of only two colors per category in the Novel condition meant that there would be a repetition of the target color in a category from one block to the next on approximately half of the trials. This allowed us to estimate category-specific, inter-block repetition effects and to test whether there was learning in the Repeated condition above that attributable to color repetition from the previous block.

Following the visual search blocks, participants completed a surprise memory test for the colors in Repeated categories to examine whether participants could explicitly retrieve and report the repeated attributes at the end of the experiment. Specifically, they completed a two-alternative forced-choice task, in which they were presented with two differently colored exemplars from each Repeated category. They were instructed to choose the exemplar with the color that had been associated consistently with that category.

Method

Participants

All human subjects' procedures were approved by the University of Iowa Institutional Review Board. Participants reported normal or corrected-to-normal vision. In the first four experiments, participants (18–30 years old) were recruited from the University of Iowa undergraduate subject pool and received course credit. The key effect of interest in the present study (within-category feature consistency) was observed in a previous study (Bahle et al., 2021). The effect size in that study was adjusted $\eta_p^2 = .601$, indicating that an *N* of 7 would be sufficient to ensure 80% power. However, given that key aspects of the learning procedure changed from that earlier study to the present one, we ran a much larger *N* of 60 in Experiment 1 to ensure an accurate estimate of the effect size under these modified conditions. We then used this large-sample experiment to guide the choice of *N* in the other experiments in this study. The observed effect size for within-category feature repetition in Experiment 1 was adjusted $\eta_p^2 = .438$, indicating that an *N* of 12 would be sufficient to achieve 80% power. Conservatively, we used a sample of 20 in Experiments 2–4.

Participants were excluded from the analysis and replaced if their mean accuracy on the search task failed to meet an a priori criterion of 85% correct. Nine participants were replaced. For the final set of 60 participants, 39 were female and 21 male.[1]

Transparency and Openness

The data and materials for the experiments reported here are available upon request. None of the experiments was preregistered.

Apparatus

The experiments were conducted online. They were programmed with OpenSesame software (Mathôt et al., 2012) and converted to Javascript for web-based delivery on a server maintained by the University of Iowa. Because participants completed the experiment using their own computers, we report stimulus size in absolute pixel values. Participants were instructed to use a laptop or desktop computer with a keyboard to collect responses, to have only the experiment window open, and to run it in full-screen mode.

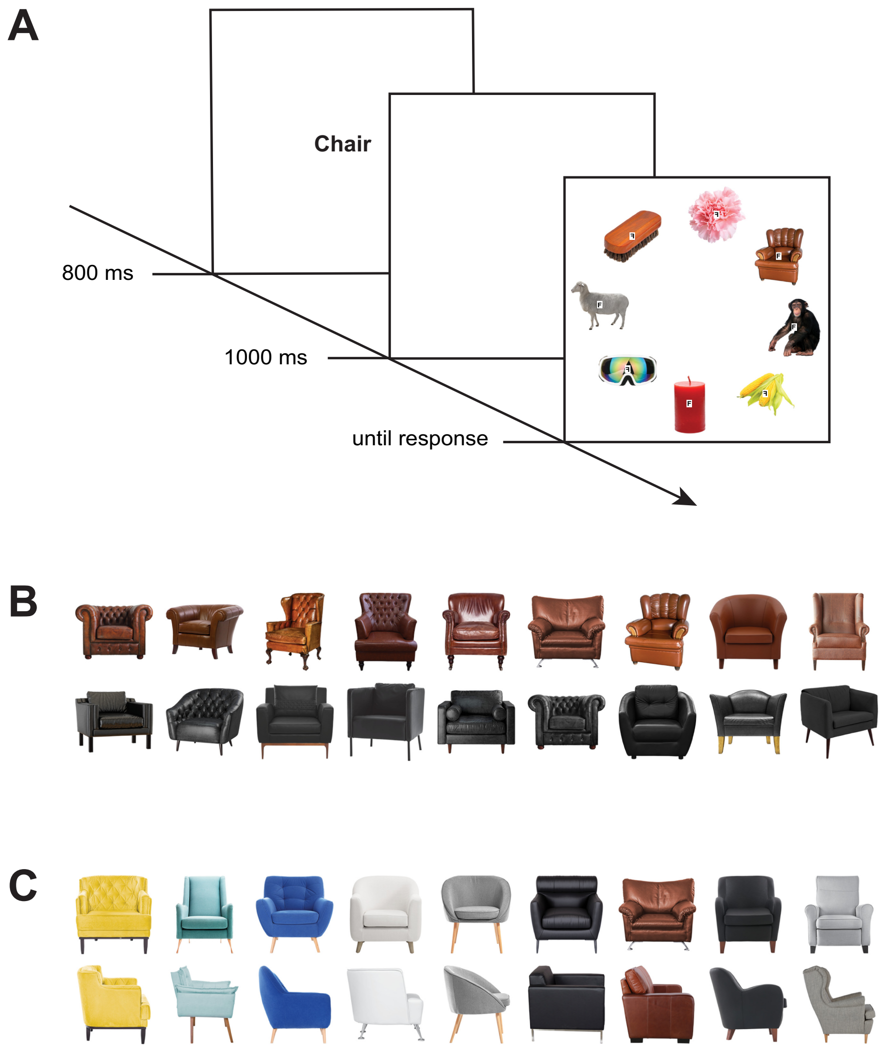
Stimuli

For Experiment 1, 20 familiar, real-world categories were chosen: 10 artifact and 10 natural (see the Appendix for a complete list of categories).[2] Most categories were defined at the basic level (e.g., "car"); a few were defined at the subordinate level (e.g., "dress shirt"). Within each category, there were 18 exemplar photographs. These were gathered from a variety of sources and scaled to fit within a 150 × 150-pixel region, against a white background. Nine of the exemplars appeared in one general color, and nine appeared in a different general color (Figure 1B). For example, in the "car" category, nine were white, and nine were blue; in the "chair" category, nine were brown, and nine were black (see the Appendix for a complete list of the two colors for each

[1] Due to a coding error in Experiments 1, 2, and 4, participant-reported gender was not stored in the data file. Gender was inferred from the participant's name.

[2] A mixture of artifact and natural categories was used to ensure a broad representation of real-world categories. We did not predict differences in learning between the two category types, particularly as no such differences were observed in Bahle et al. (2021). Thus, the analyses did not include artifact/natural as a factor.

Figure 1
Overview of Method and Design



Note. A: In the visual search task, participants saw a label describing the target category, followed by a search array. They searched for the object that matched the label and reported the orientation of a superimposed letter "F". B and C. The full set of target object stimuli for a sample category, illustrating the color value manipulation in Experiment 1 (B) and the orientation value manipulation in Experiment 3 (C). Individual categories were assigned to the Repeated condition or to the Novel condition. For Repeated categories, all target objects in a category had the same value. For Novel categories, the value randomly varied for each search trial in that category. See the online article for the color version of this figure.

Image attributes: Panel A images (clockwise starting at the top): carnation by ksena32; brown armchair by AlenKadr; chimpanzee by Eric Isselée; corn by alinamd; red candle by dule964; ski googles by azure; sheep by fotomaster; and wooden brush by Liza from Adobe Stock (stock.adobe.com). Panel B images (from left to right) brown armchairs by graphixmania, Bruce Shippee, dcw25, nuwatphoto, prescott09, nuwatphoto, AlenKadr, Tohid Hashemkhani, and bonciutoma from Adobe Stock (stock.adobe.com). Black armchairs by jockermax3d, Ramil, Anthony Paz, Pixel-Shot, Ramil, graphixmania, nuwatphoto, Singha songsak, and Anthony Paz from Adobe Stock (stock.abobe.com). Panel C images (from left to right) first row of armchairs by Anthony Paz, Pako, New Africa, artisan263, Pixel-Shot, sumetho, nuwatphoto, erhanbesimoglu, and Pixel-Shot; second row of armchairs by Anthony Paz, Anthony Paz, New Africa, SergValen, Pixel-Shot, ruzpage, Pavel_A, erhanbesimoglu, and AnselAmon from Adobe Stock (stock.abobe.com).

category). The colors were chosen so that there was a high degree of color variability across categories. In addition, each color was associated with at least two categories.

In the main visual search task, eight objects were presented on a virtual circle around central fixation against a white background. The location of the first object was selected randomly within a range of 1°–45°. The remaining objects were each offset by 45° around the virtual circle. Every search display contained one member of the cued category (i.e., all trials were target-present trials). The distractor objects on each trial were chosen from a set of 150 distractor images (75 artifact, 75 natural). Each distractor image came from a different category that did not overlap with the 20 experimental categories. Thus, there were 150 distractor categories in addition to the target categories. The distractor colors were not manipulated. Some of the colors of the distractor objects overlapped with the colors of the manipulated category objects, but because repeated colors were chosen randomly in each category for each participant, there was no systematicity in the relationship between distractor and target colors.

Each array had four artifacts and four natural objects. For example, if the target was an artifact, there were three artifact distractors (chosen randomly without replacement) and four natural object distractors (also chosen randomly without replacement). The assignment of objects to locations, including the target location, was determined randomly. A small, black letter “F” on a white background (Arial font, approximately 16 × 22 pixels) was superimposed centrally on each array object, with the orientation of the “F” (facing left or facing right) selected randomly. The cue that appeared before each search array was a word presented in Arabic font describing the category of the target object (e.g., “car”).

Procedure

After clicking the study link, participants provided informed consent. They were then given instructions for the visual search task. The sequence of events in a search trial is illustrated in Figure 1. Each trial began with a centrally presented “Press SPACEBAR to start next trial” screen. Once the participant pressed the spacebar, there was a 400-ms delay, followed by the category cue label presented centrally for 800 ms. After cue offset, there was a 1,000 ms blank delay before the presentation of the search display, which remained visible until the response. Participants searched for the object matching the category label and reported the orientation of the “F” superimposed upon it, using the “P” key to report a right-facing “F” (i.e., standard) and the “Q” key to report a left-facing “F” (i.e., mirror-reversed). Participants were instructed to make this response as quickly and as accurately as possible. Incorrect responses were followed by a frowny emoticon for 500 ms. Correct responses were followed by a smiley emoticon for 300 ms.

Participants first completed 10 practice trials, searching for objects drawn from 10 categories not used in the main experiment. They then completed eight blocks of 20 trials. Within each block, participants searched for each category once, randomly intermixed. Half of the categories were in the Repeated condition, and half were in the Novel condition. In the Repeated condition, the target objects in a particular category were drawn from the same color for all eight search blocks. In the Novel condition, four target objects in a category were drawn from one color and four from the other. The assignment of categories to the Repeated and Novel conditions was determined randomly for each participant. The order of target objects in a category was also determined randomly. Note that each target object in a category was a different exemplar; participants saw each exemplar in a category only once.

Following the visual search blocks, participants completed a memory test for the Repeated condition categories, consisting of 10 trials. Each trial again began with a centrally presented “Press SPACEBAR to start next trial” screen. Once the participant pressed the spacebar, two new exemplars from a category were presented simultaneously on the screen, one in the repeated color and one in the other color for that category. They were spaced 200 pixels apart, to the left and right of central fixation, with the left/right locations randomly selected. Participants were instructed to select the object with the color that was consistent with the color of objects from that category in the main experiment. They pressed “Q” if the object on the left matched the color they had seen and “P” if the object on the right matched the color.

Data Processing

The critical measure was mean RT in the search task as a function of repetition condition and block. The analyses were limited to correct search trials. There was also a two-step outlier trimming procedure. First, trials with RTs shorter than 250 ms (not plausibly based on letter orientation discrimination) or longer than 6,000 ms were eliminated. Next, trials with RTs more than 2.5 *SD*s from the participant’s mean in each condition were removed from the analysis. A total of 8.4% of trials were eliminated from the RT analysis. The pattern of results was not influenced by RT trimming in any experiment in this study.

Results

Search Accuracy

Overall search accuracy was 95.2% correct. There was no reliable accuracy difference between Novel (95.5%) and Repeated (95.0%) conditions, $F(1, 59) = 1.29$, $p = .261$, $\eta_p^2 = .021$, adjusted $\eta_p^2 = .005$.[3]

Search RT

Primary Analysis: Learning Rate

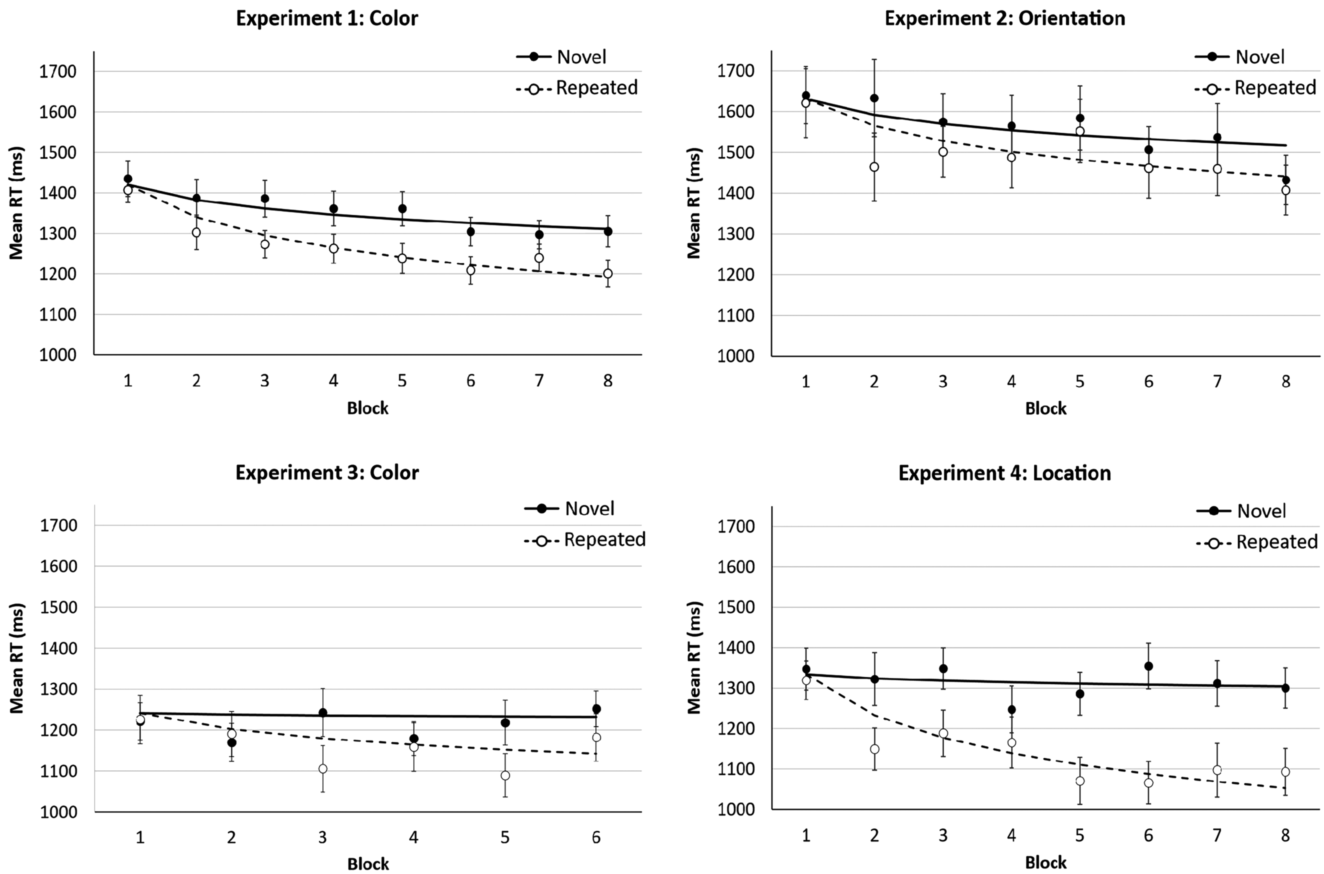
Contextual cuing and related effects are best defined as a difference in learning rate (i.e., rate of reduction in RT across blocks) as a function of repetition condition. However, contextual cuing data are conventionally analyzed using analysis of variance (ANOVA), with positive evidence for contextual cuing provided by a reliable interaction between condition and block. This is not ideal. An ANOVA treats search block as categorical rather than discrete, with no direct means to estimate the learning rate, especially given the typical, nonlinear relationship between block and RT.

Instead, we fit the individual subject RT data with a two-parameter power function in the form of $RT = ix^{-s}$. The *i* parameter describes the intercept of the function, the *s* parameter the slope of the function (i.e., learning rate), and *x* corresponds to the search block. Power functions are frequently used to characterize changes in RT with

[3] Unadjusted and adjusted η_p^2 values accompany each test (Mordkoff, 2019). Adjusted η_p^2 corrects for the positive bias inherent in standard η_p^2.

Figure 2

Mean Search RT as a Function of Repeated or Novel Condition and Search Block



Note. Points represent observed means. Lines represent model-predicted RT. Error bars are condition-specific, within-subject 95% confidence intervals (Morey, 2008).

learning (e.g., Logan, 1988), and the decrease in RT across blocks in contextual cuing studies has been well described by the learning rate parameter of the power function (Annac et al., 2019; Chen et al., 2021; Chun & Jiang, 2003; D. I. Brooks et al., 2010). The intercept for each subject was a constant estimated as mean RT in Block 1, collapsing across Repeated and Novel conditions, since all searches were novel in Block 1. The main analysis then probed for differences in learning rate as a function of repetition condition using a nonlinear mixed-effects (NLME) approach (Pinheiro & Bates, 2000). The fixed-effects structure consisted of the two levels of repetition condition. The random effects structure included a random intercept and a random slope for participant. Analyses were implemented with the NLME package (Version 1.1-153) in R (Version 4.0.3). Degrees of freedom for the statistical tests were estimated using the lmerTest package (Version 3.1-3).[4]

The observed data, along with the model fits, are presented in Figure 2. There was a reliable difference in the slopes of the power functions, $F(1, 839) = 41.69$, $p < .001$, with more rapid RT improvement across blocks in the Repeated condition ($s = 0.084$) than in the Novel condition ($s = 0.038$). Thus, we observed robust categorical cuing for within-category color consistency.

Onset of the Repetition Effect

To investigate the time-course of categorical cuing, we examined whether there was a repetition effect in the second block of trials, the first opportunity where such an effect could have been observed. Mean RT was reliably lower for Block 2 in the Repeated condition (1,302 ms) than in the Novel condition (1,387 ms), $F(1, 59) = 7.14$, $p = .010$, $\eta_p^2 = .108$, adjusted $\eta_p^2 = .093$. Thus, search facilitation was observed for the very first repetition within the categories.

Inter-Block Color Repetition in the Novel Condition

Due to the randomization procedure in the Novel condition, the target color often repeated within a category from one block to the next. Considering Blocks 2–8, we examined mean RT on trials when the search target for that category in the previous block had the same color (*repeat* trials) or a different color (*switch* trials).

[4] For discussion of the advantages of this general analytical approach for contextual-cuing-related data, see D. I. Brooks et al. (2010).

Mean RT on repeat trials (1,312 ms) was reliably lower than on switch trials (1,366 ms), $F(1, 59) = 15.22$, $p < .001$, $\eta_p^2 = .205$, adjusted $\eta_p^2 = .192$.

Comparison of Inter-Block Repetition in the Novel Condition With Learning in the Repeated Condition

The inter-block repetition effect indicates that some proportion of the categorical cuing effect was likely caused by retrieval of the preceding search episode for that category. To what extent could this account for the entire difference between the Repeated condition and the Novel condition in the main analysis? That is, was there a categorical cuing effect in the Repeated condition above that attributable to within-category color repetition from the preceding block? We compared mean RT in Blocks 3–8 for the Repeated condition and for repeat trials in the Novel condition (Block 3 is the first block where consistent color in the Repeated condition could potentially diverge from the repetition of the immediately preceding target color in the Novel condition). If inter-block repetition generated the entire learning effect, then RT in the Repeated condition should be no lower than RT for repeat trials in the Novel condition. Mean RT was reliably lower in the Repeated condition ($M = 1{,}237$ ms) than for repeat trials in the Novel condition ($M = 1{,}305$ ms), $F(1, 59) = 18.64$, $p < .001$, $\eta_p^2 = .240$, adjusted $\eta_p^2 = .227$, indicating that there was cumulative, category-specific learning in the Repeated condition, extending beyond that attributable to the repetition of the category-specific target color from the preceding block.

Memory Test Accuracy

Mean accuracy on the two-alternative memory test was 89.8% ($SD = 14.8\%$). A one-sample t test revealed a significant difference against chance of 50%, $t(59) = 20.87$, $p < .001$, $\eta_p^2 = .881$, adjusted $\eta_p^2 = .879$. Thus, by the end of the experiment, participants could reliably retrieve and report the colors that had been associated consistently with the categories.

Discussion

In Experiment 1, a categorical cuing effect was observed, with more rapid improvement in search times when the colors of targets within a category remained constant than when they varied. The effect demonstrates that participants remembered the perceptual attributes of previous search targets, and this memory biased subsequent searches toward objects with similar attributes. Critically, this learning was structured by the target object category, with the learning process operating simultaneously over 20 different real-world categories.

In addition to this central effect, we observed an inter-block repetition effect in the Novel condition: RT was reliably lower when the color of the target within a category repeated from one block to the next than when it switched. However, this effect was not sufficient to account for the entire difference in RT between the Repeated and Novel conditions, indicating cumulative learning of target object regularities in the Repeated condition. Note that the inter-block repetition effect observed here is distinct from typical intertrial priming effects (e.g., Maljkovic & Nakayama, 1994), since searches for the same category in the present experiment were separated by 20 trials, on average. Instead, the effect was likely to be due to the same long-term, episodic retrieval mechanisms as responsible for the categorical cuing effect itself, for certain forms of intertrial effects (Asgeirsson & Kristjansson, 2011; Huang et al., 2004; Thomson & Milliken, 2012, 2013), and for contextual cuing (Chun & Jiang, 1998, 2003).

By the end of the experiment, participants could reliably retrieve and report the colors that had been associated with the Repeated condition categories. Such end-of-experiment tests are often used as a measure of "awareness," and, if performance does not reliably exceed chance, then researchers often conclude that the underlying memory representation was implicit. Such tests are also taken as diagnostic of participant strategy: if participants can report a repeated attribute, then they may have developed a strategy consistent with that knowledge; if not, then the effects were unlikely to have been strategic. However, such inferences are not necessarily appropriate in the present design. The memory test was administered at the end of the experiment, but this was long after the categorical cuing effect first emerged, and thus accurate memory performance does not necessarily indicate that explicitly available memory representations were responsible for the difference in the learning rate, since they may have been acquired after the effect first emerged.

Moreover, the difference between Repeated and Novel conditions was statistically reliable in Block 2, the first block where a repetition effect could have been observed. In Block 2, participants had not previously observed color repetition for any of the categories, and thus the within-category repetition effect in that block could not plausibly have been driven by a strategy to search for color values observed to have been repeating. Thus, category-specific guidance was likely to be nonstrategic, at least early in the experiment. In general, participants are highly accurate at reporting the attributes of large numbers of briefly viewed natural objects (Brady et al., 2008; Hollingworth, 2004, 2005), including search targets (Williams et al., 2005). Thus, we suspect that the information supporting categorical cuing was explicitly retrievable throughout the experiment, but this was not necessarily used strategically to generate the cuing effects, at least those observed early in the experiment. This possibility is explored further in Experiments 5 and 6.

Experiment 2

In Experiment 2, we extended the study of categorical cuing to an additional perceptual dimension, orientation, using the same general design as in Experiment 1.

Method

Participants

One of the 20 participants was replaced for failing to achieve 85% search accuracy. Of the final 20, 18 were female, and two were male.

Stimuli and Procedure

Experiment 2 manipulated the repetition of object orientation. Twenty artifact categories were used. For each, nine exemplar photographs in each of the two orientations/viewpoints were chosen. For example, chairs were chosen either in a front view or a right-facing side view, and trucks were chosen either in a left-facing side view or in a left-facing three-fourth view (see Figure 1C). The categories and orientations used in Experiment 2 are listed in the Appendix.

In all other respects, the method was the same as in Experiment 1.

Data Processing

A total of 7.8% of trials were eliminated from the RT analysis.

Results and Discussion

Search Accuracy

Overall mean search accuracy was 95.6% correct. There was no difference between Novel (95.6%) and Repeated (95.6%) conditions, $F(1, 19) = 0.00$, $p = 1.00$, $\eta_p^2 = .000$, adjusted $\eta_p^2 = -0.053$.

Search RT

Primary Analysis: Learning Rate

The data were analyzed using the same method as in Experiment 1. The observed data, along with the model fits, are presented in Figure 2. There was a reliable difference in the slopes of the power functions, $F(1, 279) = 7.24$, $p = .008$, with more rapid learning in the Repeated condition ($s = 0.060$) than in the Novel condition ($s = 0.035$). Thus, we observed categorical cuing for orientation consistency.

Onset of the Repetition Effect

We examined whether a repetition effect was present in the second block of trials. A one-factor, repeated-measures ANOVA indicated that mean RT was reliably lower in the Repeated condition (1,464 ms) than in the Novel condition (1,633 ms), $F(1, 19) = 21.78$, $p < .001$, $\eta_p^2 = .534$, adjusted $\eta_p^2 = .510$.

Inter-Block Repetition in the Novel Condition

Trials from Blocks 2–8 were divided into repeat trials (within-category orientation repeated) and switch trials. Mean RT on repeat trials (1,532 ms) was not reliably lower than on switch trials (1,560 ms), $F(1, 19) = 0.81$, $p = .380$, $\eta_p^2 = .041$, adjusted $\eta_p^2 = -0.010$. Thus, we did not observe a reliable inter-block repetition effect.

Memory Test Accuracy

Mean accuracy on the memory test was 70.0% ($SD = 26.6\%$). A one-sample t test revealed a significant difference against chance of 50%, $t(19) = 3.37$, $p = .003$, $\eta_p^2 = .374$, adjusted $\eta_p^2 = .341$. By the end of the experiment, participants could reliably retrieve and report the orientations/viewpoints that had been associated consistently with the categories.

Experiment 3

In Experiments 1 and 2, colors and orientations were selected so that there was substantial variability across categories, and the values for each category were chosen to be quite frequent (e.g., black and brown are common colors for chairs, white and blue are common colors for cars, and so on). A potential drawback of this approach, however, is that it did not necessarily equate overall exposure to each of the target colors and orientations across Repeated and Novel conditions. Thus, in Experiment 3, we again manipulated color consistency but in a design ensuring that each possible color appeared equally often as a target in the experiment and also appeared equally often in the Repeated and Novel conditions.

Method

Participants

Two of the 20 participants were replaced for failing to achieve 85% search accuracy. Of the final 20, 13 were female, and seven were male.

Stimuli and Procedure

The method is illustrated in Figure 3. Twelve artifact categories were used (see Appendix for a complete list). For each category, seven exemplar photographs were chosen in each of six colors, for a total of 42 exemplars per category (Figure 3B). The same six colors were used for all 12 categories: red, blue, white, yellow, green, and black. The distractor images were replaced with new artifact object images, with 25 distractor exemplars in each of the six possible colors. As in Experiment 1, none of the 150 distractor categories overlapped with the experimental categories.

For each participant, half of the categories were randomly selected for the Repeated and half for the Novel condition. Each Repeated condition category was assigned, randomly without replacement, to one of the six possible colors. There were six blocks of search. For the Repeated categories, all six blocks of search presented a target exemplar in the same color (e.g., all six armchair targets were red). For the Novel categories, each block of search presented a different target color, with each of the six colors assigned to one of the six blocks. Thus, the target color within a category never repeated in the Novel condition. The assignment of colors to blocks in the Novel condition categories was determined randomly with the constraint that within each block, one Novel condition target appeared in each of the six colors. In this method, targets appeared in each of the six colors equally often across the Repeated and Novel conditions.

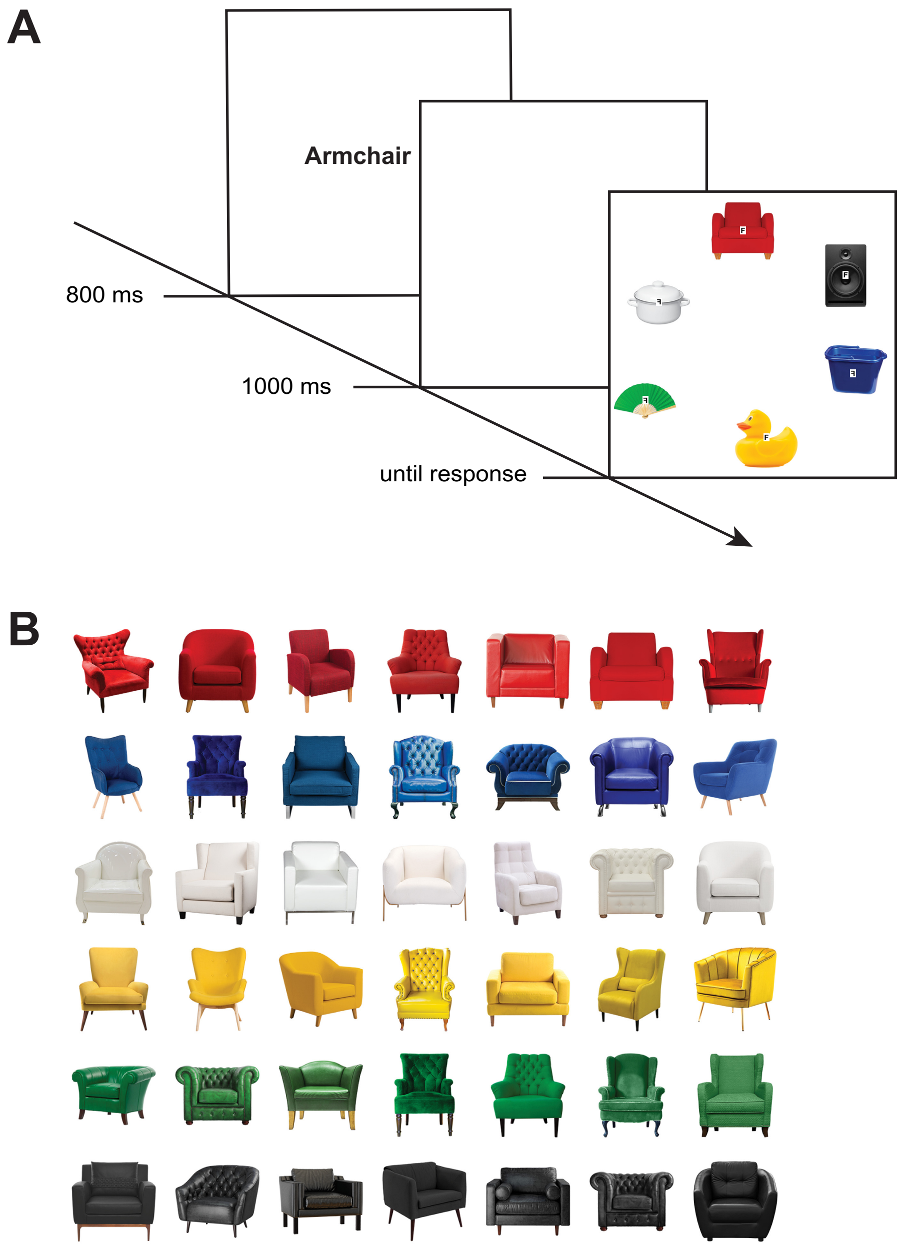
Each search display was composed of six objects, evenly spaced around the circular array at the same eccentricity used in Experiment 1. One object in each array appeared in each of the six possible colors. The target color was determined based on the condition assignment, described above. Each of the five distractors was chosen randomly from the 25 alternatives in each of the five remaining colors.

In the test phase, memory was probed for the six Repeated categories. The method was the same as in Experiment 1, with the following exceptions. Participants were presented with a row of six new exemplars, one in each of the six possible colors, spaced 160 pixels apart. The numbers 1 through 6 were presented above the pictures, and participants were asked to select the number that corresponded to the consistent color for each category by pressing the corresponding number key on the keyboard.

Data Processing

A total of 8.7% of trials were eliminated from the RT analysis.

Figure 3
Overview of Method and Design of Experiment 3



Note. A. In the visual search task, participants saw a label describing the target category, followed by a search array that contained six objects, one in each of six colors (red, blue, white, yellow, green, and black). They searched for the object that matched the label and reported the orientation of a superimposed letter "F". B. The full set of target object stimuli for a sample category, illustrating the color value manipulation. For Repeated categories, all target objects in a category had the same color value. For Novel categories, the target color varied for each search trial in that category. See the online article for the color version of this figure.
Image attributes: Panel A images (clockwise starting at the top): Red chair by natrot; black speaker by Denis Rozhnovsky; blue bucket by Coprid; rubber duck by Ruslan Ivantsov; green fan photomelon: and white pot by ILYA AKINSHIN from Adobe Stock (stock.abobe.com). Panel B images (from left to right) red armchairs by narokzaad, artisan263, Erik, Oksana, bonciutoma, natrot, and prescott09; blue armchairs by hafizismail, kongsky, Africa Studio, tungphoto, oktober64, Akhilesh Sharma, and New Africa; white armchairs by Vladislav Gajic, imagstock, ruzpage, ArtoBarto, Alex Zegrachov, Artem Zatsepilin, and artisan263; yellow armchairs by nexusseven, prescott09, artisan263, DECHA, Pixel-Shot, oktober64, and ArtoBarto; green armchairs by Bruce Shippee, graphixmania, Singha songsak, kongsky, and Oksana; black armchairs by Anthony Paz, Ramil, jockermax3d, Anthony Paz, Ramil, graphixmania, and nuwatphoto from Adobe Stock (stock.abobe.com).

Results and Discussion

Search Accuracy

Overall mean search accuracy for Experiment 3 was 94.2% correct. There was no difference between Novel (94.3%) and Repeated (94.0%) conditions, $F(1, 19) = 0.08$, $p = .781$, $\eta_p^2 = .004$, adjusted $\eta_p^2 = -0.048$.

Search RT

Primary Analysis: Learning Rate

The data were analyzed using the same method as in Experiments 1 and 2. The observed data, along with the model fits, are presented in Figure 2. There was a reliable difference in the slopes of the power functions, $F(1, 199) = 7.51$, $p = .007$, with more rapid learning across blocks in the Repeated condition ($s = 0.046$) than in the Novel condition ($s = 0.004$).

Onset of the Repetition Effect

We examined whether a repetition effect was present in the second block of trials. A one-factor, repeated-measures ANOVA indicated that there was no mean RT difference in Block 2 between the Repeated condition (1,191 ms) and the Novel condition (1,170 ms), $F(1, 19) = 0.18$, $p = .680$, $\eta_p^2 = .009$, adjusted $\eta_p^2 = -0.043$.

Memory Test Accuracy

Mean accuracy on the memory test was 73.3% ($SD = 27.8\%$). A one-sample t test revealed a significant difference against chance of 16.7%, $t(19) = 9.12$, $p < .001$, $\eta_p^2 = .814$, adjusted $\eta_p^2 = .804$. Thus, by the end of the experiment, participants could reliably retrieve and report the colors that had been associated consistently with the categories in the Repeated condition.

Experiment 4

In Experiment 4, we probed location regularities, as this is the typical manipulation in contextual cuing studies, which hold the target location constant in repeated search arrays (Chun & Jiang, 1998). For categories in the Repeated condition, targets always appeared in the same location within the eight-item array. For categories in the Novel condition, the target position randomly varied from block to block.

Method

Participants

Six of the 20 participants were replaced for failing to achieve 85% accuracy. Of the final 20, 14 were female, and six were male.

Stimuli and Procedure

The stimuli and procedure were the same as in Experiment 1, with the following modifications. There were 16 familiar real-world categories (eight artifact and eight natural) in the experiment, adapted from the set used in Experiment 1. Within each category, there were eight exemplar photographs. Four of the exemplars appeared in one general color, and four appeared in a different general color. For each participant, eight of the categories (four natural and four artifact) were randomly assigned to the Repeated condition and the other eight to the Novel condition.

Each search array consisted of eight objects displayed at 0°, 45°, 90°, and so on around a virtual circle. The array contained one cue-matching target and seven distractors, with distractors drawn from the same set as in Experiment 1. Participants completed eight blocks of 16 trials. Within each block, they searched for each category once, randomly intermixed. For the Repeated condition, each of the eight categories was assigned, randomly without replacement, to one of the eight target locations. Targets from a Repeated condition category appeared in the same location in all eight blocks of the experiment. The locations of targets from the Novel condition categories were randomly determined from block to block, with the constraint that within each block, one Novel condition target appeared in each of the eight possible locations. Thus, each location contained a target object equally often across the experiment, and each location contained a target equally often in the Repeated and Novel conditions. The order of exemplar target images within each category was randomized.

Following the visual search blocks, participants completed a memory test for the Repeated condition categories. Each trial again began with a centrally presented "Press SPACEBAR to start next trial" screen. Once the participant pressed the spacebar, there was a delay of 400 ms before a category cue label appeared for 800 ms. Following the cue, there was another delay of 1,000 ms. Finally, an array of eight circles appeared with numbers 1–8 presented in each of the locations, starting at the bottom and moving counterclockwise. Participants were instructed to press the number on the keyboard corresponding to the repeated location for the cued category.

Data Processing

A total of 7.7% of trials were eliminated from the RT analysis.

Results and Discussion

Search Accuracy

Overall search accuracy was 95.6%. There was no reliable difference between Novel (96.2%) and Repeated (95.1%) conditions, $F(1, 19) = 1.13$, $p = .300$, $\eta_p^2 = .056$, adjusted $\eta_p^2 = .006$.

Search RT

Primary Analysis: Learning Rate

The data were analyzed using the same method as in previous experiments. The observed data, along with the model fits, are presented in Figure 2. There was a reliable difference in the slopes of the power functions, $F(1, 279) = 30.57$, $p < .001$, with more rapid learning in the Repeated condition ($s = 0.114$) than in the Novel condition ($s = 0.011$). Thus, we observed categorical cuing for consistent position.

Onset of the Repetition Effect

We examined whether a repetition effect was present in the second block of trials. A one-factor repeated-measures ANOVA indicated that mean RT was reliably lower in the Repeated condition (1,149 ms) than in the Novel condition (1,322 ms), $F(1, 19) = 8.88$, $p = .008$, $\eta_p^2 = .319$, adjusted $\eta_p^2 = .283$.

Inter-Block Repetition in the Novel Condition

There were not enough repetition trials in the Novel condition (expected on only 12.5% of trials) to generate a reliable estimate of inter-block position repetition effects. However, since two colors were used in each category, we were able to examine inter-block color repetition effects, as in Experiment 1. Mean RT on color repeat and color switch trials were calculated independently for the eight categories in which the position was held constant and the eight in which it randomly varied, examining the possibility that color repetition would have a larger effect when attention was not guided by consistent location. The data were entered in a 2×2 repeated-measures ANOVA. First, there was a reliable main effect of color repeat/switch, $F(1, 19) = 5.89$, $p = .025$, $\eta_p^2 = .237$, adjusted $\eta_p^2 = .196$, with lower RT on repeat trials (1,195 ms) than on switch trials (1,248 ms). Second, there was a reliable main effect of position consistency condition, $F(1, 19) = 33.9$, $p < .001$, $\eta_p^2 = .641$, adjusted $\eta_p^2 = .622$, in accordance with the main analysis, above. Finally, these two factors did not interact, $F(1, 19) = 0.00$, $p = .998$, $\eta_p^2 = .000$, adjusted $\eta_p^2 = -0.053$. Thus, we found a reliable inter-block repetition effect for color within a category, replicating Experiment 1, and this effect did not vary significantly as a function of position consistency condition.

Memory Test Accuracy

Mean accuracy on the memory test was 75.0% ($SD = 21.5\%$). A one-sample t test revealed a significant difference against chance of 12.5%, $t(19) = 13.03$, $p < .001$, $\eta_p^2 = .899$, adjusted $\eta_p^2 = .894$. We also calculated the distance between the correct and reported locations. Location differences ranged from 0 (correct location) to 4 (opposite side of the search array). An average value of 2.0 would have been expected if participants had guessed. Participants had a mean error of 0.44 locations ($SD = 0.44$), which was significantly smaller than 2.0, $t(19) = -15.83$, $p < .001$, $\eta_p^2 = .930$, adjusted $\eta_p^2 = .926$. Thus, by the end of the experiment, participants could reliably retrieve and report the locations that had been associated consistently with the categories in the Repeated condition.

Experiments 5 and 6: Memory Following a Single Exposure

A key issue in research on learning and selection history in visual search is whether the effects are generated strategically or nonstrategically. If they are strategic, then guidance by learning would simply constitute a conventional implementation of goal-directed control. That is, only nonstrategic guidance from learning/selection history challenges the traditional dichotomy between goal-directed and stimulus-driven control (Awh et al., 2012). In our view, this distinction regarding strategy is more important, vis-à-vis theories of attention control, than the distinction between implicit and explicit memory that has typically been examined in this literature (e.g., Chun & Jiang, 1998). If information that *could be* retrieved and explicitly reported nevertheless guides attention nonstrategically, this constitutes just as strong a challenge to the goal-directed/stimulus-driven distinction as does guidance by implicit memory. In the present experiments, we suspect precisely this sort of circumstance: nonstrategic guidance by information that could have been retrieved and reported. Supporting this hypothesis requires establishing two points of evidence: (a) that the guidance effects were generated nonstrategically at some point in the experiment and (b) at this point, participants were nevertheless able to retrieve and report the relevant attribute.

The experiments thus far provide strong evidence that the effects were, at least initially, nonstrategic. Reliable differences between the Repeated and Novel conditions were observed in Block 2 of Experiments 1, 2, and 4. Since the second block was the first opportunity for participants to observe that an attribute repeated, the effects of repetition in this block were not plausibly driven by a strategy based on knowledge of the repeated value in each of the categories. With respect to the second criterion, the end-of-experiment memory tests indicate that participants could reliably retrieve and report the repeated attribute after 6–9 presentations as the search target. However, this falls short of demonstrating that they could retrieve and report those attributes at the point where evidence of nonstrategic guidance was observed (in Block 2), since they may have acquired the information supporting retrieval and report during later stages of the experiment.

To provide that evidence, we conducted two control experiments in which one block of search was followed immediately by a memory test, allowing us to test whether participants had access to the colors (Experiment 5) and locations (Experiment 6) of search targets after a single exposure. If so, then it is likely that participants in the main experiments had access to memory for the relevant attributes of the target objects during the second block of trials. We predicted above-chance memory performance after a single block of search given that the visual properties of hundreds of natural objects can be retrieved and reported following a single exposure (Brady et al., 2008; Hollingworth, 2004; Williams et al., 2005).

Method

Participants

Participants (18–30 years old) were recruited from Amazon Mechanical Turk. The effect size for the end-of-experiment memory test in Experiment 1 indicated that an N of 3 would be necessary to achieve 80% power. As a conservative approach, we set a target N of 10. Due to the posting of an extra sign-up slot, 11 participants (three female and eight male) completed Experiment 5 (the extra participant did not alter the results). Ten participants (five female and five male) completed Experiment 6.

Stimuli and Procedure

The stimuli and procedures in Experiments 5 and 6 were the same as in Experiments 1 (color) and 4 (position), respectively, except participants completed just one block of search trials. They then completed the memory test: a two-alternative color test for Experiment 5 and an eight-alternative location test for Experiment 6. The memory test instructions were altered slightly from those in Experiments 1 and 4. Instead of being asked to report the attribute that had been repeated, they were asked to report the attribute consistent with the one object from that category appearing during the search block. Since there was no repetition in this experiment, memory was tested for all 20 categories in Experiment 5 and all 16 categories in Experiment 6.

Results

Search Accuracy and Manual RT

Overall search accuracy was 98.2% correct in Experiment 5 and 95.6% correct in Experiment 6. After outlier trimming, mean RT for the one block of the search was 1,333 ms in Experiment 5 and 1,649 ms in Experiment 6.

Memory Test

For Experiment 5, mean accuracy on the color memory test was 79.6% ($SD = 10.83\%$). A one-sample t test revealed a significant difference against chance of 50%, $t(10) = 9.05$, $p < .001$, $\eta_p^2 = .891$ (90% CI [0.70, 0.93]), adjusted $\eta_p^2 = .880$, demonstrating reliable memory for the colors of the individual targets presented in the single search block. For Experiment 6, mean accuracy on the position memory test was 58.1% ($SD = 9.34\%$). A one-sample t test revealed a significant difference against chance of 12.5%, $t(9) = 15.45$, $p < .001$, $\eta_p^2 = .964$ [0.88, 0.98], adjusted $\eta_p^2 = .960$. In addition, participants' mean location-report error was 0.67 locations ($SD = 0.22$), which was significantly smaller than the value of 2.0 locations expected by chance, $t(9) = -19.1$, $p < .001$, $\eta_p^2 = .976$ [0.92, 0.98], adjusted $\eta_p^2 = .973$. Thus, participants could also reliably report the locations of the individual targets presented in the search block.

Discussion

The memory test results in Experiments 5 and 6 indicate that, after one block of search and exposure to just one target exemplar in each of the categories, participants could reliably retrieve and report the colors and locations of the targets. Thus, in the main experiments, when we obtained evidence of nonstrategic guidance in Block 2, it is likely that this was based not on an inherently implicit form of memory but rather on an incidental application of memory representations that could have been retrieved and reported. This application of memory is neither an example of stimulus-driven control (as the targets were not physically salient) nor an example of goal-directed control (as the effects were unlikely to have been strategic), consistent with the need to consider certain learning and selection history effects as lying outside the traditional dichotomy (Awh et al., 2012). The present results highlight the fact that such effects need not be limited to implicit forms of memory. A similar conclusion can be drawn from contextual cuing experiments in which blocks of search were interleaved with explicit recognition tests, indicating that contextual cuing can occur in parallel with explicit awareness but is largely independent of it (Geyer et al., 2010).

General Discussion

In the present study, we examined how real-world categories structure the acquisition and expression of target object regularities, guiding visual search. The basic task was modeled after the contextual cuing literature (Chun & Jiang, 1998), except the repeated attribute that cued the target was defined relative to the category of the target object rather than relative to the spatial configuration of the array. There were five main findings. First, we observed "categorical cuing" in each of the experiments: specifically, the reduction of search RT across blocks was larger when a category-specific attribute of target objects remained constant (Repeated condition) than when it varied randomly (Novel condition). Second, categorical cuing was observed generally across three different target attributes: color, orientation/viewpoint, and location. Third, search was facilitated both by local repetition (i.e., the repetition of the category-specific attribute from Block N to Block $N + 1$) and by cumulative learning across blocks. Fourth, the cuing effect developed very rapidly, with a reliable difference between Repeated and Novel conditions typically observed in the second block of trials (i.e., the very first repetition in the Repeated condition). Fifth, participants could reliably retrieve and report the critical attributes of each of the categories, both at the end of the entire experiment and after the very first block of search, when the search effect first emerged; thus, learning did not necessarily rely on an implicit form of memory.

In sum, categorical cuing exhibited a close correspondence to the pattern of results observed in the contextual cuing literature. We can conclude that both scene context and the category of the target object structure the learning of environmental regularities guiding visual search, and it is likely that the two forms of structured learning depend on overlapping mechanisms. Specifically, each can be considered as depending on the episodic retrieval of previous searches, with the influence of this retrieval either biasing the formation of a feature-based template guiding search (for dimensions such as color, shape, or orientation) or directly cuing the location of the target (for position). An apparent difference between the two phenomena concerns explicit access to the repeated values. As we will argue below, this is likely to reflect differences in the memorability of the stimuli (natural objects vs. abstract letter arrays) rather than a fundamental difference in the underlying learning mechanism.

Episodic Retrieval

The phenomenon of contextual cuing is definitionally episodic; rather than being generalized, the learning is linked to individual contexts. In addition, the mechanism of contextual cuing is often characterized as depending on the retrieval of previous search instances (Chun & Jiang, 1998, 2003), with this retrieval strongly influenced by the context established by the current search array or scene. In the present experiments, the most parsimonious explanation is that biases in search were driven by a similar, episodic retrieval mechanism. This was evident in the inter-block repetition effect and in the difference between Repeated and Novel conditions in Block 2. In both cases, retrieval of the preceding search episode within a category was likely to have led to retrieval of the perceptual attributes of the earlier search target, biasing the categorical template toward exemplar-specific properties of that object. Cumulative learning in each of the present experiments could also be explained by the simultaneous retrieval of multiple episodes of recent search within a category, consistent with instance-based models of learning (Logan, 1988).

If categorical cuing can be explained by selective retrieval of search instances specific to a particular target object category, to what extent is this learning episodic in the sense of being also structured by scene *context*. Recently, Kershner and Hollingworth (2022) probed how object categories and scene contexts act in conjunction to structure the acquisition and use of statistical regularities to guide visual search. The basic method was similar to the two-session design of Bahle et al. (2021). In an exposure session, participants viewed object exemplars from 42 different categories in two colors presented against different contexts (e.g., red staplers presented with a classroom scene and blue staplers with an office scene). Then, participants completed a visual search task, in which they searched for target exemplars matching a category label cue among arrays of eight objects superimposed over a scene background. Search RT was reliably lower when the color of the target exemplar was consistent with the color associated with that combination of category and scene context (e.g., a red stapler in a classroom scene) than when it mismatched (e.g., a blue stapler in a classroom scene). Thus, category-specific feature biases were episodic in the sense of being structured by scene context, with the retrieval of previous target exemplars, and thus the properties of the template guiding search, contingent on associated contextual features. Note that a similar effect has been obtained in the contextual cuing literature. In D. I. Brooks et al. (2010), repeated abstract arrays were embedded within different real-world scenes. The expression of array-specific learning was contingent on re-instantiating the original scene context in which the learning occurred.

Strategy and “Awareness”

Studies on learning and the guidance of attention often include an “awareness test” at the end of the experiment. For example, participants might be asked to discriminate repeated arrays from novel arrays or to indicate the location most likely to have contained the target (for a discussion of the structure of awareness tests, see Vadillo et al., 2016, 2022). The purpose of such tests is usually two-fold. First, if participants cannot reliably report the repeated value on which the learning effect relies (e.g., the target location in repeated arrays) then the effect could not plausibly have been strategic. Second, if participants cannot reliably report the repeated value, then researchers have some degree of evidence that learning was based on an implicit form of memory (e.g., Chun & Jiang, 1998; but see Vadillo et al., 2022).

Here, we are concerned more with the issue of strategy than with the issue of implicit memory. Although the question of implicit/explicit memory is important in its own right, from the perspective of theories of attention control, it is not necessarily the critical distinction. First, phenomena such as contextual cuing are observed both under conditions where participants have very limited ability to retrieve and report the repeated value (e.g., Chun & Jiang, 1998) and under conditions where they can reliably report that value (Brockmole et al., 2006; Brockmole & Henderson, 2006). Second, individual differences in explicit awareness do not reliably alter the magnitude of the guidance effects during visual search (Annac et al., 2019; Malejka et al., 2021; Shanks et al., 2021; Vadillo et al., 2022), indicating that similar guidance is observed regardless of the implicit/explicit distinction. Third, episodic retrieval models of learning and automaticity are agnostic to the explicit/implicit distinction (Logan, 1988); implicit memory is not a condition for the application of the type of model typically used to explain phenomena such as contextual cuing.

In contrast, the question of *strategy* is critical for identifying the mechanism of guidance, since only nonstrategic effects would fall outside the traditional dichotomy between stimulus-driven and goal-directed mechanisms of control (Awh et al., 2012). Despite the importance of assessing strategy, typical end-of-experiment awareness tests are poorly structured to provide relevant evidence. If participants have minimal ability to report the repeated value, then they were unlikely to have developed an explicit strategy. However, evidence that the repeated values can be retrieved and reported at the end of the session does not necessarily indicate that participants developed a search strategy based on this knowledge. At the broadest level, reflexive behaviors clearly are not limited to implicit memory. Consider conditioned taste aversion: Vivid recall of the funky shrimp and the subsequent illness does not make the aversion any less reflexive. Thus, above-chance retrieval and report cannot be taken as strong evidence that a search effect was not reflexive. In addition, the awareness test usually occurs long after the learning effect first emerged in the main search session; the memory representations supporting above-chance performance could have developed long after, or even as a result of, the attentional bias of interest (Smyth & Shanks, 2008; Vadillo et al., 2022). Moreover, end-of-experiment memory tests often provide extremely specific retrieval cues and unlimited time to implement retrieval, conditions that were not necessarily available during the search session. For example, in the present experiments, the memory test involved forced-choice recognition of sample stimuli with unlimited time for decision, whereas the search effect involved the recall of previous search targets based on an abstract category label cue under time constraints. Showing above-chance performance on the memory test does not necessarily indicate that participants spontaneously engaged in similar retrieval during the experiment to strategically guide attention.

In the present study, we assessed strategy by examining whether a learning effect was observed at a point in the experiment when participants could not have plausibly developed a strategy based on explicit knowledge of the repeated values. In three of the four main experiments, a reliable categorical cuing effect was observed in the second block of search, that is, the first block of repetition in the Repeated condition. Given that the second block of trials was the first opportunity for participants to observe the repeated values, it is unlikely that they developed a strategy based on knowledge of repetition in this block. This test of strategy is limited, to some extent, in that we cannot conclude that categorical cuing was similarly nonstrategic at later points in the experiment, but it establishes that category-specific learning can, in principle, guide attention in a nonstrategic manner.

Memory for the repeated values was tested at two time points: after all blocks of search in the first four experiments, and after one block of search in the last two experiments. In both cases, participants could reliably retrieve and report the repeated features in forced-choice recognition tests. Accurate memory performance, even after a single exposure to an exemplar in each category, is to be expected given that natural object stimuli were used in the experiments. Visual memory for natural object stimuli is typically very accurate (Brady et al., 2008; Hollingworth, 2004), even if, as here, the stimuli are search targets, and participants do not know that a memory test will follow the search blocks (Williams et al., 2005). Explicitly available memory representations are likely to be normative in real-world instantiations of both contextual (Brockmole & Henderson, 2006) and categorical cuing, since these operate over natural scenes and objects. That is, highly limited explicit memory may be restricted to artificial, laboratory stimuli, such as arrays of Ts and Ls, with high inter-item similarity and without direct connection to the wealth of existing knowledge available for naturalistic stimuli. Of course, this does not necessarily mean that people will be able to explicitly retrieve *every* real-world episode contributing to learning, nor does it mean that explicit recall of previous episodes is *necessary* for the guidance of attention, but rather that the format of the memory representation is likely to be inherently explicit rather than implicit. Given that participants in the main experiments typically showed a repetition effect in Block 2, and participants in Experiments 5 and 6 could reliably retrieve and report the critical properties of the search target after a single exposure, the present data indicate that explicitly retrievable properties of objects can guide visual search in a non-strategic manner; effects of selection history on visual search need not be limited to implicit memory.

Episodic Malleability of Category Representations

In real-world visual search tasks, the searcher must form a template from long-term memory (only in the laboratory is one shown a picture of the target immediately before searching for it). In addition, many real-world searches involve finding any member of a particular category, such as finding any member of the category "pen" or any member of the category "banana." Understanding this type of *categorical search* (Malcolm & Henderson, 2009; Vickery et al., 2005; Yang & Zelinsky, 2009), requires understanding how search templates are formed from LTM representations of real-world categories. In previous work on categorical search, templates guiding search have been shown to bias attention toward objects that share visual features with the target category (Alexander & Zelinsky, 2011), especially typical features of that category (Maxfield et al., 2014). Moreover, these effects have been observed to influence, primarily, the efficiency of attention guidance to the target rather than post-selection processes, such as target confirmation or response generation (Bahle et al., 2021).

Here, we have shown that categorical search templates are strongly biased toward the properties of recently viewed exemplars in a category (see also Bahle et al., 2021). This was observed for real-world categories with which participants had extensive experience before entering the experiment. For example, participants presumably had seen many thousands of cars before coming to the laboratory. They could have used this accumulated knowledge to form a template that was stable from one search to the next. Instead, searches for members of a category were strongly influenced by the properties of the last few exemplars observed in that category. These results are consistent with theories of categorization that propose either that exemplar representations are the foundation of the category representation (Medin & Schaffer, 1978; Nosofsky, 1987) or that highly accessible exemplar representations influence the use of categories in addition to more stable, abstract knowledge (e.g., L. R. Brooks et al., 1991). Although our knowledge and application of categories may seem constant, the expression of the category may instead be quite variable, depending on the properties of recently viewed exemplars. Such dynamic category representation would allow predictions about the properties of category members —such as their predicted appearance and location, as here—to be optimized based on recent environmental regularities.

References

Alexander, R. G., & Zelinsky, G. J. (2011). Visual similarity effects in categorical search. *Journal of Vision*, *11*(8), Article 9. https://doi.org/10.1167/11.8.9

Alexander, R. G., & Zelinsky, G. J. (2012). Effects of part-based similarity on visual search: The Frankenbear experiment. *Vision Research*, *54*, 20–30. https://doi.org/10.1016/j.visres.2011.12.004

Anderson, B. A., Kim, H., Kim, A. J., Liao, M. R., Mrkonja, L., Clement, A., & Grégoire, L. (2021). The past, present, and future of selection history. *Neuroscience & Biobehavioral Reviews*, *130*, 326–350. https://doi.org/10.1016/j.neubiorev.2021.09.004

Annac, E., Pointner, M., Khader, P. H., Müller, H. J., Zang, X., & Geyer, T. (2019). Recognition of incidentally learned visual search arrays is supported by fixational eye movements. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *45*(12), 2147–2164. https://doi.org/10.1037/xlm0000702

Asgeirsson, A. G., & Kristjansson, A. (2011). Episodic retrieval and feature facilitation in intertrial priming of visual search. *Attention, Perception, & Psychophysics*, *73*(5), 1350–1360. https://doi.org/10.3758/s13414-011-0119-5

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: A failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443. https://doi.org/10.1016/j.tics.2012.06.010

Bahle, B., Kershner, A. M., & Hollingworth, A. (2021). Categorical cuing: Object categories structure the acquisition of statistical regularities to guide visual search. *Journal of Experimental Psychology: General*, *150*(12), 2552–2566. https://doi.org/10.1037/xge0001059

Brady, T. F., Konkle, T., Alvarez, G. A., & Oliva, A. (2008). Visual long-term memory has a massive storage capacity for object details. *Proceedings of the National Academy of Sciences of the United States of America*, *105*(38), 14325–14329. https://doi.org/10.1073/pnas.0803390105

Brady, T. F., & Oliva, A. (2008). Statistical learning using real-world scenes: Extracting categorical regularities without conscious intent. *Psychological Science*, *19*(7), 678–685. https://doi.org/10.1111/j.1467-9280.2008.02142.x

Brockmole, J. R., Castelhano, M. S., & Henderson, J. M. (2006). Contextual cueing in naturalistic scenes: Global and local contexts. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *32*(4), 699–706. https://doi.org/10.1037/0278-7393.32.4.699

Brockmole, J. R., & Henderson, J. M. (2006). Using real-world scenes as contextual cues for search. *Visual Cognition*, *13*(1), 99–108. https://doi.org/10.1080/13506280500165188

Brooks, D. I., Rasmussen, I. P., & Hollingworth, A. (2010). The nesting of search contexts within natural scenes: Evidence from contextual cuing. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(6), 1406–1418. https://doi.org/10.1037/a0019257

Brooks, L. R., Norman, G. R., & Allen, S. W. (1991). Role of specific similarity in a medical diagnostic task. *Journal of Experimental Psychology: General*, *120*(3), 278–287. https://doi.org/10.1037/0096-3445.120.3.278

Chen, S., Shi, Z., Müller, H. J., & Geyer, T. (2021). Multisensory visuo-tactile context learning enhances the guidance of unisensory visual search. *Scientific Reports*, *11*(1), Article 9439. https://doi.org/10.1038/s41598-021-88946-6

Chun, M. M. (2000). Contextual cueing of visual attention. *Trends in Cognitive Sciences*, *4*(5), 170–178. https://doi.org/10.1016/S1364-6613(00)01476-5

Chun, M. M., & Jiang, Y. (1998). Contextual cueing: Implicit learning and memory of visual context guides spatial attention. *Cognitive Psychology*, *36*(1), 28–71. https://doi.org/10.1006/cogp.1998.0681

Chun, M. M., & Jiang, Y. (1999). Top-down attentional guidance based on implicit learning of visual covariation. *Psychological Science*, *10*(4), 360–365. https://doi.org/10.1111/1467-9280.00168

Chun, M. M., & Jiang, Y. (2003). Implicit, long-term spatial contextual memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *29*(2), 224–234. https://doi.org/10.1037/0278-7393.29.2.224

Failing, M., & Theeuwes, J. (2018). Selection history: How reward modulates selectivity of visual attention. *Psychonomic Bulletin & Review*, *25*(2), 514–538. https://doi.org/10.3758/s13423-017-1380-y

Geng, J. J., & Behrmann, M. (2005). Spatial probability as an attentional cue in visual search. *Perception & Psychophysics*, *67*(7), 1252–1268. https://doi.org/10.3758/bf03193557

Geyer, T., Shi, Z., & Müller, H. J. (2010). Contextual cueing in multiconjunction visual search is dependent on color- and configuration-based intertrial contingencies. *Journal of Experimental Psychology: Human Perception and Performance*, *36*(3), 515–532. https://doi.org/10.1037/a0017448

Goujon, A., Didierjean, A., & Marmèche, E. (2009). Semantic contextual cuing and visual attention. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(1), 50–71. https://doi.org/10.1037/0096-1523.35.1.50

Hollingworth, A. (2004). Constructing visual representations of natural scenes: The roles of short- and long-term visual memory. *Journal of Experimental Psychology: Human Perception and Performance*, *30*(3), 519–537. https://doi.org/10.1037/0096-1523.30.3.519

Hollingworth, A. (2005). The relationship between online visual representation of a scene and long-term scene memory. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *31*(3), 396–411. https://doi.org/10.1037/0278-7393.31.3.396

Hollingworth, A. (2012). Task specificity and the influence of memory on visual search: Comment on Võ and Wolfe (2012). *Journal of Experimental Psychology: Human Perception and Performance*, *38*(6), 1596–1603. https://doi.org/10.1037/A0030237

Huang, L. Q., Holcombe, A. O., & Pashler, H. (2004). Repetition priming in visual search: Episodic retrieval, not feature priming. *Memory & Cognition*, *32*(1), 12–20. https://doi.org/10.3758/bf03195816

Jiang, Y. V., Swallow, K. M., Rosenbaum, G. M., & Herzig, C. (2013). Rapid acquisition but slow extinction of an attentional bias in space. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(1), 87–99. https://doi.org/10.1037/a0027611

Jiang, Y. V., Swallow, K. M., Won, B. Y., Cistera, J. D., & Rosenbaum, G. M. (2015). Task specificity of attention training: The case of probability cuing. *Attention, Perception, & Psychophysics*, *77*(1), 50–66. https://doi.org/10.3758/s13414-014-0747-7

Jiang, Y. V., Won, B. Y., & Swallow, K. M. (2014). First saccadic eye movement reveals persistent attentional guidance by implicit learning. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(3), 1161–1173. https://doi.org/10.1037/a0035961

Kabata, T., & Matsumoto, E. (2012). Cueing effects of target location probability and repetition. *Vision Research*, *73*, 23–29. https://doi.org/10.1016/j.visres.2012.09.014

Kershner, A. M., & Hollingworth, A. (2022). Real-world object categories and scene contexts conjointly structure statistical learning for the guidance of visual search. *Attention, Perception, & Psychophysics*, *84*(4), 1304–1316. https://doi.org/10.3758/s13414-022-02475-6

Logan, G. D. (1988). Toward an instance theory of automatization. *Psychological Review*, *95*(4), 492–527. https://doi.org/10.1037/0033-295x.95.4.492

Makovski, T. (2016). What is the context of contextual cueing? *Psychonomic Bulletin & Review*, *23*(6), 1982–1988. https://doi.org/10.3758/s13423-016-1058-x

Malcolm, G. L., & Henderson, J. M. (2009). The effects of target template specificity on visual search in real-world scenes: Evidence from eye movements. *Journal of Vision*, *9*(11), Article 8. https://doi.org/10.1167/9.11.8

Malejka, S., Vadillo, M. A., Dienes, Z., & Shanks, D. R. (2021). Correlation analysis to investigate unconscious mental processes: A critical appraisal and mini-tutorial. *Cognition*, *212*, Article 104667. https://doi.org/10.1016/j.cognition.2021.104667

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition*, *22*(6), 657–672. https://doi.org/10.3758/bf03209251

Mathôt, S., Schreij, D., & Theeuwes, J. (2012). Opensesame: An open-source, graphical experiment builder for the social sciences. *Behavior Research Methods*, *44*(2), 314–324. https://doi.org/10.3758/s13428-011-0168-7

Maxfield, J. T., Stalder, W. D., & Zelinsky, G. J. (2014). Effects of target typicality on categorical search. *Journal of Vision*, *14*(12), Article 1. https://doi.org/10.1167/14.12.1

Medin, D. L., & Schaffer, M. M. (1978). Context theory of classification learning. *Psychological Review*, *85*(3), 207–238. https://doi.org/10.1037/0033-295X.85.3.207

Mordkoff, J. T. (2019). A simple method for removing bias from a popular measure of standardized effect size: Adjusted partial eta squared. *Advances in Methods and Practices in Psychological Science*, *2*(3), 228–232. https://doi.org/10.1177/2515245919855053

Morey, R. D. (2008). Confidence intervals from normalized data: A correction to Cousineau (2005). *Tutorials in Quantitative Methods for Psychology*, *4*(2), 61–64. https://doi.org/10.20982/tqmp.04.2.p061

Nosofsky, R. M. (1987). Attention and learning processes in the identification and categorization of integral stimuli. *Journal of Experimental Psychology: Learning Memory and Cognition*, *13*(1), 87–108. https://doi.org/10.1037/0278-7393.13.1.87

Otsuka, S., Nishiyama, M., & Kawaguchi, J. (2014). Constraint on the semantic flexibility in visual statistical learning. *Visual Cognition*, *22*(7), 865–880. https://doi.org/10.1080/13506285.2014.923548

Pinheiro, J. C., & Bates, D. M. (2000). *Mixed-effects models in S and S-PLUS*. Springer.

Shanks, D. R., Malejka, S., & Vadillo, M. A. (2021). The challenge of inferring unconscious mental processes. *Experimental Psychology*, *68*(3), 113–129. https://doi.org/10.1027/1618-3169/a000517

Sisk, C. A., Remington, R. W., & Jiang, Y. (2019). Mechanisms of contextual cueing: A tutorial review. *Attention, Perception, & Psychophysics*, *81*(8), 2571–2589. https://doi.org/10.3758/s13414-019-01832-2

Smyth, A. C., & Shanks, D. R. (2008). Awareness in contextual cuing with extended and concurrent explicit tests. *Memory & Cognition*, *36*(2), 403–415. https://doi.org/10.3758/mc.36.2.403

Thomson, D. R., & Milliken, B. (2012). Perceptual distinctiveness produces long-lasting priming of pop-out. *Psychonomic Bulletin & Review*, *19*(2), 170–176. https://doi.org/10.3758/s13423-011-0199-1

Thomson, D. R., & Milliken, B. (2013). Contextual distinctiveness produces long-lasting priming of pop-out. *Journal of Experimental Psychology: Human Perception and Performance*, *39*(1), 202–215. https://doi.org/10.1037/a0028069

Vadillo, M. A., Konstantinidis, E., & Shanks, D. R. (2016). Underpowered samples, false negatives, and unconscious learning. *Psychonomic Bulletin & Review*, *23*(1), 87–102. https://doi.org/10.3758/s13423-015-0892-6

Vadillo, M. A., Malejka, S., Lee, D. Y. H., Dienes, Z., & Shanks, D. R. (2022). Raising awareness about measurement error in research on unconscious mental processes. *Psychonomic Bulletin & Review*, *29*(1), 21–43. https://doi.org/10.3758/s13423-021-01923-y

Vickery, T. J., King, L. W., & Jiang, Y. (2005). Setting up the target template in visual search. *Journal of Vision*, *5*(1), 81–92. https://doi.org/10.1167/5.1.8

Võ, M. L. H., & Wolfe, J. M. (2012). When does repeated search in scenes involve memory? Looking at versus looking for objects in scenes. *Journal of Experimental Psychology: Human Perception and Performance*, *38*(1), 23–41. https://doi.org/10.1037/a0024147

Williams, C. C., Henderson, J. M., & Zacks, R. T. (2005). Incidental visual memory for targets and distractors in visual search. *Perception & Psychophysics*, *67*(5), 816–827. https://doi.org/10.3758/BF03193535

Yang, H., & Zelinsky, G. J. (2009). Visual search is guided to categorically-defined targets. *Vision Research*, *49*(16), 2095–2103. https://doi.org/10.1016/j.visres.2009.05.017

Zellin, M., von Mühlenen, A., Müller, H. J., & Conci, M. (2014). Long-term adaptation to change in implicit contextual learning. *Psychonomic Bulletin & Review*, *21*(4), 1073–1079. https://doi.org/10.3758/s13423-013-0568-z

(*Appendix follows*)

Appendix

Table 1
Stimuli for Experiments 1 and 5

Category	Color 1	Color 2
Apple	Red	Green
Backpack	Yellow	Black
Bean	White	Red
Bed	Brown	White
Butterfly	Orange	Blue
Camera	Black	Purple
Car	White	Blue
Cat	Gray	Orange
Dog	White	Brown
Dress	Green	Yellow
Dress shirt	Blue	Purple
Frog	Red	Green
Grape	Purple	Green
Hair brush	Black	Blue
Chair	Brown	Black
Mushroom	White	Brown
Pear	Yellow	Green
Pot	Gray	Red
Rabbit	Brown	Black
T-shirt	Gray	Yellow

Table 2
Stimuli for Experiment 2

Category	Orientation 1	Orientation 2
Backpack	Front	Side
Bed	Front	Side
Camera	Front	Side
Car	Front	Front 3/4
Coffee maker	Front	Side
Cup	Above	Front
Flip flops	Above	Front
Hair brush	Front	Side
Hat	Front	Side
High heels	Front	Side
Iron	Flat	Back 3/4
Laptop	Front	Front 3/4
Chair	Front	Side
Phone	Front	3/4
Shoe	Front	Side
Teapot	Front	Above
Tricycle	Angle/side	Front
Truck	Front 3/4	Side
Violin	Front	Side
Watch	Front	Front 3/4

Table 3
Stimuli for Experiment 3

Category
Armchair
Backpack
Car
Coat
Dress
Hat
Mug
Pillow
Purse
Sneakers
T-shirt
Teapot

Table 4
Stimuli for Experiments 4 and 6

Category	Color 1	Color 2
Apple	Red	Green
Backpack	Yellow	Black
Butterfly	Orange	Blue
Camera	Black	Purple
Car	White	Blue
Cat	Gray	Orange
Dog	White	Brown
Dress	Green	Yellow
Grape	Purple	Green
Hair brush	Black	Blue
Chair	Brown	Black
Mushroom	White	Brown
Pear	Yellow	Green
Pot	Gray	Red
Rabbit	Brown	Black
T-shirt	Gray	Yellow

Received August 17, 2022
Revision received November 19, 2022
Accepted November 22, 2022 ■