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BRIEF REPORT

Implicit location probability learning does not induce baseline shifts of visuospatial attention

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Abstract

We tested whether implicit learning causes shifts of spatial attention in advance of or in response to stimulus onset. Participants completed randomly interspersed trials of letter search, which involved reporting the orientation of a *T* among *L*s, and scene search, which involved identifying which of four scenes was from a target category (e.g., forest). In Experiment 1, an initial phase more often contained target letters in one screen quadrant, while the target scenes appeared equally often in all quadrants. Participants persistently prioritized letter targets in the more probable region, but the implicitly learned preference did not affect the unbiased scene task. In Experiment 2, the spatial probabilities of the scene and letter tasks reversed. Participants unaware of the probability manipulation acquired only a spatial bias to scene targets in the more probable region, with no effect on letter search. Instead of recruiting baseline shifts of spatial attention prior to stimulus onset, implicit learning of target probability yields task-dependent shifts of spatial attention following stimulus onset. Such shifts may involve attentional behaviors unique to certain task contexts.

Keywords Location probability learning · Spatial attention · Implicit attention · Baseline shifts of attentional resources

Many factors influence how people attend to the visual world. Task demands dictate certain goals, salient stimulus properties may capture attention, and how one has attended in the past influences selection in the future (Awh, Belopolsky, & Theeuwes, 2012; Jiang, 2018). One "selection history" effect is location probability learning (LPL), in which people find stimuli more efficiently in frequently attended locations (Jiang, Swallow, & Rosenbaum, 2013; Shaw & Shaw, 1977). For instance, when a visual-search task contains targets in one screen quadrant disproportionately often, people develop attentional biases to that quadrant. Unlike goal-driven attention, LPL is largely implicit and has long-lasting effects. Still, many differences between the two forms of guidance are not fully understood. Here, we investigate whether LPL leads to "baseline" spatial shifts of attention—shifts occurring in anticipation of a trial, prior to any visual stimuli.

Goal-driven attention operates by shifting spatial attention in advance of stimulus presentation (for a review, see Beck & Kastner, 2014). Evidence for these baseline shifts of attention includes the observation that endogenous cues are more effective when participants have longer to deploy goal-driven attention in anticipation of target onset and increase activity in early visual areas prior to stimulus appearance. Because LPL recruits spatial attention, it may also enhance baseline activity at high-probability regions. However, rather than using baseline shifts, LPL may bias attention through a search habit encoded as motion vectors guiding attentional behavior (Jiang, 2018). Required motion vectors differ across tasks; those used in serial search, for instance, could differ substantially from those used in parallel search. Because the dynamics of shifting attention are specific to a given task, implicit LPL would only bias attention in tasks closely resembling the one used to establish the implicit bias. According to this account, LPL would affect attention *during*, not *before,* search. Investigating whether LPL yields baseline shifts could reveal important differences between goal-driven and implicitly learned attention.

Related research has investigated whether LPL affects attention narrowly—only in the trained task—or broadly—across any task involving spatial attention. Findings show that LPL is task-general only when two tasks involve similar search behaviors. For example, LPL acquired in letter search

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transfers to a similar search task for a small arrow superimposed on natural scenes (Salovich, Remington, & Jiang, 2017). Conversely, no transfer was observed from letter search to a letter foraging task that required selection of any one of many target letters to receive a reward (Jiang, Swallow, Won, Cistera, & Rosenbaum, 2015), or from letter search to scene memory (Addleman, Tao, Remington, & Jiang, 2018). Unfortunately, these studies' two-phase designs, in which participants trained on one task and then completed a second task, prevent conclusions about whether LPL yields baseline shifts of attention; because participants knew the upcoming task, they could adjust their attentional set for each task.

The present study tests whether implicit LPL induces baseline shifts of spatial attention using two interleaved visual search tasks. One task involves finding a letter *T* among *H*s. The other involves finding a particular scene category (e.g., forest) among other scenes. Critically, our study randomly intermixes the two tasks, departing from previous studies' blocked designs. Participants cannot predict an upcoming trial's task, so learned baseline shifts of spatial attention would influence performance on both tasks. If LPL instead yields only poststimulus attentional shifts, the dissimilarity of search behaviors across tasks may prevent transfer. Such task-specificity would argue against baseline shifts in LPL.

Experiment 1

Method

Experiment 1 manipulated the location probability of targets in a letter search task and probed prestimulus baseline shifts of attention with a scene search task. Most trials (two-thirds) involved letter search—participants searched among briefly presented letters for a target *T* and reported its orientation. Unbeknownst to them, the target appeared disproportionately often in one screen quadrant, a manipulation shown to facilitate letter search in the high-probability quadrant (Jiang et al., 2013). Importantly, we unpredictably interspersed trials in which participants searched four scenes for one from a prespecified category (e.g., forest). Target scenes occurred equally often in each quadrant. If LPL acquired during letter search induces prestimulus baseline shifts of attention, then it should enhance scene search in the letter task's high-probability quadrant.

Participants Analysis of previous research (Salovich et al., 2017) suggested that 80% power (at $\alpha = .05$) required testing 20 participants. Because some people may become aware of probability manipulations, we tested 32 participants to obtain data from at least 20 unaware participants.

Participants were college students naïve to the experimental purpose. They reported normal or corrected-to-normal visual acuity and normal color vision. All participants signed informed consent and were compensated with extra course credit. Thirteen females and 19 males with a mean age of 20 years (range: 18–24 years) completed Experiment 1.

Equipment Participants were tested individually with fluorescent overhead lighting. They sat at an unconstrained distance, approximately 60 cm, from a 19-in. CRT monitor (1,024 × 768 resolution; 75 Hz). Experiments were run using Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) implemented in MATLAB (www.mathworks.com).

Stimuli Our paradigm was adapted from Addleman et al. (2018). Throughout the experiment, a red fixation dot subtending 0.15° visual angle remained in the display's center.

Letter search trials (see Fig. 1a) each presented eight white letters between 0.7° and 2.7° in size. Letters farther from fixation were larger, in proportion to the cortical magnification factor (Carrasco, Evert, Chang, & Katz, 1995). Each letter could appear in any of 32 possible locations. Locations were divided evenly into four eccentricities (approximately 1.5°, 4°, 6.5°, and 12°), and each quadrant contained exactly two letters per trial. Each trial included one *T* and seven *H*s. Each letter had a random orientation: either 0°, 90°, 180°, or 270°.

Scene search trials (see Fig. 1b) presented four natural scenes, one per quadrant (11.5° × 11.5°). The center of each scene was 8.75° from fixation. Each trial contained one scene from each of four categories: beach, mountain, forest, and field. Scenes were selected randomly (with counterbalanced frequency) from among 48 images within each category, taken from the SUN397 database (Xiao, Hays, Ehinger, & Torralba, 2010).[1] Following the scenes, an arrow (5° in length) appeared in each quadrant, each with a unique orientation selected randomly from 0° (pointing upward), 90°, 180°, and 270°.

Procedure Following two practice blocks without spatial biases, participants completed 720 trials divided into 20 blocks of 36 trials each. Each block contained 24 letter search and 12 scene search trials, randomly intermixed. For 16 participants we induced a spatial bias in letter search by creating a high-probability, "rich" quadrant that had 62.5% of targets, compared with 12.5% in each of the low-probability, "sparse" quadrants. To further reduce explicit awareness, the other 16 were trained with 50% of targets in the rich quadrant and 16.7% in each sparse quadrant. Data from these two groups were qualitatively similar and were combined. The first 12 blocks used this design to induce LPL. To assess the

[1] Beach, mountain, and forest scenes were from categories labeled as such in the SUN database. Field images were images with few trees and no water or mountains from several SUN categories: cornfield, cultivated field, wild field, hill, pasture, valley, and vineyard.

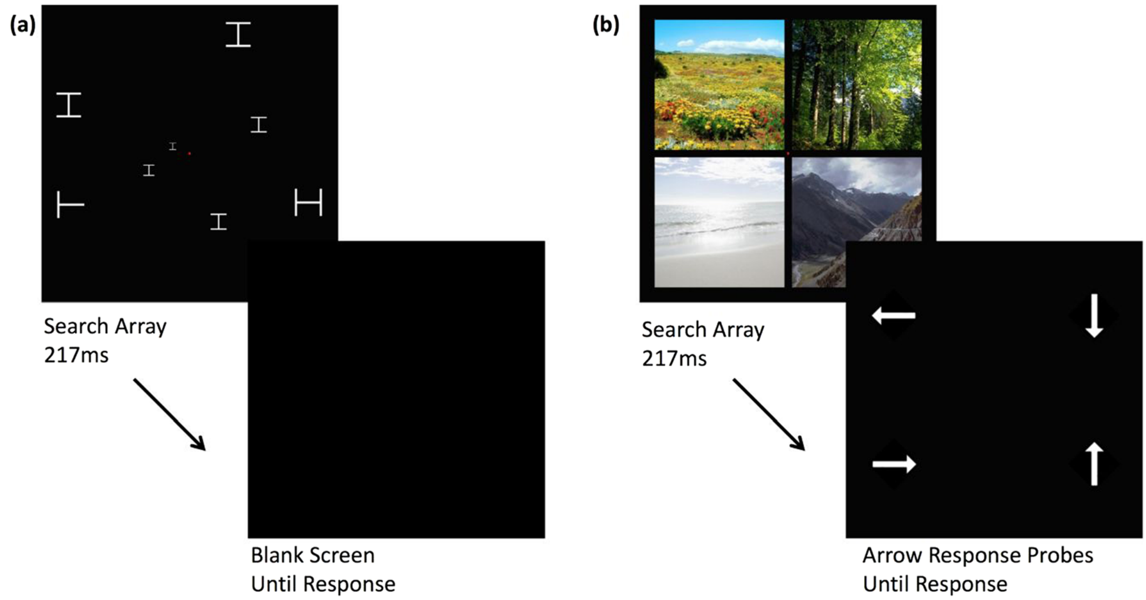

Fig. 1 Example search arrays in the two tasks. **a** In letter search, participants searched for a target *T* and reported its orientation. **b** In scene search, participants searched for a scene of a target category. When the search array disappeared, it was replaced by a randomly arranged array of arrows. Participants reported the orientation of the arrow in the same screen location as target scene

persistence of LPL, the final eight blocks (the testing phase) contained letter targets in each quadrant equally often. To probe prestimulus baseline shifts of attention, one-third of trials involved scene search. Scene targets occurred equally often in each quadrant throughout the experiment.

Participants began each trial by clicking the fixation dot, a task requiring hand–eye coordination to ensure central fixation. The search array then appeared for 216 ms. On scene search trials, the array was then immediately replaced with four arrows, each pointing a different direction. The participants indicated the orientation of the target: the target *T* in letter search (an upright *T*, due to the direction of the long stem of the *T*, corresponded to a "down" response), or the arrow in the same location as the target scene in scene search. Scene targets were those belonging to a fixed category for each participant, with target category counterbalanced across participants. The same buttons (W-A-S-D) were used in both tasks, corresponding respectively to up, left, down, and right. Upon response, a tone provided accuracy feedback; following each block, participants were given their proportion of correct responses in the block. Instructions emphasized both speed and accuracy.

Analysis Performance was indexed by RT and accuracy. We excluded trials with outlier reaction times (more than three standard deviations above the mean task RT for that participant; between 1.5% and 2.6% of trials were excluded across all experiments) from all analyses, and trials with incorrect responses from RT analyses. To reduce noise, we binned every two blocks into an epoch, yielding six training and four testing epochs.

To avoid confounding effects of LPL and endogenous attention, we administered a postexperiment survey probing awareness of the experiment's probability manipulations. The survey asked two questions: "Did the target occur more often in some places than others?"; "If you had to choose one quadrant in which you feel the target occurred most often, which would you choose?" Participants demonstrating awareness—those who thought the letter target's location was biased and correctly identified the high-probability quadrant—were excluded from analyses. This yielded 23 unaware participants.

Results

Primary task: Letter search (Fig. 2a–b) Participants acquired LPL in the letter search task during training. In training, an ANOVA on target quadrant (rich vs. sparse) and epoch (1–6) showed faster RTs in the rich quadrant, $F(1, 22) = 47.33$, $p < .001$, $\eta_p^2 = .68$; an effect of epoch, $F(5, 110) = 15.38$, $p < .001$, $\eta_p^2 = .41$, indicating that participants responded faster as training progressed; and no interaction, $F < 1$. Accuracy also showed main effects of target quadrant, $F(1, 22) = 19.23$, $p < .001$, $\eta_p^2 = .47$, and epoch, $F(5, 110) = 3.66$, $p = .004$, $\eta_p^2 = .14$, and no interaction, $F < 1$.

LPL persisted into testing; when letter targets occurred equally often in each location, RT remained faster in the previously high-probability quadrant, $F(1, 22) = 4.376$, $p = .048$, $\eta_p^2 = .17$. There was no effect of epoch, $F(3, 66) = 2.042$, $p = .117$, and no interaction, $F(3, 66) = 2.042$, $p = .117$. Accuracy data were similar: higher in the previously high-probability quadrant, $F(1, 22) = 8.063$, $p = .009$, $\eta_p^2 = .27$, with no effect

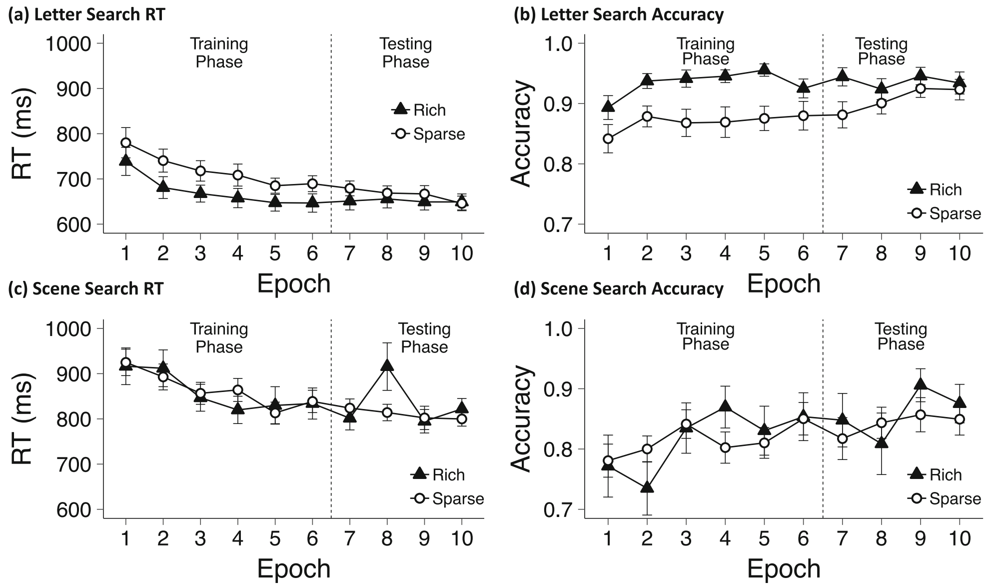

Fig. 2 Results from unaware participants ($N = 23$) in Experiment 1. Experiment 1 manipulated target location probability only in the letter task. **a** Letter task reaction time. **b** Letter task accuracy. **c** Scene task reaction time. **d** Scene task accuracy. Error bars show ±1 standard error of the mean (*SEM*)

of epoch, $F(3, 66) = 1.552$, $p = .209$, and no interaction, $F(3, 66) = 1.885$, $p = .141$.

Probe task: Scene search (Fig. 2c–d) We next examined whether LPL acquired from letter search induced baseline shifts of spatial attention. If so, scene search should benefit when targets appeared in the letter-rich quadrant. We found no evidence of this effect.

During training, an ANOVA of target quadrant and epoch for RT showed no effect of target quadrant, $F < 1$, a significant effect of epoch, $F(5, 110) = 7.294$, $p < .001$, $\eta_p^2 = .25$, and no interaction, $F(5, 110) = 1.029$, $p = .404$. Accuracy data were similar: no effect of target quadrant, $F < 1$, a significant effect of epoch, $F(5, 110) = 3.654$, $p = .004$, $\eta_p^2 = .14$, and no interaction, $F(5, 110) = 1.522$, $p = .189$.

Testing showed similar results. RT again showed no effect of target quadrant, $F(1, 22) = 2.512$, $p = .127$, an effect of epoch, $F(3, 66) = 4.235$, $p = .008$, $\eta_p^2 = .16$, and an interaction, $F(3, 66) = 4.893$, $p = .003$, $\eta_p^2 = .18$. The interaction was likely spurious, driven by a single data point in Epoch 8 but not in other epochs, *p*s < .05. Accuracy showed no significant effects during testing, *p*s > .05.

Cross-task comparison We tested whether LPL was stronger during letter search than scene search. Training phase RT showed an interaction between task (letter vs. scene search) and quadrant (rich vs. sparse), $F(1, 22) = 6.148$, $p = .021$, $\eta_p^2 = .22$; during training, the rich-quadrant advantage was larger in letter search than scene search. The interaction was marginally significant in accuracy, $F(1, 22) = 3.172$, $p = .089$. During testing, the interaction was significant for RT, $F(1, 22) = 4.291$, $p = .050$, $\eta_p^2 = .16$, but not accuracy, $F < 1$.

Discussion

Experiment 1 demonstrated a persistent attentional bias in the primary letter task. We found no evidence that this bias yielded prestimulus, baseline shifts of spatial attention; a randomly interspersed scene search task did not benefit from LPL. If spatial attention were already deployed at the high-probability quadrant before the task, participants should find targets in the high-probability quadrant more efficiently in both search tasks. Moreover, the higher frequency of letter trials than scene trials may have further incentivized the deployment of attention in anticipation of letter trials, but we found no evidence of this effect. LPL benefitted only letter search, indicating that it results in an online search habit initiated after stimuli appear (Addleman et al., 2018; Jiang, 2018).

Because the probe task involved half as many trials as did the primary task, the lack of LPL in the probe task could reflect insufficient statistical power. If so, analyzing a random half of primary task trials should yield fewer significant results. Instead, target quadrant significantly influenced primary task RT in all four split-half ANOVAs (accuracy and RT in the training and testing phases). Experiment 2 showed a similar pattern. The lack of probe task effects likely indicates failure for LPL to transfer across tasks, not insufficient power.

Experiment 2

Experiment 2 manipulated the location probability of scene targets and probed baseline shifts of attention using letter search, conceptually replicating Experiment 1. It also examines the sensitivity of scene search to LPL. Because scene search relies more on global gist perception and less on serial scanning (Rousselet, Fabre-Thorpe, & Thorpe, 2002; Wolfe, Vo, Evans, & Greene, 2011), it may be insensitive to LPL. Acquisition of LPL in scene search would strengthen the conclusions of Experiment 1.

Method

Experiment 2 was identical to Experiment 1, except it reversed the roles of the scene and letter tasks. Each block contained 24 scene search trials and 12 letter search trials. The scene task more frequently contained targets in one quadrant during training (62.5% for half of participants and 50% for the other half), while scene targets occurred equally often in each quadrant during testing. In both phases for letter search, targets occurred in each quadrant at equal rates. Twenty-seven females, four males, and one nonbinary participant with a mean age of 20 years (range: 18–31 years) completed Experiment 2. Analyses report data from 22 unaware participants (10 participants were excluded based on responses about the primary scene task).

Results

Primary task: Scene search (Fig. 3a–b) Participants acquired LPL in the scene task. During training, an ANOVA of target quadrant and epoch showed faster RT in the rich quadrant, $F(1, 21) = 9.542$, $p = .005$, $\eta_p^2 = .31$, a significant effect of epoch, $F(5, 105) = 10.28$, $p < .001$, $\eta_p^2 = .33$, and no interaction, $F(1, 105) = 1.218$, $p = .306$. Analyses of training accuracy as well as both accuracy and RT in testing showed no effects of quadrant, epoch, or their interaction, *p*s > .1. While we found significant LPL in training, it did not persist into testing.

Probe task: Letter search (Fig. 3c–d) We found no evidence that LPL for scene search induced a baseline shift of attention reflected in letter search. In letter search, an ANOVA of target quadrant and epoch for RT during training showed no effect of quadrant, $F < 1$, a significant effect of epoch, $F(5, 105) = 14.71$, $p < .001$, $\eta_p^2 = .41$, and no interaction, $F(5, 105) = 1.031$, $p = .403$. Accuracy data showed a similar pattern: no significant effect of quadrant, $F < 1$, a significant effect of epoch, $F(5, 105) = 3.651$, $p = .004$, $\eta_p^2 = .15$, and no interaction, $F(5, 105) = 2.074$, $p = .074$. Testing phase analyses showed no effects of quadrant, epoch, or their interactions, *p*s > .05.

Cross-task comparison Comparing scene and letter RT during training showed a significant interaction between task and quadrant, $F(1, 22) = 6.102$, $p = .022$, $\eta_p^2 = .23$, with the rich-quadrant advantage significantly larger in scene search than letter search. The task-quadrant interactions in terms of training phase accuracy, testing phase RT, and testing phase accuracy were insignificant, *p*s > .25.

Discussion

Experiment 2 showed a failure for spatial attentional biases acquired during scene search to influence letter search. We also report LPL in the training phase of the scene task, showing that LPL can facilitate scene search. This finding informs discussions about how attention influences scene categorization. Some have argued that gist perception relies primarily on

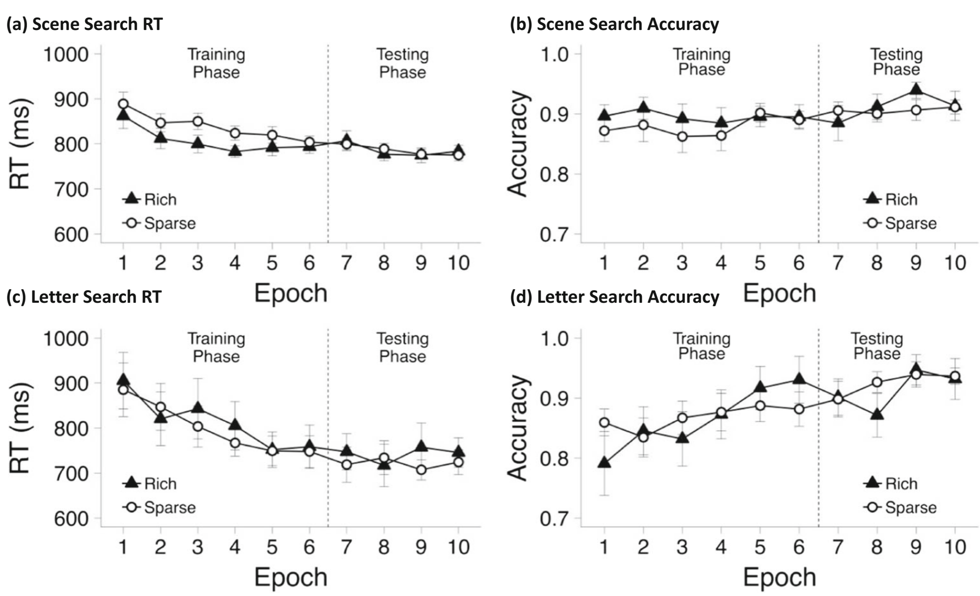

Fig. 3 Results from unaware participants ($N = 22$) in Experiment 2. Experiment 2 manipulated target location probability only in the scene task. Error bars show ±1 standard error of the mean (*SEM*)

preattentive parallel processing (Rousselet et al., 2002). Other studies show that, although parallel processing aids scene categorization more than it does many search tasks, selective attention does benefit scene processing (Gronau & Izoutcheev, 2017; Wolfe et al., 2011). Our results are consistent with the latter findings, as spatial attentional biases benefited scene search.

LPL acquired from scene search did not persist into testing. This is unique among LPL studies, which typically use letter search. The lack of persistence could indicate that the current study's effect is due to intertrial location priming (Maljkovic & Nakayama, 1996), wherein attention is biased toward very recently attended locations. However, post hoc RT analyses show evidence for LPL during training when only considering trials in which scene targets were in a different quadrant than the previous trial's target, $F(1, 21) = 8.828$, $p = .007$, $\eta_p^2 = .30$. Instead, the lack of persistence into testing may reflect the reduced role of serial attentional shifts in scene category search (Rousselet et al., 2002; Wolfe et al., 2011). In any case, evidence indicates that scene search is sensitive to LPL during training.

Experiment 2's findings on the letter search task are consistent with the lack of baseline shifts in Experiment 1. Baseline shifts would have influenced letter search. Instead, we found no facilitation of letter search in the high-probability quadrant.

General discussion

The present study reports no transfer of implicitly learned attentional biases between letter search and scene category search tasks. Although LPL can be induced in both tasks, a learned, implicit attentional bias in one task failed to influence performance in the other task. Unlike previous studies, our tasks were unpredictably intermixed, preventing participants from predicting the upcoming task. Therefore, if participants had deployed attention in anticipation of search, LPL would have influenced both tasks. The lack of such an effect is strong evidence that implicit LPL does not elicit baseline shifts of spatial attention. Instead, it suggests that probability cuing influences attention in response to, rather than in anticipation of, a specific task. This could be achieved by learning a vector of attentional movement that is only suitable for certain tasks. This differs from goal-driven attention, which enhances baseline visual processing at attended regions (Beck & Kastner, 2014). Baseline shifts may rely on conscious control to allocate attention, whereas implicitly learned attention may rely on the nature of attentional shifts in the active task. Consistent with this distinction, we found some evidence of cross-task transfer in participants who became aware of the target's location probability (see supplement available at https://doi.org/10.31234/osf.io/dhmf4).

Could LPL reflect response-level processes rather than attentional ones? Perhaps primary task targets outside the rich quadrant violate expectations, slowing response times. Alternatively, memory traces specific to the primary task could facilitate response preparation for biased quadrant targets (as has been argued for other search biases; Treisman, Vieira, & Hayes, 1992). However, response-level effects would primarily influence mean RT, while LPL can also significantly improve rich-quadrant accuracy (as in Experiment 1) and search efficiency (through reducing per-item processing time; Jiang et al., 2013). This suggests that LPL reflects attentional biases.

In our task, participants exhibited a spatial bias in a task containing biased targets and no spatial bias in a task with an unbiased target distribution. This reflects a remarkable ability to update attentional control based on learned task statistics. Such control is comparable to findings from the additional singleton paradigm, in which location-dependent task statistics influence the degree to which color singletons capture attention (Crump, Milliken, Leboe-McGowan, Leboe-McGowan, & Gao, 2018). Our results provide evidence for similar, task-appropriate spatial shifts: When participants learn to prioritize one region for one task, presentation of a different task can prevent these shifts.

Our results are the first to demonstrate a failure for location probability learning to transfer between two visual search tasks. Despite the acquisition of a search habit in one task, learning did not affect a second interleaved task, suggesting that LPL leads to task-dependent, rather than baseline, shifts of attention. Our findings have implications for cognitive training. They suggest that training spatial attention in one task can significantly influence that task's performance, but transfer appears limited to similar tasks. This finding may inform effective attentional training methods for both healthy populations and people with neurological conditions or sensory loss, suggesting that training environments should closely mimic people's everyday problems.

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