



Independence of implicitly guided attention from goal-driven oculomotor control

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Abstract

Location probability learning—the acquisition of an attentional bias toward locations that frequently contained a search target—shows many characteristics of a search habit. To what degree does it depend on oculomotor control, as might be expected if habit-like attention is grounded in eye movements? Here, we examined the impact of a spatially incompatible oculomotor signal on location probability learning (LPL). On each trial of a visual search task, participants first saccaded toward a unique C-shape, whose orientation determined whether participants should continue searching for a T target among L distractors. The C-shape often appeared in one, “C-rich” quadrant that differed from where the T was frequently located. Experiment 1 showed that participants acquired LPL toward the high-probability, “T-rich” quadrant, an effect that persisted in an unbiased testing phase. Participants were also faster finding the target in the vicinity of the C-shape, but this effect did not persist after the C-shape was removed. Experiment 2 found that the C-shape affected search only when it was task-relevant. Experiment 3 replicated and extended the findings of Experiment 1 using eye tracking. Thus, location probability learning is robust in the face of a spatially incompatible saccade, demonstrating partial independence between experience-guided attention and goal-driven oculomotor control. The findings are in line with the modular view of attention, which conceptualizes the search habit as a high-level process abstracted from eye movements.

Keywords Spatial attention · Visual search · Selection history effects · Location probability learning · Oculomotor control

Introduction

The visual world is more complex than what we can process at one time. Attention allows us to select relevant sensory input for further processing. Although it is possible to attend to an object without directly looking at it, selection is often achieved by a sequence of eye movements that bring task-relevant information to the fovea. The importance of eye

movements in selection leads some researchers to propose that the brain mechanisms underlying oculomotor control also support visual attention (Rizzolatti et al., 1987). This *premotor theory of attention* can be contrasted with the *modular theory of attention*, according to which attention is a high-level cognitive function detached from the oculomotor circuit (Posner & Dehaene, 1994). To date, research on the relationship between attention and oculomotor control has primarily focused on transient drivers of attention, such as perceptual salience and current task goals. These studies have found both a close connection and partial independence between eye movements and attention (for reviews, see Hunt et al., 2019; Kowler, 1995; Smith & Schenk, 2012). However, increasing evidence has shown that visual attention is also sensitive to one’s previous experience, often without the participants’ awareness (Addelman & Jiang, 2019; Awh et al., 2012). The abundance of selection history effects raises the question about whether experience-guided attention relies on oculomotor control, as predicted by the premotor theory, or whether it is independent of eye movements. We address this question in the context of a well-characterized selection history effect—location probability learning.

Significance statement Visual search in daily activities often occurs with a sequence of eye movements that bring important objects to the fovea. This study shows that frequently looking toward a region does not induce a habitual spatial bias of searching in that region. Instead, a habit of searching in a specific region emerges only as a result of frequently finding a target in that region. Experience-guided attention is partly independent of oculomotor control. It may remain robust in people with a vision deficit that affects their eye movements.

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Location probability learning (LPL) refers to the acquisition of a spatial attentional bias toward locations that contain a visual search target disproportionately often. In studies of LPL, participants search for a target, such as a letter T, among distractors (e.g., letter Ls) presented in random locations. Unbeknownst to the participants, across multiple trials, the target appears more frequently in one region of space than in other regions. Although often unaware of the target's location probability, participants respond more quickly to the target when it is in the high-probability rather than the low-probability locations (Druker & Anderson, 2010; Geng & Behrmann, 2002, 2005; Jiang, 2018; Jiang et al., 2013). LPL is not restricted to the learning of the target's location probability. If a distractor, such as a visually salient singleton, frequently occurs in one region, participants acquire a spatial attentional bias away from that region (Britton & Anderson, 2020; Ferrante et al., 2018; Sauter et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c, 2020; Won et al., 2019).

The spatial attentional bias acquired through LPL differs from goal-driven attention in several ways. These unique features suggest that LPL reflects the development of a search habit (Salovich et al., 2018). First, like traditional motor habits, LPL is insensitive to outcome devaluation. After participants have acquired an attentional bias toward one region, the attentional bias persists in that region for several hundred trials after the target's location probability becomes unbiased (Jiang et al., 2013). Second, LPL yields a viewer-centered, rather than environment-centered, bias of spatial attention. In Jiang and Swallow (2013), participants were first trained to develop a spatial bias toward one region of a computer screen placed flat on a desk (e.g., the east corner of the screen). Subsequently, they changed their sitting position by 90°, resulting in a viewpoint change in the relative location of the screen corners and their perspective. After the viewpoint change, participants no longer prioritized the east corner of the screen. Instead, they preferred to search in a corner in the same visual field as the previously high-probability corner. Third, LPL demonstrates a key feature of habits—automaticity. Although explicit awareness can increase the size of LPL (Jiang, Swallow, et al., 2014; Vadillo et al., 2020), LPL is robust even when participants lack awareness of the target's location probability (Jiang et al., 2018). Imposing a secondary working memory load interferes with goal-driven attention but not with LPL (Won & Jiang, 2015). These features lead Jiang (2018) to propose a multiple-levels framework of attention, according to which spatial attention has both a map-like, *where* component and a dynamic, action like *how* component. Frequently finding a target in one region reinforces not only where to attend, but also the direction of the attentional shift that lands on the target.

By emphasizing the dynamic aspect of attention, the habitual attention account raises the possibility that eye movements play a crucial role in the acquisition and maintenance of LPL.

Might it be that LPL simply reflects a tendency to move one's eyes toward the high-probability locations? Empirical data on the role of eye movements in LPL have yielded mixed answers. On one hand, LPL not only speeds up search but also changes the direction of the first saccadic eye movement. Following training, participants are more likely to direct the first saccadic eye movement toward the high-probability locations, and this tendency persists after training (Jiang, Won, et al., 2014). This finding suggests that LPL results in both an overt eye movement habit and a covert spatial attentional bias. Other studies, however, suggest that the covert spatial bias does not depend on an overt eye movement. For example, participants can acquire LPL while maintaining central fixation, either with the enforcement of an eye tracker or because the display was presented too briefly for eye movements (Addleman et al., 2018; Geng & Behrmann, 2005; Jiang & Swallow, 2013). This finding suggests that much like endogenous or exogenous attention, experience-guided attention shows partial independence from eye movements.

Although LPL can emerge in the absence of an overt eye movement, this finding does not imply complete independence of LPL from oculomotor control. When people maintain central fixation, the oculomotor system is in a neutral state—it does not conflict with the emerging search habit. A stronger test of the independence of LPL from oculomotor control would come from a study design that pits the two factors against each other. Suppose the search target most often appears in the lower right. If people always have to look in a different direction first, such as toward the upper left, this can introduce an oculomotor signal incompatible with the habit of searching in the lower right. The premotor theory of attention predicts that the spatially incompatible oculomotor signal should interfere with the development of LPL. In contrast, if the search habit underlying LPL is a relatively high-level mechanism, then LPL may remain robust in the presence of an incompatible oculomotor signal. The three experiments reported here tested these competing hypotheses.

Experiment 1

To introduce a spatially incompatible oculomotor signal, we combined the standard LPL task with a secondary task that required an immediate saccadic eye movement. On each trial, participants viewed 12 white letters that included one rotated T and 11 Ls, along with a black C-shaped object. The task they performed depended on the orientation of the C-shape. Because the C-shape was presented briefly and its gap was small, accurate identification of its orientation necessitated an immediate eye movement toward the C-shape. On the occasional trials in which the gap pointed up (9% of the trials), participants pressed the space bar to end the trial. These trials

served as a probe to ensure that participants had followed instructions to look at the C-shape (Kowler, 1995). On the other trials when the gap pointed down, participants made no response to the gap, but instead had to find the T and report its orientation.

To introduce spatial incompatibility between LPL and the initial saccade, in a training phase, we presented the C-shape in a “C-rich” quadrant 70% of the time and in each of the other quadrants 10% of the time. The task goal, therefore, required participants to frequently saccade toward the C-rich quadrant. The target T, however, appeared frequently in a different, “T-rich” quadrant on 50% of the trials. Because the T-rich quadrant rarely contained the C-shape, the search habit toward the T-rich quadrant would need to form following a spatially incompatible, goal-directed oculomotor signal. By examining search RT across different target quadrants in the training phase, we could determine whether the spatially incompatible C-task interfered with LPL. Furthermore, we examined the persistence of any spatial attentional biases in an unbiased testing phase. The C-shape was removed in the testing phase. In addition, the target T was equally probable in all four quadrants. We examined whether participants were faster finding the target in the previously T-rich quadrant, as might be expected if the search habit had persisted. We also tested whether there was a search advantage in the previously C-rich quadrant, as might be expected if frequently saccading toward it had produced a lasting oculomotor habit.

Because the oculomotor signal toward the C-rich quadrant was both goal-driven and spatially incompatible with the emerging search habit, Experiment 1 allowed us to simultaneously address the role of goal-driven attention and oculomotor control in experience-guided attention. The relationship between goals and habits is complex. A learned habit, such as a tendency to drive home after work, can sometimes override a momentary goal (e.g., stopping by a pharmacy), suggesting partial independence between habits and goals. However, goals can also interfere with the spontaneous emergence of a habit (for a review, see Wood & R nger, 2016). Consequently, both endogenous orienting and saccade toward the C-rich quadrant could interfere with LPL. Any preservation of LPL under these stringent conditions would suggest that LPL is a robust effect, partially independent of task goals and oculomotor control.

Method

Testing platform

Experiment 1 was conducted using an online platform (Pavlovio.org) during a period when in-person testing was halted due to COVID-19. The online platform was validated by a recent publication that revealed LPL in online testing (Ivanov & Theeuwes, 2021). In addition, we conducted a pilot

experiment to validate online testing. This pilot experiment was identical to Experiment 1, except that the C-shape was omitted, rendering it a standard LPL task. The 24 participants in the pilot experiment acquired an LPL (18% of RT saving) that was comparable in size to previous in-person studies (10–25% of RT savings in Jiang et al., 2013). Further details about the pilot experiment can be found on Open Science Framework (<https://osf.io/9vdpw/>).

Sample size determination

We prespecified 24 participants as the targeted sample size in each experiment. This sample size was determined based on Experiment 1 of Jiang et al. (2013), which reported an effect size of 1.34 in Cohen’s f for LPL. Assuming comparable effect sizes, G*Power analysis (Faul et al., 2007) showed that five participants were needed to reach a power of .95 at an alpha-level of 0.05 in a two-tailed test. The pilot experiment online had a smaller effect size (0.88 in Cohen’s f), necessitating a minimal sample size of 7. Taking into consideration of noise in online data collection, reduced power in a dual-task design, and the need to counterbalance quadrant assignments across participants, we aimed to collect data from 24 participants.

Participants in all three experiments reported here were between the ages of 18 and 45 years of age and were naïve to the purpose of the study. They were fluent in English and had normal or corrected-to-normal visual acuity and normal color vision. Participants in Experiments 1 and 2 provided informed consent online, after which they launched the experiment on Pavlovio.org and completed the experiment on their own laptop or desktop computers. Participants in Experiment 3 received informed consent in person and completed the experiment with eye tracking. Participants were students from the University of Minnesota who volunteered their time for extra course credit or cash reward. Participants in Experiment 1 included 18 females and six males with a mean age of 20.8 years ($SD = 2.7$ years).

Equipment

Stimuli in the online experiments were presented on the participants’ own laptop or desktop computers with an unrestrained viewing distance. We used MATLAB (www.mathworks.com) to generate condition files for PsychoPy. Stimulus presentation was controlled by PsychoPy (Peirce et al., 2019) and converted into JavaScript for testing on Pavlovio.org. Stimulus size was specified in pixels.

Materials and procedure

The experiment contained four phases: practice, training, testing, and recognition test. Each practice trial started with a

small fixation point at the center of the display. After 500 ms, an array of white letters along with a black C-shape was displayed. The black C-shape (15×15 pixels) contained a gap (5 pixels) pointing either up or down and was presented for just 300 ms. The search items included one rotated white letter T (40×40 pixels; rotated 90° to the left or right) and 11 rotated white letter Ls (40×40 pixels; each randomly rotated 90° , 180° , 270° , or 0°) and were presented until participants made a response. The location of all the items was selected randomly from a 10×10 invisible matrix that subtended 600×600 pixels, with the constraint that there were three search letters in each quadrant. The orientation of the target T was selected randomly, with the constraint that both responses (left/right) occurred equally often. Participants were instructed to immediately move their eyes to the C-shape and identify its gap direction. On trials when the gap pointed up, participants pressed the space bar to terminate the trial. On the remaining trials when the gap pointed down, participants were asked to make no response to the C-shape, but instead to find the letter T and press either the left or the right arrow key to report the orientation of the T. The search display was erased upon the keypress response. Correct responses received a brief feedback (“Correct!” printed in green for 200 ms). Incorrect responses to the letter T received a longer feedback (“Incorrect!” printed in red for 2 s). Incorrect responses to the C-shape led to a 2-s feedback with a full screen of colorful blobs along with the word “Incorrect” printed in red. Participants were instructed to aim for 100% accuracy in the C-task and to respond as accurately and as quickly as possible in the T-task. The practice phase contained 12 trials with just the C-shape, where participants pressed the space bar for upward Cs (6 trials) and made no response to downward Cs (6 trials). This was followed by 24 trials that combined the C- and T-tasks. These included 12 trials with an upward C-shape and 12 practice trials with a downward C-shape. To ensure that participants understood what they were asked to do, after practice, we asked participants to answer two short questions about how to respond to the C-shape and the letter T. All participants correctly answered these questions.

The training phase contained six blocks of trials with 66 trials in each block. The trials were similar to the dual-task trials participants experienced during practice. In each block, probe trials with an upward C-shape occurred six times, leaving the majority of the trials with a downward C-shape that signaled visual search.

The testing phase contained 3 blocks of trials with 60 trials in each block. In this phase, the C-shape was no longer presented. Participants searched for the letter T and reported its orientation on all trials.

Finally, the recognition phase asked participants to answer a few questions that gauged their awareness of the spatial distribution of the C-shape and the target T.

Design

To introduce spatial incompatibility between the oculomotor task toward the C-shape and the search task, in the training phase we manipulated the location probability of the C-shape and the T. On search trials (i.e., when the C-shape pointed down), the target T appeared in a T-rich quadrant 50% of the time and in each of the other three quadrants 16.7% of the time. The C-shape appeared in a different, C-rich quadrant 70% of the time and in each of the other three quadrants 10% of the time. On probe trials (i.e., when the C-shape pointed up), the target T also appeared in the T-rich quadrant 50% of the time and in each of the other quadrants 16.7% of the time. The C-shape was presented in the C-rich quadrant 66.7% of the time, the T-rich quadrant 16.7% of the time, and in each of the other two quadrants 8.3% of the time.¹ Because the trial terminated after the probe response, there was no search on these trials. The designation of the specific quadrants to T-rich, C-rich, and sparse was counterbalanced across participants.

In the testing phase, the target T appeared in each quadrant 25% of the time. In addition, the C-shape was removed (Fig. 1).

Participants were not informed of the location probability of the letter T or the C-shape, nor were they alerted to the transition from the training to the testing phase.

Recognition

The recognition phase contained the following questions. First, participants were asked whether they thought the target T was equally likely to appear in all locations, or whether it was more often found in some locations than others. After this first response, participants were informed that the target was more likely to appear in one visual quadrant. They were asked to select the quadrant where the target T most often appeared. Finally, we asked participants to choose the quadrant that most often contained the C-shape.

Results

C-task

In the training phase, participants correctly made a Go response to upward C-shapes 93.1% of the time ($SE = 1.4\%$). The false alarm rate to a downward C-shape was 2.9% ($SE = 0.5\%$), yielding an overall accuracy of 96.8% ($SE = 0.5\%$). The high level of accuracy suggests that participants successfully oriented toward the C-shape.

¹ Because each block contained just six probe trials, we could only approximate the C-shape’s spatial distribution on these trials to be close to the 7:1:1:1 ratio used on search trials. The closest approximation was used in this experiment, yielding a distribution of 6.7:1.7:0.8:0.8 distribution across the C-rich, T-rich, and sparse quadrants).

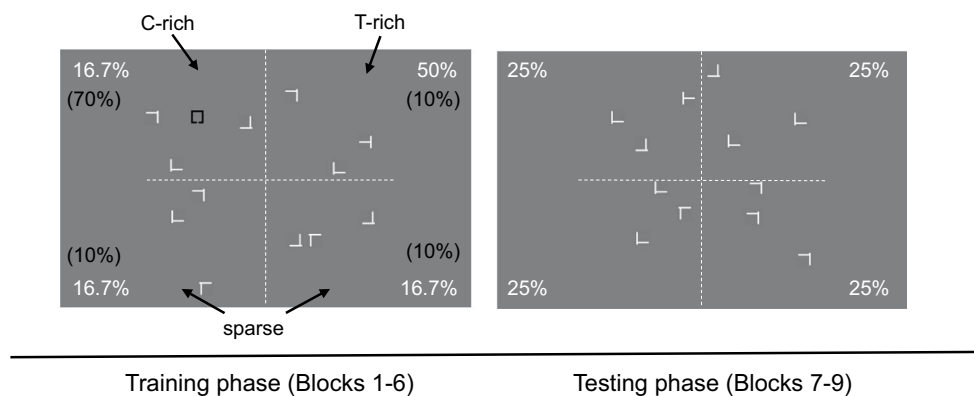


Fig. 1 A schematic of stimuli and design used in Experiment 1. During training (Blocks 1–6), a black C-shaped object was presented concurrently with the T-and-L items, but it offset after 300 ms, leaving the T and Ls on the display. Participants performed a combination of a go/no-go task to the C-shape and a T-among-Ls search task. Participants first saccaded toward the black C-shape to identify the direction of its gap. On 9% of the trials in which the gap pointed up, participants pressed the space bar to terminate the trial. On 91% of the trials in which the gap pointed down, participants made no response to the gap, but proceeded to search for a

target T and reported its orientation. The C-shape appeared most often (70% of the time) in one quadrant, the “C-rich” quadrant. The target T appeared most often (50% of the time) in another quadrant, the “T-rich” quadrant. The other two quadrants were considered “sparse” quadrants. The testing phase (Blocks 7–9) did not include the C-shape. The T’s location was unbiased in the testing phase (i.e., 25% in each quadrant). Items are not drawn to scale. The dashed lines and the numbers illustrating the target’s location probability are for illustrative purposes only

Visual search: T-task

On trials when the C-shape pointed downward, participants correctly responded to the T’s orientation 97% of the time. Mean accuracy was unaffected by whether the T was in the T-rich quadrant ($M = 97.3\%$, $SE = 0.5\%$), the C-rich quadrant ($M = 96.9\%$, $SE = 0.6\%$), or the sparse quadrants ($M = 96.9\%$, $SE = 0.4\%$), $F(2, 46) = 0.96$, $p = .391$, $\eta_p^2 = .040$. In the following search RT analysis, we removed probe trials (i.e., Go trials with an upward C-shape) as well as trials with an incorrect search response. Figure 2a displays mean RT across blocks.

Training phase An ANOVA using target location (T-rich, C-rich, or sparse quadrants) and training block (1–6) as factors showed a significant main effect of target location, $F(2, 46) = 17.79$, $p < .001$, $\eta_p^2 = .436$. The main effect of block was also significant, with faster RT in later blocks than earlier ones, $F(5, 115) = 17.18$, $p < .001$, $\eta_p^2 = .428$. These two factors interacted, driven by a larger effect of target location in later than in earlier blocks, $F(10, 230) = 2.53$, $p = .007$, $\eta_p^2 = .099$.

To understand how target’s location affected RT, we computed mean RT when the target was in the T-rich, C-rich, or the sparse quadrants. We performed three planned pairwise t tests using a critical alpha level of 0.0167, adjusted for multiple comparisons. RT was significantly faster in the T-rich quadrant than the sparse quadrants, $t(23) = 6.43$, $p < .001$, Cohen’s $d = 1.312$, demonstrating location probability learning. RT was also faster in the C-rich quadrant than the sparse quadrants, $t(23) = 3.46$, $p = .002$, Cohen’s $d = 0.706$, showing an effect of overtly orienting to the C-rich quadrant at trial onset. RT was faster in the T-rich quadrant than in the C-rich quadrant, $t(23) = 2.41$, $p = .025$, Cohen’s $d = 0.491$, but

this effect missed the critical alpha level. Thus, both the task goal of overtly orienting to the C-rich quadrant and LPL affected search RT.

To further examine how overt orienting toward the C-shape influenced search, we examined how the spatial relationship of the T and C-shapes affected search RT. We divided trials based on whether the C-shape and the T occurred in the same or different quadrants, and which quadrant the T was in. As shown in Fig. 2b, this analysis revealed a significant main effect of spatial relationship, with faster RT when the T and C-shape appeared in the same rather than different quadrants, $F(1, 23) = 20.28$, $p < .001$, $\eta_p^2 = .469$. The main effect of the target quadrant was significant, $F(2, 46) = 20.22$, $p < .001$, $\eta_p^2 = .468$, with faster RT when the T appeared in the T-rich rather than the other quadrants. These two factors did not interact, $F(2, 46) = 1.14$, $p = .328$, $\eta_p^2 = .047$. Thus, if the target T happened to appear in the same quadrant as the C-shape, search was faster, suggesting that overt orienting to the C-shape modulated the allocation of attention in the ensuing search task.

Testing phase The testing phase examined whether the search advantage in the T-rich and C-rich quadrants persisted after both the C-shape and the probability cue were removed. An ANOVA on target location (previously C-rich, T-rich, or sparse quadrants) and block (7–9) showed a significant main effect of target location, $F(2, 46) = 10.97$, $p < .001$, $\eta_p^2 = .323$, no main effect of testing block, $F(2, 46) = 0.504$, $p = .607$, $\eta_p^2 = .021$, and no interaction, $F(4, 92) = 0.172$, $p = .952$, $\eta_p^2 = .007$.

Follow-up planned t tests showed that RT was faster in the previously T-rich quadrant than both the C-rich quadrant and the sparse quadrants, $t(23) = 3.12$, $p = .005$, Cohen’s $d = 0.637$ comparing T-rich with C-rich, and $t(23) = 4.88$, $p < .001$,

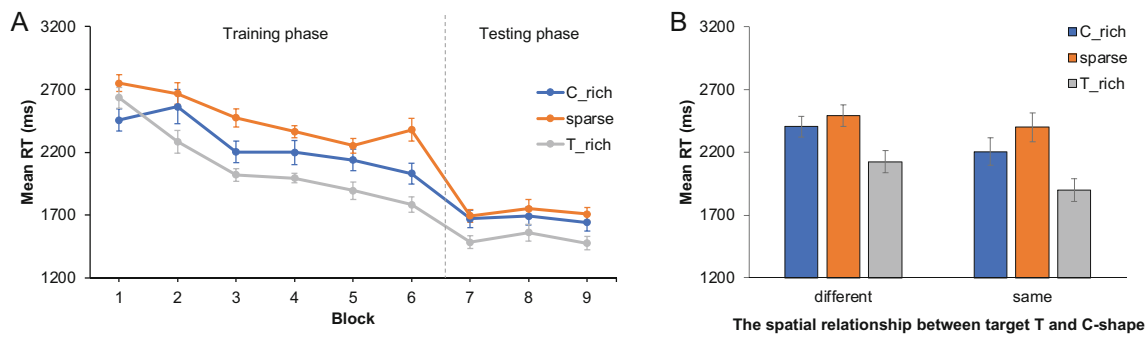


Fig. 2 Mean RT in Experiment 1. **a** Search RT across blocks. The target T was presented more often in the T-rich quadrant in the training phase (Blocks 1–6) but had an unbiased spatial distribution in the testing phase (Blocks 7–9). The C-shape appeared more frequently in the C-rich

quadrant in the training phase. It was omitted from the testing phase. **b** Training phase RT as a function of whether the target T and the C-shape were located in the same quadrant, and where the target T was. Error bars show ± 1 within-subject *SE* of the mean

Cohen's $d = 0.996$ comparing T-rich with sparse. Thus, LPL induced a persisting spatial bias toward the previously high-probability T-rich quadrant. In contrast, RT was not faster in the previously C-rich quadrant than the sparse quadrants, $t(23) = 1.14$, $p = .268$, Cohen's $d = 0.232$. We conducted a Bayesian analysis for null results (Dienes, 2014; Morey & Rouder, 2011). This analysis produced the Bayes Factor B_{01} , which indexed how much more likely the observed data came from the null model relative to the alternative model. Values greater than 3 favor the null hypothesis, whereas values less than 0.333 favor the alternative hypothesis. In our study, the Bayes factor B_{01} (null vs. alternative hypothesis) was 3.47 in the comparison between C-rich and sparse, providing evidence in favor of the null hypothesis (Dienes, 2014; Morey & Rouder, 2011). Thus, once the task goal of saccading to the C-shape was removed, there was no longer any attentional preference for the C-rich quadrant.

Recognition test

Most participants—17 out of 24—successfully identified the C-rich quadrant during the recognition test, $\chi^2(1) = 26.89$, $p < .001$, suggesting that they were aware that the C-shape frequently appeared in one specific region. In contrast, just 5 of the 24 participants indicated that they thought the target's location was biased. On the forced-choice task, eight of the 24 participants (33%) correctly identified the T-rich quadrant as the high-probability quadrant, a level that was not higher than chance, $\chi^2(1) = 0.89$, $p = .346$. This was numerically below the rate of explicit recognition in a previous study (42.2% in Jiang et al., 2018). However, because the recognition test used just a single forced-choice trial, it may have underestimated the degree of explicit awareness (Vadillo et al., 2020). The Appendix contained additional analysis that split participants into aware and unaware participants based on their forced choice response. This analysis did not find evidence of increased LPL in aware relative to unaware participants.

Discussion

Experiment 1 provided strong evidence that experience-guided attention can be acquired in the presence of a spatially incompatible oculomotor signal. The accurate responses to the C-shape suggests that participants had followed the task goal of orienting to the C-shape. In addition, search RT was faster when the target appeared in the vicinity of the C-shape, confirming that participants attended to locations around the C-shape. Despite the C-shape appearing frequently in a region away from the target's high-probability region, participants successfully acquired LPL of the T-rich quadrant. The magnitude of LPL was comparable to that observed in previous studies (15% of RT saving in the present experiment, relative to 10–25% of RT savings found in Jiang et al., 2013). The effect persisted through the unbiased testing phase, ruling out short-term repetition priming as an adequate account of LPL. The presence of LPL in the face of a spatially incompatible saccadic eye movement suggests that LPL is relatively independent of oculomotor control.

The persistence of LPL in the testing phase could be contrasted with a lack of durable attentional preference for the C-rich quadrant, suggesting that frequently saccading to the C-shape was insufficient for inducing an automatic attentional bias. Thus, whereas repeatedly finding a target in a location produced LPL, frequently saccading toward a location based on instruction did not.

The robustness of LPL in Experiment 1 was striking, but the experimental design left two questions unanswered. First, although participants showed a spatial bias toward the C-rich quadrant during training, it is unclear whether this reflected endogenous orienting toward the C-rich quadrant, or exogenous orienting toward a singleton stimulus. The C-shape was unique in both color and shape, making it a candidate stimulus for exogenous orienting. This could lead to attentional capture and LPL of the C-shape. Previous studies showed that people learn to bias attention away from a singleton distractor

(Britton & Anderson, 2020; Ferrante et al., 2018; Sauter et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c, 2020; Won et al., 2019), suggesting that salient distractors may have briefly captured attention but are then suppressed (Gaspelin et al., 2015). The inhibitory effect may have counteracted any attentional preference for the C-rich quadrant, resulting in a lack of a persisting attentional preference in the testing phase. To understand whether exogenous orienting had taken place in Experiment 1, it is important to repeat this experiment but render the C-shape task-irrelevant. Experiment 2 aimed to do this. Second, the online testing platform used in Experiment 1 prevented us from recording participants' eye movements. Although saccades were likely made toward the C-shape given its small size and short duration, we did not have eye data to corroborate this assumption. When in-person data collection resumed, we conducted Experiment 3 as a replication of Experiment 1 with the addition of eye tracking.

Experiment 2

This experiment was the same as Experiment 1, except that participants were not asked to perform any task on the C-shape. Instead, they performed a single task of finding the letter T. The C-shape was therefore a task-irrelevant singleton distractor. This design allowed us to examine whether the C-shape may have triggered exogenous orienting, as well as a learned attentional bias away from the C-rich quadrant.

The C-shape had several properties that made it a candidate stimulus for exogenous attention. In addition to having a common onset with the search items, it was the only black item on the display, the only stimulus with a curved line, and the only stimulus that abruptly offset after 300 ms. If the C-shape was effective in capturing attention, we may expect search RT in the C-rich quadrant to be faster than in the sparse quadrants, at least early in the experiment. As training progressed, participants may develop a spatial attentional bias away from the C-rich quadrant, resulting in slower search RT in the C-rich relative to the sparse quadrants. However, other features of the C-shape may render it an ineffective stimulus for automatic attentional capture. First, because the C-shape was black and the other items were white, its luminance was low, reducing its visual salience. Second, the C-shape always differed from the target letter in color and shape, making it easy for participants to adopt an attentional set that did not include any features of the C-shape (Folk et al., 1992). Over time, participants may habituate to the C-shape and minimize attentional capture (Kelley & Yantis, 2009). If this is the case, then performance should be comparable between the C-rich and the sparse quadrants.

Method

Participants

Twenty-four new participants, including 20 females and four males with a mean age of 19.8 years ($SD = 1.3$), completed Experiment 2. The experiment was conducted using the same online platform as in Experiment 1.

Materials, procedure, and design

The experiment was identical to Experiment 1 except that participants were not asked to perform any task on the C-shape. In fact, the instructions did not mention the C-shape. Because the C-shape was task-irrelevant, there were no probe trials. Therefore, each of the nine blocks contained 60 trials, all of which required visual search.

Recognition

The recognition test was similar to that of Experiment 1, except that participants were first asked whether they had noticed the C-shape. Participants made a forced-choice response among three options: (a) Yes, and I found the black C distracting; (b) Yes, but it did not bother me at all; and (c) No, I did not notice any black letters. Following this question, participants answered the same two recognition questions about the letter T's spatial distribution as those used in Experiment 1.

Results

Participants were equally accurate when the target was in the T-rich ($M = 98.3\%$, $SE = 0.3\%$), C-rich ($M = 98.1\%$, $SE = 0.3\%$), and the sparse quadrants ($M = 97.8\%$, $SE = 0.4\%$), $F(2, 46) = 1.34$, $p = .272$, $\eta_p^2 = .055$. In the RT analysis, we excluded incorrect trials. Figure 3a shows the mean RT across blocks.

Training phase

An ANOVA using training block (1-6) and target location (T-rich, C-rich, or sparse) as within-subject factors showed a significant main effect of block, with faster RT as training progressed, $F(5, 115) = 15.04$, $p < .001$, $\eta_p^2 = .395$. The main effect of target location was also significant, $F(2, 46) = 37.46$, $p < .001$, $\eta_p^2 = .620$, an effect that did not interact with block, $F(10, 230) = 1.31$, $p = .227$, $\eta_p^2 = .054$.

To understand how RT differed across quadrants, we conducted three planned contrasts comparing the mean RT when the target was in the T-rich, C-rich, or the sparse quadrants. The critical alpha for these tests was $p < .0167$ to control for multiple comparisons. We found that RT was significantly

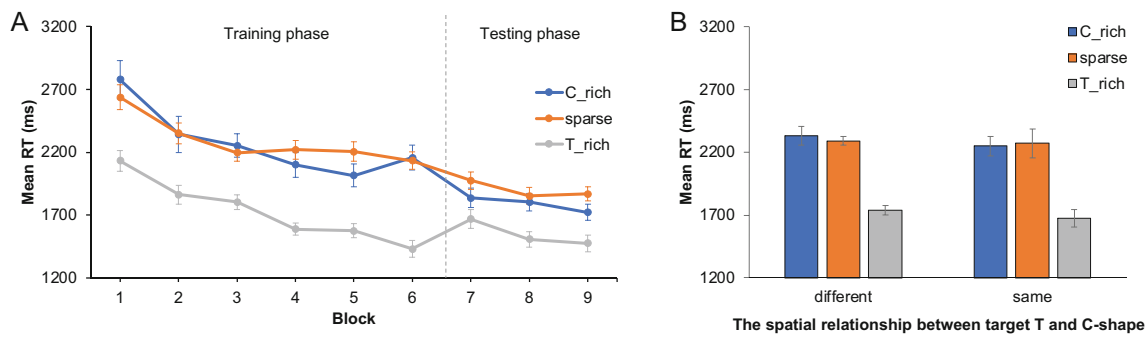


Fig. 3 Results from Experiment 2. **a** Search RT across blocks. The target T's location was biased toward the T-rich quadrant in Blocks 1–6 (training phase) and was unbiased in Blocks 7–9 (testing phase). The C-rich quadrant frequently contained the task-irrelevant C-shape in the training phase. The C-shape was removed in the testing phase. **b** Search RT in the

training phase as a function of whether the target T and the C-shape appeared in the same quadrant or in different quadrants, and as a function of where the target T was. Error bars show ± 1 within-subject *SE* of the mean

faster in the T-rich quadrant than both the C-rich, $t(23) = 6.14$, $p < .001$, Cohen's $d = 1.253$, and the sparse quadrants, $t(23) = 12.46$, $p < .001$, Cohen's $d = 2.543$. RT did not differ between the C-rich and the sparse quadrants, $t(23) = 0.17$, $p = .870$, Cohen's $d = 0.034$, Bayes Factor B_{01} (null vs. alternative) = 6.29 in favor of the null hypothesis. This finding shows that participants developed a spatial bias toward the T-rich quadrant, but not toward the C-rich quadrant.

If the C-shape had captured attention, then search should be faster if the target T appeared in the same, rather than a different, quadrant as the C-shape. To determine if this was the case, we separated trials based on whether the target T was in the same quadrant as the C-shape and which quadrant the target T was located (T-rich, C-rich, or sparse). This analysis (Fig. 3b) revealed just a significant main effect of target location, $F(2, 46) = 26.20$, $p < .001$, $\eta_p^2 = .533$. The main effect of the T-C spatial relationship was not significant, $F(1, 23) = 1.86$, $p = .186$, $\eta_p^2 = .075$, meaning that RT was not faster when the T happened to be in the same quadrant as the C-shape than when they occurred in different quadrants. A Bayesian analysis for null hypothesis showed a Bayes factor B_{01} (null vs. alternative) of 4.64, providing evidence in favor of the null hypothesis. These two factors did not interact, $F(2, 46) = 0.08$, $p = .922$, $\eta_p^2 = .004$. Thus, there was no evidence that the C-shape effectively captured attention.

Testing phase

To find out whether participants had acquired a persisting spatial bias either toward or away from the C-rich quadrant, we examined the search RT data in the testing phase after the C-shape was removed and when T's spatial distribution was unbiased. An ANOVA on testing block (7–9) and target location (previously T-rich, C-rich, or sparse quadrants) as factors showed a significant main effect of block, $F(2, 46) = 4.88$, $p = .012$, $\eta_p^2 = .175$, with faster RT in later blocks than earlier ones. The main effect of target location was significant, $F(2,$

$46) = 15.02$, $p < .001$, $\eta_p^2 = .395$, but it did not interact with block, $F(4, 92) = 0.481$, $p = .750$, $\eta_p^2 = .020$.

Follow-up tests showed that search RT was significantly faster in the previously T-rich quadrant than both the C-rich and the sparse quadrants, $t(23) = 3.40$, $p = .002$, Cohen's $d = 0.694$ comparing T-rich with C-rich, and $t(23) = 5.58$, $p < .001$, Cohen's $d = 1.140$ comparing T-rich with sparse quadrants. The C-rich and sparse quadrants did not differ, $t(23) = 1.78$, $p = .088$, Cohen's $d = 0.363$. Bayesian analysis for null hypothesis yielded a Bayes factor B_{01} (null vs. alternative) of 1.51, a value that did not strongly support either the null hypothesis or the alternative. Thus, we were able to detect a persisting spatial bias toward the previously T-rich quadrant, but there was a lack of clear evidence for a persisting attentional bias toward the C-rich quadrant.

Across experiment comparisons

Other than the task-relevance of the C-shape, Experiments 1 and 2 were conducted under comparable conditions. To determine how this factor affected performance, we conducted an exploratory analysis that contrasted the two experiments. This comparison focused on the testing phase, which was identical other than what participants had experienced up to that point. We performed an ANOVA using target location (previously T-rich, C-rich, or sparse) and testing block (7–9) as within-subject factors, and experiment (Experiments 1 vs. 2) as a between-subject factor. This analysis showed a significant main effect of target location, $F(2, 92) = 25.77$, $p < .001$, $\eta_p^2 = .359$, showing faster RT when the target appeared in the previously T-rich quadrant relative to the other quadrants. The main effect of testing block was not significant, $F(2, 92) = 1.72$, $p = .185$, $\eta_p^2 = .036$, neither was the main effect of experiment, $F(1, 46) = 1.29$, $p = .262$, $\eta_p^2 = .027$. LPL did not interact with experiment, $F(2, 92) = 1.47$, $p = .235$, $\eta_p^2 = .031$, or testing block, $F(2, 92) = 2.23$, $p = .113$, $\eta_p^2 = .046$, and there was no three-way interaction, $F(4, 184) = 0.49$, $p =$

.744, $\eta_p^2 = .011$. Thus, the only persisting effect in both experiments was an attentional bias toward the previously T-rich quadrant. The need to overtly orient toward the C-shape, as was done in Experiment 1 but not in Experiment 2, did not have lasting effects on LPL.

Recognition

Even though the C-shape was presented several hundred times, the majority of the participants—17 out of 24—reported that they did not notice it. Of the seven who reported noticing it, four found it distracting, and the other three were not bothered. These seven participants showed the same pattern of search behavior as the other participants (see the Appendix). The general lack of subjective salience was consistent with the ineffectiveness of the C-shape in capturing attention.

In the awareness test of the T's spatial distribution, 11 participants said that they felt that it was more often in some locations than in others. In the forced-choice recognition test, 14 participants correctly identified the T-rich quadrant, a level that was significantly above chance, $\chi^2(1) = 14.22, p < .001$. A further analysis separating the 14 aware participants from the 10 unaware participants showed qualitatively similar results in search RT. Like aware participants, unaware participants developed an LPL toward the T-rich quadrant that persisted in the testing phase. Detailed analysis on recognition results can be found in the Appendix.

Discussion

When the C-shape was task-irrelevant, it did not influence search RT in the training phase. Search was not faster when the target happened to be in the same quadrant as the C-shape. The testing phase also did not uncover a persisting spatial bias either toward or away from the C-rich quadrant. Thus, the search advantage in the C-rich quadrant of Experiment 1 can be attributed to endogenous orienting to the C-shape, rather than exogenous orienting to a singleton stimulus.

Why did we only observe an LPL for the target, but not an LPL for the singleton distractor? The finding may seem at odds with previous studies that reported LPL for salient distractors. For example, in Ferrante et al. (2018), participants searched for a target—a double arrow facing the same direction—among three distractors (double arrows facing opposite directions). On half of the trials, all items were red or green; on the other half of the trials, one distractor was in a different color (e.g., red) from the other items (e.g., green), making it visually salient (i.e., it is a color singleton). In one experiment, the target appeared disproportionately often in one of the four locations, and the color singleton appeared disproportionately often in another location. Participants demonstrated both types of learning: search was faster when the

target appeared in the high target-probability location, but slower when it appeared in the high distractor-probability location, relative to the other two locations. Our study may seem inconsistent with Ferrante et al. (2018). However, the salient distractor in Ferrante et al. (2018) was part of the search array. Its color, though unique on a specific trial, could be the target's color on other trials. These features made the salient distractor not only partially task-relevant, but also confusable with the target. They increased the likelihood that participants would actively suppress the salient distractor in Ferrante et al. (2018). In contrast, the C-shape in the current study differed from the search items. This reduced its tendency to capture attention when it was task-irrelevant (as in Experiment 2). Even when it was task-relevant (as in Experiment 1), its distinction from the other search items made it unlikely that active suppression was needed. The use of a challenging T-among-L search task that exerted a high perceptual load may also have reduced attentional capture by the singleton stimulus (Forster & Lavie, 2008).

Having demonstrated that Experiment 1 reflected mainly endogenous orienting rather than exogenous orienting to the C-shape, in the next experiment we used eye tracking to both replicate Experiment 1's finding and characterize eye movements.

Experiment 3

Experiment 1 showed that the target's location probability learning was robust even when participants frequently saccaded away from where the target was most often placed. The online testing format, however, prevented us from obtaining eye movement data. The goal of Experiment 3 was to replicate these results in an in-person study with eye tracking. The eye data allowed us to verify that participants had made a saccade toward the C-shape. It also provided additional insights into the dynamics of search behavior, such as the frequency of first saccades toward each quadrant, saccade latency, and the direction of the second saccade.

Method

Participants

The 24 participants in Experiment 3 were students at the University of Minnesota, who volunteered their time for extra course credit or cash payment. There were 17 females and seven males with a mean age of 20.5 years ($SD = 3.6$ years).

Equipment

Participants completed the experiment individually in a laboratory room with normal interior lighting. Viewing distance

was kept at 90cm with the use of a chinrest. Stimuli were displayed on a 19-inch CRT monitor (spatial resolution: $1,024 \times 768$ pixels; vertical refresh rate: 100 Hz). The experiment was programmed in MATLAB and Psychtoolbox (Kleiner et al., 2007). An EyeLink 1000 eye tracker (SR Research, Mississauga, ON, Canada) tracked the left eye at a sampling rate of 1000 Hz. Eye position was calibrated using a 9-point calibration procedure before the experiment and verified with drift check before each trial.

Materials and procedure

Other than being tested in-person with an eye tracker, participants in Experiment 3 went through the same procedure as those in Experiment 1. The stimuli and experimental design were identical as well. The only difference was the addition of an eye-position drift check before each trial. Specifically, to initiate each trial, participants first fixated at a central fixation point and pressed the space bar. If the eye tracker verified their central fixation, the search display would appear on the screen. Recalibration of eye position was conducted if needed.

Results

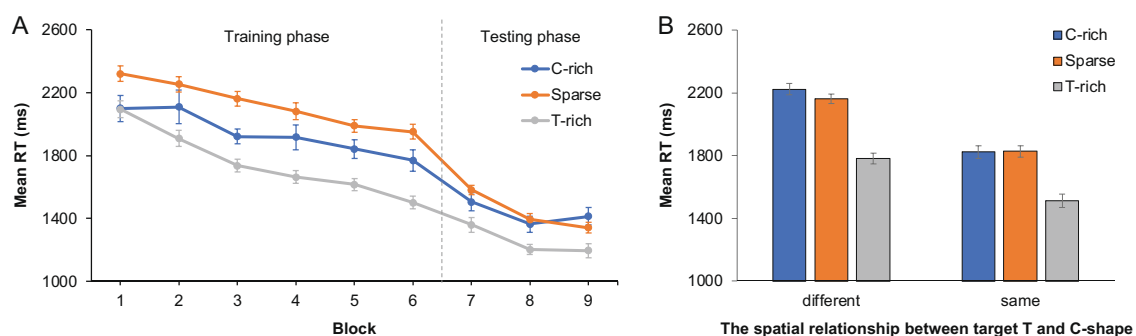
Behavioral results

The C-task Participants responded to upward C-shapes 97.1% ($SE = 0.5\%$) of the time, along with a false alarm rate of 1.1% ($SE = 0.2\%$), for an overall accuracy of 98.8% ($SE = 0.2\%$). The high accuracy in the C-task showed that participants had followed the instructions to orient toward the C-shape.

The T-task Participants searched and responded to the T target on trials when the C-shape pointed downward. Search accuracy was uniformly high across all quadrants: T-rich ($M = 99.1\%$, $SE = 0.2\%$), C-rich ($M = 98.8\%$, $SE = 0.3\%$), and the sparse quadrants ($M = 99.2\%$, $SE = 0.1\%$), $F(2, 46) = 0.96$, $p = .392$, $\eta_p^2 = .040$. In the RT and eye data analysis, probe trials (i.e., with an upward C-shape) and incorrect search trials were removed. As is apparent from Fig. 4, search RT results replicated those of Experiment 1.

Training phase RT An ANOVA on the target's location (T-rich, C-rich, or sparse) and training block (1–6) revealed a significant main effect of target location, $F(2, 46) = 29.74$, $p < .001$, $\eta_p^2 = .564$, a significant main effect of block, $F(5, 115) = 22.53$, $p < .001$, $\eta_p^2 = .495$, without an interaction between the two, $F(10, 230) = 1.06$, $p = .399$, $\eta_p^2 = .044$. Planned *t*-tests comparing the mean RT in the T-rich, C-rich, and sparse quadrants showed significant differences across all three conditions. Demonstrating LPL of the target's location probability, RT was faster in the T-rich quadrant than both the C-rich, $t(23) = 3.64$, $p = .001$, Cohen's $d = 0.743$, and the sparse quadrants, $t(23) = 8.66$, $p < .001$, Cohen's $d = 1.768$. Overt orienting toward the C-shape also affected search RT: RT was faster in C-rich quadrant than the sparse quadrants, $t(23) = 3.69$, $p = .001$, Cohen's $d = 0.754$. Thus, both LPL and endogenous orienting toward the C-shape affected search.

As in Experiment 1, we divided trials based on whether the target T appeared in the same quadrant as the C-shape, and where the T was located (T-rich, C-rich, or sparse). An ANOVA on these two factors (Fig. 4b) again showed a significant main effect of T-C relationship, with faster RT when the letter T was in the same quadrant as the C-shape, $F(1, 23) = 110.72$, $p < .001$, $\eta_p^2 = .828$. The main effect of target location



The six bars shown in Panel B represented the mean RT of six types of trials. The number of trials falling into the six bars differed. In the "same" location condition, the number of trials contributing to C-rich, Sparse, and T-rich conditions (assuming all trials received a correct response) was 18, 108, and 162, respectively. In the "different" condition, the number of trials contributing to the C-rich, Sparse, and T-rich conditions was 42, 12, and 18, respectively. When all trials were considered, mean RT across conditions followed the same order as in Panel A (e.g., faster RT in the C-rich than the Sparse condition). However, differences in RT across conditions, in combination with an unequal number of trials, led to the "same" and "different" subsets of the data to have averages that did not always follow the same order.

Fig. 4 Search RT from Experiment 3. **a** Search RT across blocks. The target T was presented more often in the T-rich quadrant in the training phase (Blocks 1–6) and was unbiased in the testing phase (Blocks 7–9). The C-shape appeared more frequently in the

training phase and was removed in the testing phase. **b** Training phase RT as a function of whether the target T and the C-shape were located in the same quadrant, and where the target T was. Error bars show ± 1 within-subject SE of the mean

was significant, $F(2, 46) = 43.65, p < .001, \eta_p^2 = .655$, without an interaction, $F(2, 46) = 1.64, p = .206, \eta_p^2 = .066$. Thus, once participants had overtly oriented toward the C-shape, they tended to prioritize that region in the search for the letter T.

Testing phase RT Results in the testing phase replicated those of Experiment 1. An ANOVA on target location (previously C-rich, T-rich, or sparse) and testing block (7–9) revealed significant main effects of target location, $F(2, 46) = 10.02, p < .001, \eta_p^2 = .303$, and block, $F(2, 46) = 19.71, p < .001, \eta_p^2 = .461$, without an interaction, $F(4, 92) = 0.99, p = .420, \eta_p^2 = .041$. Follow-up t tests showed faster RT in the T-rich quadrant than both the C-rich, $t(23) = 3.29, p = .003$, Cohen's $d = 0.671$, and the sparse quadrants, $t(23) = 5.26, p < .001$, Cohen's $d = 1.073$. RT did not differ between the C-rich and the sparse quadrants, $t(23) = 0.25, p = .803$, Cohen's $d = 0.052$, Bayes Factor B_{01} (null vs. alternative) = 6.18 in favor of the null hypothesis. Thus, training induced a persisting LPL toward the T-rich quadrant, without evidence of a residual attentional bias toward the C-rich quadrant.

Eye movement results

The majority of the first saccadic eye movement—86.5% ($SE = 1.2%$)—landed in the vicinity (i.e., same quadrant) of the C-shape, indicating that participants had prioritized the C-task and directed their eyes toward the C-shape. In the following analysis, we removed probe trials and trials with an incorrect search response. Of particular interest is how eye movements differed across visual quadrants in the visual search task.

First saccades Given that the C-shape was in the C-rich quadrant 70% of the time during training, it is not surprising that participants directed their first saccade toward that quadrant 68.6% ($SE = 1.1%$) of the time, showing good probability matching. The remaining trials showed a small preference for the T-rich quadrant (11.9%; $SE = 0.7%$), relative to either

of the two sparse quadrants (9.8%; $SE = 0.5%$), $t(23) = 2.56, p = .017$, Cohen's $d = 0.523$. As seen in Fig. 5a, these proportions were stable across all 6 training blocks. An ANOVA on first saccade quadrant and training block found just a main effect of quadrant, $F(2, 46) = 1220.36, p < .001, \eta_p^2 = .982$, no effect of block, $F(5, 115) = 1.50, p = .194, \eta_p^2 = .061$, and no interaction, $F(10, 230) = 0.63, p = .786, \eta_p^2 = .027$.

The preference for the C-rich quadrant in the training phase was additionally reflected in the latency of the first saccades. On trials when participants successfully directed their first saccades toward the C-shape, they did so more quickly if the C-shape was in the C-rich quadrant rather than in the other quadrants (Fig. 5b). An ANOVA on quadrant and block (1–6) revealed a significant main effect of the saccade's quadrant, $F(2, 46) = 34.18, p < .001, \eta_p^2 = .598$, no effect of block, $F(5, 115) = 0.72, p = .610, \eta_p^2 = .030$, and no interaction, $F(10, 230) = 0.89, p = .546, \eta_p^2 = .037$.

Once the C-shape was removed in the testing phase, the first saccades no longer favored the C-rich quadrant. That quadrant received 25.5% ($SE = 3.0%$) of the first saccades, a level not different from chance, $t(23) = 0.16, p = .877$, Cohen's $d = 0.032$. Instead, there was a preference for the T-rich quadrant, which attracted 34.5% ($SE = 2.6%$) of the first saccades, a level that was significantly higher than chance, $t(23) = 3.63, p = .001$, Cohen's $d = 0.741$. Saccade latency in the testing phase showed no clear pattern, $F(2, 46) = 1.23, p = .301, \eta_p^2 = .051$, for the main effect of the saccade quadrant.

Consistent with the RT data, participants showed a strong oculomotor preference for the C-rich quadrant during training, but this effect did not persist in the testing phase. The only persisting oculomotor bias in the testing phase was toward the T-rich quadrant.

Second saccades Because we instructed participants to direct their first saccades toward the C-shape in training, the first saccade direction reflected, for the most part, their ability to follow this instruction. It did not capture how participants

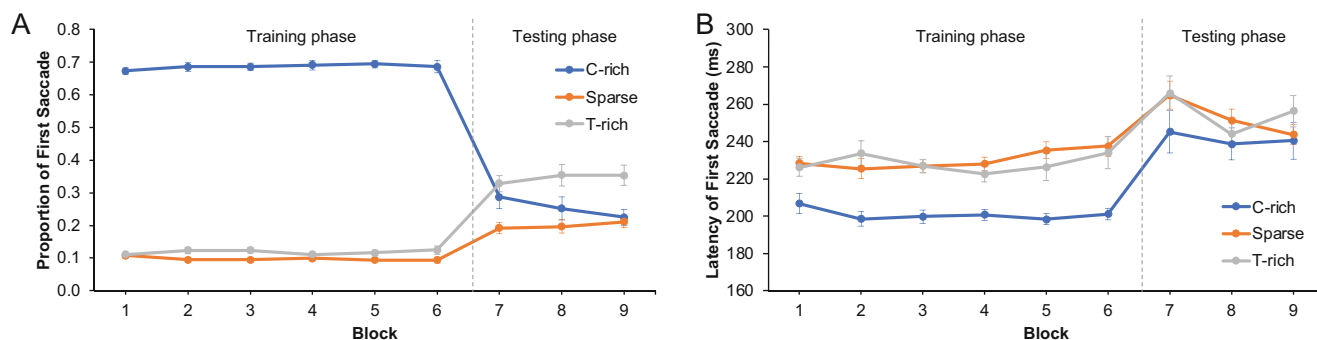


Fig. 5 First saccadic eye movements in Experiment 3. **a** Proportion of first saccadic eye movements landing in each quadrant. Note there were two sparse quadrants. The figure plots the average of the two. **b** Latency of the first saccadic eye movement on trials when it landed on the C-shape. Error bars show ± 1 within-subject SE of the mean. The target T

was presented more often in the T-rich quadrant in the training phase (Blocks 1–6) and was unbiased in the testing phase (Blocks 7–9). The C-shape appeared more frequently in the C-rich quadrant in the training phase and was removed in the testing phase

would have spontaneously allocated attention. The second saccadic eye movement provided insights into this question. Because the second saccade could be strongly influenced by where the first saccade landed on, in this analysis, we separated trials based on the landing location of the first saccade.

On the majority of the trials (68.6%), the first saccade landed on the C-rich quadrant. As shown in Fig. 6a, on these trials, there was a strong tendency for the second saccade to remain in the C-rich quadrant. As training progressed, the tendency for the second saccade to stay in the C-rich quadrant waned while a tendency to direct the second saccade to the T-rich quadrant increased. An ANOVA on quadrant and training block revealed a significant main effect of quadrant, $F(2, 46) = 40.63$, $p < .001$, $\eta_p^2 = .639$. Although the main effect of block was not significant, $F(5, 115) = 0.83$, $p = .534$, $\eta_p^2 = .035$, there was a significant interaction between quadrant and block, $F(10, 230) = 10.92$, $p < .001$, $\eta_p^2 = .322$, reflecting a rising tendency to saccade toward the T-rich quadrant.

A similar pattern of results was found on trials when the first saccade landed on one of the two sparse quadrants (19.5% of the trials). On these trials, the second saccade tended to remain in the sparse quadrant. But over the course of training, this tendency weakened as the tendency to saccade toward the T-rich quadrant strengthened. An ANOVA on quadrant and training block again revealed a significant main effect of quadrant, $F(2, 46) = 20.23$, $p < .001$, $\eta_p^2 = .491$, as well as a significant interaction between quadrant and block, $F(10, 230) = 3.19$, $p < .001$, $\eta_p^2 = .122$.

Finally, when the first saccade landed on the T-rich quadrant (11.9% of the trials), the second saccade tended to remain there. This pattern was maintained throughout training, yielding a main effect of quadrant, $F(2, 46) = 322.09$, $p < .001$, $\eta_p^2 = .933$, but no quadrant by block interaction, $F(10, 230) = 1.36$, $p = .202$, $\eta_p^2 = .056$.

Thus, on top of a preference for looking in the vicinity of the first saccade, participants also developed a tendency to direct the second saccade toward the T-rich quadrant as training progressed.

Recognition

In the recognition test, 7 of the 24 participants reported that the target T appeared more often in some locations than in others. In the forced-choice recognition test, 11 of the 24 participants correctly identified the T-rich quadrant, a level higher than chance, $\chi^2(1) = 5.56$, $p = .018$, but comparable to previous reports (Jiang et al., 2018). A further analysis comparing aware and unaware participants revealed no interaction between awareness status and other factors on search RT. Detailed analysis on the role of awareness can be found in the Appendix.

Discussion

Experiment 3 replicated key findings from Experiment 1 while ensuring that participants had overtly oriented toward the C-shape. This initial saccade led to faster search RT when the target was in the C-rich relative to the sparse quadrants. However, it did not yield a persisting attentional bias toward the C-rich quadrant. It also did not prevent participants from acquiring LPL toward the target-rich quadrant.

The eye data in Experiment 3 ruled out the possibility that instead of being spatially incompatible, the first saccade toward the C-rich quadrant was integrated with the next saccade toward the T-rich quadrant. On this account, participants may have acquired a habit of sequentially saccading first to the C-rich quadrant and then to the T-rich quadrant. The eye tracking data are inconsistent with this complex, “C-then-T,” search habit. First, after directing the first saccade to the C-rich quadrant, participants did not habitually saccade to the T-rich quadrant. Instead, they had a strong tendency to keep the second saccade in the C-rich quadrant. The proportion of trials where eye movements followed the “C-rich, then T-rich” sequence was low—a mere 22.5% even at the end of training. Second, if participants had acquired the “C-then-T” oculomotor habit, then in the testing phase they should have retained the habit

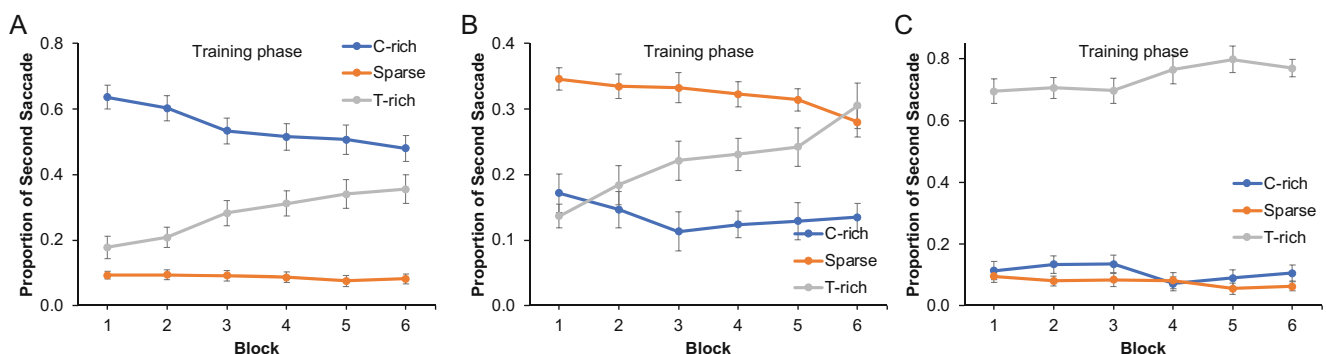


Fig. 6 Proportion of the second saccadic eye movement toward each quadrant in Experiment 3. The three panels separated trials based on where the first saccade was directed at (a) the C-rich quadrant, (b) a

sparse quadrant, and (c) the T-rich quadrant. Note that there were two sparse quadrants. The figures plot the average of the two. Error bars show ± 1 within-subject *SE* of the mean

of directing their first saccade toward the C-rich quadrant. Our data did not show such persistence.

The robustness of LPL may, in part, be attributed to the sequential nature of the oculomotor and the search tasks. After all, the search task commenced only after the C-task had completed. Nonetheless, both RT and eye movements showed evidence of dependency between the two tasks. Search RT was faster when the target happened to be in the vicinity of the C-shape, suggesting that participants preferentially attended to that region. In addition, after participants fixated on the C-shape, they were highly likely to direct the next eye movement to an item near the C-shape (i.e., within the same quadrant). Both measures showed that the initial oculomotor response to the C-shape altered the starting state of visual search. Unlike standard LPL studies where participants initially fixated at the center and could start search from anywhere, in our study, there was a strong tendency for search to start from the C-rich quadrant. The sequential dependency between the two tasks suggests that the initial oculomotor response altered how participants subsequently conducted visual search. The preservation of LPL under this condition provides, to date, the strongest evidence that the search habit underlying LPL is a high-level mechanism abstracted from an oculomotor habit.

General discussion

The strong connection between eye movements and attention has led researchers to ask whether eye movements are necessary for covert attentional selection. When this question was posed in the context of endogenous or exogenous attention, studies have uncovered partial independence of attention from eye movements. For example, people can preferentially attend to locations outside of the eyes' reach (Hanning & Deubel, 2020; Hanning et al., 2019; also see Craighero et al., 2004). Neuropsychological patients who suffer from paralysis to the eyes nonetheless benefit from attentional cueing (Masson et al., 2020). These studies, however, have primarily focused on attention driven by task goals or perceptual salience. Using a location probability learning (LPL) paradigm, here we examined the relationship between goal-directed eye movements and a third driver of attention: experience-driven attention. Our results showed that LPL was preserved even when participants had to frequently saccade away from the target-rich locations.

In Experiment 1, participants were instructed to first look at a small C-shaped object presented frequently in one, C-rich quadrant. They then searched for a letter T that most often appeared in a different, T-rich quadrant. The goal-directed eye movement was spatially incompatible with the habit of searching in the T-rich quadrant. Nonetheless, participants acquired LPL, as reflected by faster search RT when the T

appeared in the T-rich rather than the other quadrants. This effect persisted in an unbiased testing phase during which the T was equally likely to appear in all quadrants. In contrast, although participants exhibited faster RT in the C-rich quadrant during training, once the C-shape was removed in the testing phase, the attentional preference for the C-rich quadrant ceased. Thus, repeatedly finding a target, but not repeatedly looking in a specific direction, produced lasting attentional biases.

Experiment 2 tested whether the C-shape, which was a shape and color singleton, had influenced performance in a bottom-up manner. Participants were not asked to perform any task on the C-shape. Under this condition, search was unaffected by the location of the C-shape, or its biased spatial distribution. Unlike some previous studies (e.g., Ferrante et al., 2018), in Experiment 2, participants did not acquire a spatial bias away from the C-rich quadrant. This may be attributed to the lack of featural overlap between the C-shape and the search items, enabling participants to effectively filter out the C-shape. In the absence of potent attentional capture, we did not observe evidence for LPL of the singleton distractor. LPL for the search target, however, was robust. This finding suggests that spatial orienting toward the C-shape in Experiment 1 was endogenously driven rather than exogenously driven. It is important to note that the lack of LPL for the C-shape in Experiment 2 does not rule out the possibility that participants can acquire LPL for distractors. In fact, accumulating evidence supports the idea that LPL applies both to frequent target locations and to frequent distractor locations (Britton & Anderson, 2020; Ferrante et al., 2018; Sauter et al., 2019; Wang & Theeuwes, 2018a, 2018b, 2018c, 2020; Won et al., 2019). Experiment 2 only indicates that the stimuli used in our study did not trigger LPL of the task-irrelevant singleton.

Using eye tracking, Experiment 3 replicated the findings of Experiment 1 and validated the assumption that participants preferentially moved their eyes toward the C-shape. First saccades landed in the vicinity of the C-shape on a vast majority of the trials. In addition, on trials when participants fixated on the C-shape, they did so with faster saccade latency if the C-shape was in the C-rich quadrant than elsewhere, demonstrating sensitivity to the C-shape's biased spatial distribution. Yet much like search RT, as soon as the C-shape was removed, first saccades no longer favored the C-rich quadrant. Instead, first saccades in the testing phase were disproportionately directed to the T-rich quadrant. Sensitivity to the T's spatial distribution additionally manifested in the second fixation in the training phase. After participants had fixated the C-shape, they tended to saccade to another location in the same quadrant, showing sequential dependency between two successive saccades. Nonetheless, as training progressed, the tendency to remain in the same quadrant weakened while a tendency to saccade toward the T-rich quadrant strengthened.

These results provide insights into several mechanisms associated with LPL. First, the findings help clarify the nature of search habit that is acquired through LPL. This habit has been conceptualized as an attentional vector that is preferentially directed toward the target-rich region. The degree to which this habit is linked to oculomotor control, however, was unclear. LPL often produces both faster search RT in the target's high-probability quadrant and an oculomotor habit of saccading toward that quadrant (Jiang, Won, et al., 2014). On the other hand, LPL can be acquired even when participants must maintain central fixation during the search task (Geng & Behrmann, 2005), suggesting that frequently moving one's eyes toward the high-probability region is unnecessary for learning. By requiring participants to frequently look in a direction away from the target-rich quadrant, the current study provides even stronger evidence that LPL is partially dissociated from an oculomotor habit. These findings suggest that LPL reflects a relatively high-level search habit, one that is not completely instantiated in eye movements.

Second, our study also showed that a habit of saccading to one location is insufficient for inducing a lasting attentional bias toward that region. In our Experiments 1 and 3, participants frequently looked in the direction of a C-rich quadrant. Yet once the C-task was removed, this tendency ceased: search RT was no longer faster in the previously C-rich quadrant than in the other quadrants, neither was there a persisting oculomotor habit of saccading toward the C-rich quadrant. The lack of a persisting oculomotor habit can be contrasted with the presence of LPL in the testing phase. This finding suggests that LPL results from successful target detection, rather than frequent overt orienting toward a certain location or direction. This finding is consistent with theoretical proposals from a different experimental paradigm—the attentional boost effect. In that paradigm, successfully detecting and responding to a target boosts memory for concurrently presented background images (Lin et al., 2010; Swallow & Jiang, 2010, 2013). Seitz and Watanabe (2005) proposed that successful target detection triggers reinforcement learning of concurrently presented stimuli. Such reinforcement learning may also occur in visual search tasks, reinforcing the spatial attentional shifts that lead to successful target detection (Jiang et al., 2013).

Third, our study clarifies the relationship between goal-directed attention and LPL when these two sources of attention occur in close temporal proximity. In our design, participants must first endogenously orient toward the C-shape, followed immediately by the search task, with attention guided by previous experience of the target's location probability. We showed that LPL was preserved under this condition, even though the initial task goal produced endogenous orienting away from the target-rich region. As shown in the eye movement data, the C-task and the subsequent search showed sequential dependency. Following the initial saccade to the C-

shape, participants were strongly likely to start search in the vicinity of the C-shape, meaning that their starting search location was frequently not where the target was. Nonetheless, LPL was observed in this condition, suggesting that it is, in part, independent of goal-driven attention. Our design does not inform us how LPL interacts with goal-driven attention when the two cues are concurrent rather than sequential. A previous study that cued participants to the target's likely location using a central arrow found the coexistence of both goal-driven attention and LPL (Geng & Behrmann, 2005). Additional studies are needed to further elucidate the summation of goal-driven attention and LPL when both sources exist to affect visual search.

To summarize, by introducing biased spatial distributions to both an oculomotor target and the search target, this study helped elucidate the interaction between different drivers of spatial attention. Although the oculomotor target led to voluntary spatial attentional shift and sped up search in its vicinity, it did not yield a persisting spatial bias toward that region. In addition, frequently looking away from the target-rich region did not prevent participants from developing LPL. Our results showed that experience-guided attention is robust in the face of spatially incompatible oculomotor signal. These results are in line with the modular view of attention, suggesting that the search habit derived from LPL is, in part, a high-level process abstracted from eye movements. At an applied level, our finding raises the possibility that LPL may facilitate attentional allocation in patients with a vision impairment that restricts or impairs their eye movements.

Appendix. Recognition results

Experiment 1

The eight participants who correctly identified the T-rich quadrant were placed in the “aware” group, whereas the remaining 16 participants were in the “unaware” group. To examine how awareness affected search RT, we conducted an ANOVA using awareness as a between-subject factor, and target location (T-rich, C-rich, or sparse) and experimental block as within-subject factors. In the training phase (the first 6 blocks), we found a significant main effect of target location, revealing LPL, $F(2, 44) = 14.75$, $p < .001$, $\eta_p^2 = .401$, a significant main effect of block, with faster RT in later blocks, $F(5, 110) = 19.45$, $p < .001$, $\eta_p^2 = .469$, and a significant main effect of awareness, with faster RT in unaware than aware participants, $F(1, 22) = 5.54$, $p = .028$, $\eta_p^2 = .201$. Critically, however, awareness did not interact with the target's location, $F(2, 44) = 0.19$, $p = .829$, $\eta_p^2 = .008$, nor did it produce a three-way interaction, $F(10, 220) = 1.18$, $p = .308$, $\eta_p^2 = .051$.

Likewise, in the testing phase, we found a main effect of target location, showing a persisting LPL in the T-rich quadrant, $F(2, 44) = 6.48, p = .003, \eta_p^2 = .228$. But there was no main effect of testing block, $F(2, 44) = 0.26, p = .774, \eta_p^2 = .012$, or awareness, $F(1, 22) = 1.46, p = .239, \eta_p^2 = .062$. Awareness did not interact with target location, $F(2, 44) = 0.57, p = .569, \eta_p^2 = .025$, or produce a three-way interaction, $F(4, 88) = 0.03, p = .998, \eta_p^2 = .001$. Thus, LPL of the T-rich quadrant was comparable between the aware and unaware participants in both phases of the experiment. Readers interested in results from just the aware or just the unaware participants can find additional statistical analysis on the Open Science Framework (<https://osf.io/9vdpw/>).

Experiment 2

The aware group included the 14 participants who correctly identified the T-rich quadrants; the unaware group included the other 10 participants. In the training phase, an ANOVA on awareness, target location, and block showed main effects of target location, revealing LPL, $F(2, 44) = 40.89, p < .001, \eta_p^2 = .650$, and training block, $F(5, 110) = 14.42, p < .001, \eta_p^2 = .396$. The main effect of awareness was not significant, $F(1, 22) = 3.31, p = .082, \eta_p^2 = .131$, neither did awareness interact with target location, $F(2, 44) = 2.35, p = .107, \eta_p^2 = .097$, or induce a three-way interaction, $F(10, 220) = 1.05, p = .406, \eta_p^2 = .045$.

Similarly, in testing phase, we found main effects of target location, $F(2, 44) = 3.52, p = .038, \eta_p^2 = .138$, and testing block, $F(2, 44) = 3.77, p = .031, \eta_p^2 = .146$. But there was no main effect of awareness, $F(1, 22) = 1.73, p = .202, \eta_p^2 = .073$, or interaction between awareness and LPL effect, $F(2, 44) = 2.15, p = .128, \eta_p^2 = .089$, or a three-way interaction, $F(4, 88) = 1.52, p = .203, \eta_p^2 = .065$. Thus, we did not find evidence that awareness modulated LPL. Additional results from just the aware or just the unaware participants can be found on the Open Science Framework (<https://osf.io/9vdpw/>).

Participants in Experiment 2 were also asked whether they had noticed the task-irrelevant C-shape. Seven of the 24 answered in the affirmative. To test whether these participants evidenced attentional capture, we conducted an additional analysis on the search RT of these seven participants. This analysis was qualitatively similar to the results from the full sample, revealing an LPL toward the T-rich quadrant in both phases, and no difference in RT between the C-rich and sparse quadrants. Detailed statistical results can be found on the Open Science Framework (<https://osf.io/9vdpw/>).

Experiment 3

In Experiment 3, the aware group included 11 participants and the unaware group included 13 participants. We performed an

ANOVA using awareness as a between-subject factor, target location (T-rich, C-rich, sparse) and training block (1–6) as within-subject factors. The training phase revealed main effects of target location, showing LPL, $F(2, 44) = 31.47, p < .001, \eta_p^2 = .589$, and block, $F(5, 110) = 25.08, p < .001, \eta_p^2 = .533$. But there was no main effect of awareness, $F(1, 22) = 1.96, p = .176, \eta_p^2 = .082$, nor did awareness interact with target location, $F(2, 44) = 1.71, p = .192, \eta_p^2 = .072$, or produce a three-way interaction, $F(10, 220) = 1.10, p = .364, \eta_p^2 = .048$.

Similarly, in the testing phase, we found significant main effects of target location, $F(2, 44) = 10.49, p < .001, \eta_p^2 = .323$ and block, $F(2, 44) = 19.25, p < .001, \eta_p^2 = .467$. But there was no main effect of awareness, $F(1, 22) = 1.89, p = .183, \eta_p^2 = .079$, or interaction between awareness and target location, $F(2, 44) = 1.12, p = .336, \eta_p^2 = .048$, or a three-way interaction, $F(4, 88) = 0.88, p = .479, \eta_p^2 = .038$. Thus, similar to Experiments 1 and 2, awareness did not significantly modulate LPL. Additional results from just the aware or just the unaware participants can be found on the Open Science Framework (<https://osf.io/9vdpw/>).

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Data and code availability statement These experiments were not pre-registered. Experimental scripts, verification of code accuracy, condition means, and additional data analysis can be found on the Open Science Framework (<https://osf.io/9vdpw/>).

Declarations

Conflicts of interests The authors have no relevant financial or non-financial interests to disclose.

Ethics approval and consent to participate The study received Institutional Review Board approval from the University of Minnesota [STUDY00007254]. Participants in Experiments 1 and 2 provided informed consent online, and participants in Experiment 3 gave informed consent in person.

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