American Psychological Association

Journal of Experimental Psychology: Learning, Memory, and Cognition

0278-7393/20/$12.00

2020, Vol. 46, No. 4, 669–683
http://dx.doi.org/10.1037/xlm0000749

A Spatial Bias Toward Highly Rewarded Locations Is Associated With Awareness

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Mounting evidence suggests that monetary reward induces an incidentally learned selection bias toward highly rewarded features. It remains controversial, however, whether learning of reward regularities has similar effects on spatial attention. Here we ask whether spatial biases toward highly rewarded locations are learned implicitly, or are instead associated with explicit knowledge of reward structure. Participants completed a hybrid search and choice task involving multiple targets among multiple distractors. Targets garnered varying magnitudes of reward, and participants were instructed to search for targets and guess and click on the 1 that they thought would yield the highest reward. Unbeknownst to participants, 1 side of the display offered higher reward than the other. We measured the spatial bias for targets on the high-reward side of the screen and probed explicit awareness via a multiquestion interview. Participants who were aware of the reward structure ($N = 48$) showed a selection bias for targets appearing on the high-reward side of the screen. Contrary to previous findings, unaware participants ($N = 24$) showed only a significant central bias, despite spending just as much time on the task. The strong association between explicit awareness and reward-driven spatial attention in this paradigm suggests that instead of directly affecting the attentional priority map, probabilistic spatial reward learning more frequently affects attention indirectly by modulating task goals.

Keywords: spatial attention, reward learning, implicit learning, top-down attention, statistical learning

From food choice to drug addiction, reward exerts powerful influences on human behavior. Recent evidence suggests that selective attention is susceptible to the influence of statistical regularities of features that are predictive of reward. For example, target features previously associated with high probabilities of reward produce more interference as distractors in a later search task (Anderson, 2016; Le Pelley, Pearson, Griffiths, & Beesley, 2015). Surprisingly, however, a similar bias does not consistently appear in spatial attention when locations are probabilistically associated with monetary reward. Locations associated with higher reward are preferentially attended in some cases (e.g., Chelazzi et al., 2014; Schlagbauer, Geyer, Müller, & Zehetleitner, 2014; Sharifian, Contier, Preuschhof, & Pollmann, 2017; Tseng & Lleras, 2013), but not in others (Jiang, Sha, & Remington, 2015; Sharifian et al., 2017; Won & Leber, 2016, 2018). What circumstances promote an attentional priority for rewarded locations? It is possible that, unlike the relationship between reward and featural attention, the guidance of spatial attention by monetary reward is driven in part by explicit awareness. Here, we test the association between explicit awareness and reward-guided spatial attention via probability learning using a paradigm that previously produced evidence of reward-guided spatial attention.

Several characterizations of the relationship between monetary reward and spatial attention have been offered to explain why spatial attention should be sensitive to monetary reward. First, monetary reward can motivate behavior in tasks that engage spatial attention. For example, monetary reward enhances the validity effect in a spatial cueing task (Engelmann & Pessoa, 2007). This effect can be attributed to the interaction between reward motivation and explicit, goal-directed attention. Motivation in the form of monetary reward sharpens attention to the existing task goals on which incentives are contingent: participants are more likely to attend to the task in general, and they are more likely to attend to locations that they know will yield higher reward (Jiang et al., 2015).

Second, monetary reward can interact with certain forms of attentional guidance via incidental learning. One line of work shows that monetary reward increases short-term, intertrial location priming—an effect often considered automatic, rather than

This article was published Online First July 25, 2019.

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This study was supported in part by a graduate research fellowship to Caitlin A. Sisk. Erin Motley and Abby Schmidt contributed to data collection. We thank Wilma Koutstaal and Stephen Engel for suggestions.

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goal-directed (Maljkovic & Nakayama, 1996). Hickey, Chelazzi, and Theeuwes (2014) found that when the target appeared in the same location twice, facilitation was greater when the previous trial garnered a high reward than when it garnered a low reward.

Third, monetary reward can induce enduring changes in spatial attention. Chelazzi et al. (2014) asked participants to search for a target shape among distractor shapes in eight locations. Unbeknownst to participants, each location was probabilistically associated with high, medium, or low reward. Although reward had no apparent effect on this training task, reward probability learning manifested in a subsequent testing task in which participants searched for a character among symbols and received no reward. In the testing task, on trials with two characters, participants were more likely to identify the one appearing in one of the previously high-reward locations. Trials with a single character showed no effects of reward, as was observed in the training task. Other studies show that monetary reward modulates certain long-term incidental learning effects, like contextual cueing. In contextual cueing, participants are faster finding a target when the spatial array of targets and distractors has been learned through repeated exposure. When some repeated contexts are paired with reward, contextual cueing is larger than when those contexts are paired with penalty or no reward (Tseng & Lleras, 2013). In fact, the magnitude of reward effects appears to be comparable to the magnitude of contextual cueing in some cases (Schlagbauer et al., 2014).

Finally, reward modulates choice behavior. When presented with multiple objects, one of which contained a hidden reward, participants were more likely to select objects in locations that often yielded higher reward, even though they were not informed about the reward distribution (Jiang et al., 2015; Won & Leber, 2016). Together, these findings suggest that reward modulates the attentional priority map, either through intentional, goal-directed control (i.e., by changing motivation), or via incidentally learned selection history effects (Anderson, 2016; Awh, Belopolsky, & Theeuwes, 2012; Failing & Theeuwes, 2018; Le Pelley et al., 2015; Theeuwes, 2018).

In contrast to the aforementioned studies, spatial reward probability learning does not consistently guide attention. Several studies found no effect of reward on behaviors closely linked to attention: monetary reward failed to enhance visual statistical learning of novel shapes (Rogers, Friedman, & Vickery, 2016), did not increase the attentional boost from target detection (Swallow & Atir, 2018), and did not always induce value-driven attentional capture (Sha & Jiang, 2016). In the domain of spatial attention, at least three studies have failed to observe a bias toward locations probabilistically associated with reward despite strong biases toward locations that frequently contain a search target. Won and Leber (2016) embedded high or low reward behind targets in a visual search task. In one manipulation, the target appeared in all quadrants equally often, but the magnitude of reward was greater for targets in one quadrant than in the others. In another manipulation, the magnitude of reward was equal for targets in all quadrants, but the target appeared more frequently in one quadrant than in the others. While target frequency strongly influenced search reaction time (RT), reward magnitude had negligible effects. Similar results were shown in Jiang et al. (2015) and Won and Leber (2018). In addition, pairing certain visual contexts with high or low reward does not consistently enhance the learning of repeated visual contexts. Sharifian et al. (2017) found that when certain target locations were consistently paired with high reward regardless of whether they appeared in a repeated or a novel context, reward did not enhance contextual cueing. In contrast to these findings, regularities of reward did consistently influence spatial attention when participants were informed of the underlying location-reward association (Jiang et al., 2015). These findings raise the possibility that reward-guided spatial attention may be more closely associated with explicit awareness than other forms of attentional guidance via incidental probability learning.

To better understand how monetary reward modulates attention and to assess the consistency of implicit modulation via probabilistic reward learning, here we tested the role of explicit awareness in mediating reward-based spatial selection. Although many previous studies attribute probabilistic reward-learning to implicit guidance, as Anderson (2016) and Le Pelley et al. (2015) noted, few studies have systematically probed explicit awareness about the reward contingency. Some evidence suggests that awareness affects feature-based attention. For example, Bourgeois, Neveu, Bayle, and Vuilleumier (2017) found greater value-based attentional orienting when participants were aware of the previous reward probability contingencies. However, other studies showed that value-driven attention was automatic, as it occurred even when attending to it was counterproductive (Le Pelley et al., 2015). Though there was no dedicated test of awareness in the latter study, the presence of the effect when it contradicted task goals was taken as evidence of implicit attentional guidance toward features probabilistically associated with reward.

Evidence for the association between awareness and probabilistic reward learning is mixed in the spatial domain. Anderson and Kim (2018) trained participants to associate differential reward with different regions of real-world scenes. The spatial bias acquired through this training influenced a subsequent, unrelated visual search task: participants preferentially looked at the previously high-reward area of the screen and were faster finding a target there even when there was no task-related motivation. The transfer across tasks may suggest that the attentional biases observed were driven by implicit learning. However, spatial regularities within real-world scenes often induce explicit learning (Brockmole & Henderson, 2006). Like other studies on spatial attention, Anderson and Kim (2018) did not directly probe awareness. It is unclear whether the spatial bias was formed via implicit or explicit learning of the reward structure in the training phase. Thus, while the learning was incidental, it was not necessarily implicit. The present study directly probed awareness to clarify the nature of this kind of probabilistic reward learning. In another study, explicit awareness of the reward-location contingency was systematically probed (Lucas et al., 2013). As reviewed below, Lucas et al. (2013) provides ambiguous findings regarding the role of awareness in probabilistic reward learning and, thus, warrants additional testing. Our study will directly examine how awareness modulates reward-based spatial attention in a task highly similar to that of Lucas et al. (2013).

In addition, this study explores the possibility that the effects of probabilistic reward learning on attention are most clearly present when multiple targets compete for selection. Indeed, among the studies that examined effects of spatial regularities of reward on attentional selection, positive findings were observed mainly in studies that presented participants with two or more targets

(Chelazzi et al., 2014; Lucas et al., 2013). In contrast, studies that failed to find incidental spatial reward probability cueing presented participants with just one target (Jiang et al., 2015; Won & Leber, 2016). Positive effects of monetary reward with one-target search tasks have been obtained (Schlagbauer et al., 2014; Sharifian et al., 2017; Tseng & Lleras, 2013). However, for the most part these studies show modulation of context learning, rather than formation of biases toward locations associated with high reward in the absence of contextual cues or frequency effects. Although Schlagbauer et al. (2014) found a main effect of both reward and contextual cueing, Sharifian et al. (2017) found that pairing reward with specific locations did not speed RT independently of context repetition. Thus, when a single-target is used, reward effects are observed occasionally but inconsistently. The contrast between single- and multiple-target tasks is most clearly shown in Chelazzi et al. (2014), where effects of reward manifest only on trials when two targets appear concurrently. It is possible that reward biases spatial attention mainly when attentional competition cannot be resolved by other mechanisms. When there is one target on the display, low-level stimulus differences between the target and distractors may facilitate spatial selection. With multiple targets competing for selection, their prior association with reward may become crucial in biasing selection. In addition, the presence of multiple targets may allow the locations of the targets to be coded relative to each other, facilitating spatial learning (Anderson & Kim, 2018). Because incidental reward learning is more reliable in studies using multiple targets, we used an experimental paradigm that included multiple targets to strengthen our study's sensitivity to effects of incidental reward learning (see Lucas et al., 2013).

Experiment 1

We adopted an experimental paradigm first introduced by Lucas et al. (2013) that integrated aspects of visual search and choice behavior, thus implicating both selective attention for targets and attentional competition between targets. These researchers tested healthy controls and patients with left hemifield neglect in a foraging-like task. Participants were presented with an array of colorful shapes, some were targets (e.g., purple-and-white circles) others were distractors (e.g., purple stars). Participants were asked to touch the target they guessed would have the highest points hidden behind. The task involved visual search—participants needed to discriminate targets from distractors because points were awarded only when a target was touched. As a result, the task implicated selective attention. It also involved choice—participants must decide which of the targets should be selected. Therefore, the task involved attentional competition between potential targets. Unbeknownst to participants, the display was divided into eight sectors from left to right. For some participants, reward was uniformly distributed across space; for others, reward was disproportionately high for left-sided targets. Participants tested with a symmetrical reward distribution showed no change in choice behavior. The average touch point was near the middle of the screen for healthy controls, and biased toward the right side of the screen for patients, demonstrating effects of left hemifield neglect. Participants tested with an asymmetric reward structure, however, gradually developed a leftward bias. After training, controls tended to touch the left side of the screen, and neglect patients overcame their rightward bias. The observation of a reduction in hemifield neglect further underscores the involvement of spatial attention in this task.

Lucas et al.'s (2013) study presents compelling evidence that reward can shape visual search and choice behavior, and under appropriate conditions, asymmetric reward training can overcome left hemifield neglect. Together, these results suggest a strong influence of reward on spatial attention. However, these results are compatible with two different interpretations. According to one interpretation, whenever the search display contains multiple targets, prior association between location and reward modulates which one is prioritized. Alternatively, reward learning occurs because participants become aware of the contingency between location and reward. In Lucas et al. (2013), about half of the control participants were aware of the reward contingency, while the other half did not report awareness. Although both groups developed a leftward spatial preference, the effect was numerically larger in the aware group. Though Lucas et al. (2013) suggested that learning was implicit, the observation of greater learning in the aware participants weakened this conclusion. Some consider this kind of positive association between behavior and awareness to indicate that the task involves explicit, rather than implicit learning (Annac et al., 2019; Smyth & Shanks, 2008; Vadillo, Konstantinidis, & Shanks, 2016). Here, we further examined the role of attentional competition and the association with awareness in reward learning through further testing of the Lucas et al. (2013) paradigm.

Method

Participants.

Sample size determination. Sample size was determined based on Lucas et al.'s (2013) study. That study included 11 participants using a spatially biased reward training paradigm. Six of these reported no awareness and five reported awareness. Reward learning was significant in both groups, Cohen's d was 2.24 in the unaware group, and 8.70 in the aware group. Assuming the same effect size as Lucas et al. (2013), the expected statistical power for detecting reward learning exceeded .80 for each awareness group with a sample size of 6. Because the small samples used in these previous experiments can yield unreliable effect size estimates (Halsey, Curran-Everett, Vowler, & Drummond, 2015), we set an a priori threshold of at least eight participants in each group. To this end, we collected data from participants until eight or more participants were coded as aware and eight or more were coded as unaware. In some experiments, participant scheduling led to more than eight in both groups, while in others, participants' data had to be removed from analyses, leaving fewer than eight in one group.

Experiment 1 participants. Twenty college students participated in Experiment 1. There were 19 women and 1 man (mean age = 19.60). All participants were compensated with extra credit points in psychology courses, as well as up to $5 depending on performance. The treatment of the participants was in accordance with the ethical standards of the American Psychological Association, and this study was approved by the University of Minnesota Institutional Review Board.

Materials. Participants were tested individually in a room with normal interior lighting. They sat at an unconstrained distance of about 40 cm from a 19" CRT monitor (resolution 1024 × 768 pixels; 75 Hz refresh rate). Visual angles are estimated from this distance. The visual search task was coded in MATLAB (www.mathworks.com) and Psychtoolbox (Brainard, 1997; Pelli, 1997).

The stimuli consisted of letters from the English alphabet presented in Helvetica font at sizes ranging from 20 to 54 points. The color of the items was specified in the RGB space, with the red, green, and blue values ranging from 100 to 255. Each trial included 20 distinctive letters whose size varied between 1.3–2.9°. Eight letters were in their normal orientation and 16 in a flipped (backward) orientation. The normal letters were in one randomly chosen color (the R, G, and B values were randomly selected on each trial), and the backward letters were in another randomly chosen color. The screen was divided horizontally into eight unmarked, equal size sectors, each subtending approximately 6.8°. Each sector contained one normal letter and two backward letters on each trial. The letters' *x*- and *y*-coordinate positions were randomized within their sectors. Figure 1 (left) shows a sample display.

Procedure. Participants were instructed to choose, by clicking, one of the forward-facing target letters on each trial. They were told that they should aim to accumulate as many points as possible and that the number of points allotted on each trial depended on which target they chose. There were no instructions in terms of response speed, and when asked, the experimenter clarified that speed would not affect the score. Participants were made aware of potential monetary compensation in addition to the guaranteed course credit, depending on performance. The researcher told participants of the sliding scale of compensation, in which 6,000 cumulative points at the end of the study would earn participants $1, and every 1,000 points beyond 6,000 would garner an additional $1, up to $5 total (10,000 points). This amount of potential compensation has been shown to induce reward-related attentional biases in previous studies (Sha & Jiang, 2016; Stankevich & Geng, 2015). Earning 10,000 points was possible but challenging. Earning 6,000 points was more attainable but not guaranteed. This rolling incentive was designed to directly associate points in the task with monetary reward. Once participants understood the instructions, they completed eight practice trials. The practice trials were followed by 336 experimental trials. The number of trials tested here—336—was larger than that of Lucas et al. (2013), who tested 84 trials in each of two experimental sessions. We were able to include more trials because of the testing of young adults rather than neuropsychological patients (or their controls). We believe that this fourfold increase in the number of trials is sufficient to allow for learning both because reward learning was observed in Lucas et al. (2013) with fewer trials and because this number of trials is comparable with the number of experimental trials included in many previous reward studies (e.g., Anderson, Laurent, & Yantis, 2011; Sha & Jiang, 2016).

Participants clicked on a central fixation square (0.5°) to initiate each trial. The mouse click required eye-hand coordination and ensured that fixation was centralized before the trial. Upon the mouse click, participants were presented with an array of eight distinct normal letters (targets) among 16 distinct backward letters (distractors). All targets were in one color, and all distractors were in another color—a design consistent with what Lucas et al. (2013) illustrated in their Figure 1. The two colors were randomly chosen on each trial (a random value was assigned to the red, green, and blue pixels in the RGB space), and these values changed from trial-to-trial. Participants chose one of the normal letters, or targets, on each trial by clicking on it. The stimuli remained on the screen until a mouse click was made. The mouse position was randomized at the start of the response.

We did not ask participants to touch the target, as in Lucas et al. (2013), because the touch task may associate reward with limb movement (e.g., moving the arm further in one direction yields higher reward). The mouse click is analogous to Lucas et al.'s task while diminishing the confound of motor learning. The random-

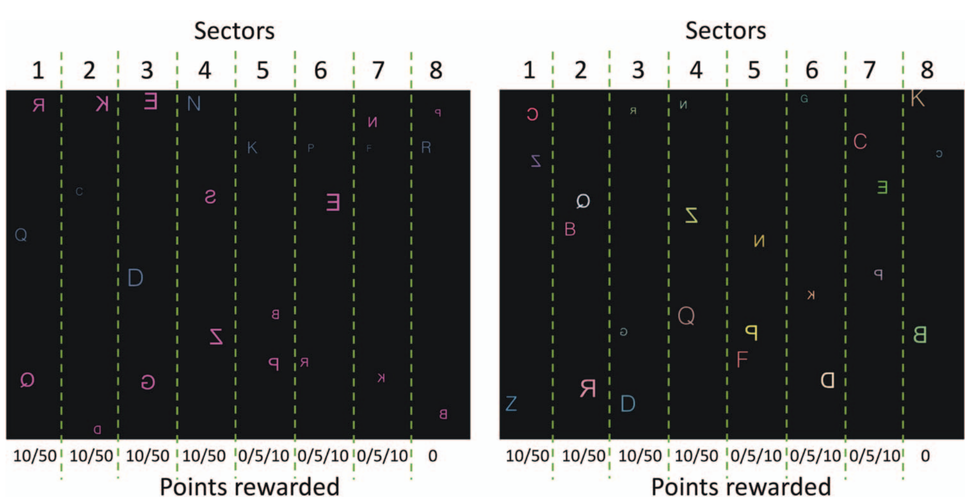

Figure 1. Left: A sample display used in Experiment 1. Right: A sample display used in Experiment 2. The lines dividing the sectors are for illustrative purposes and were not actually presented in the study. Each of the eight evenly spaced "sectors" of the screen contained one normal letter (target) and two backward letters (distractors) on each trial. Possible reward values for targets appearing in the eight sectors of the screen are shown at the bottom, assuming the high-reward half is on the left. See the online article for the color version of this figure.

ization of the starting mouse position reduced motor learning further, as the movement trajectory was variable when the initial mouse position was randomized.

After choosing a target, a yellow dot appeared at the location of that target for 1,000 ms with a number (0, 5, 10, or 50) representing the reward earned for that choice, and an ascending tone sequence played (300 ms). Clicking on a distractor led to a short high beep (100 ms) and participants were not awarded any points. Clicking on an empty space led to white noise feedback (300 ms) and no points. Then, participants' cumulative reward was displayed at the center of the screen for 1,500 ms before the next trial started. At the end of the experiment, one researcher conducted a pen-and-paper interview designed to assess whether the participant was aware of the underlying reward structure. Each participant was paid according to their cumulative score once the study was complete.

Design. The reward structure was modified from Lucas et al.'s (2013) asymmetric reward. Depending on the location of the target chosen, participants would receive different numbers of points (0, 5, 10, and 50). Participants were not told that location and reward value were related. As mentioned above, the screen was divided into eight sectors from left to right, each of which contained one target. Targets on one, highly rewarded half of the screen (e.g., Sectors 1, 2, 3, and 4) garnered either 10 or 50 points on each trial with equal probability. Choices in the most lateral sector (e.g., Sector 8) on the low-reward half of the screen always resulted in zero points. Choices within the other three sectors on the low-reward half of the screen (e.g., Sectors 5, 6, and 7) garnered 0, 5, or 10 points with equal probability. While Lucas et al. (2013) only assigned higher reward to the left half of the screen because of that study's focus on hemifield neglect patients, we counterbalanced the half of the screen (left or right) associated with high reward between participants. In doing so, we avoided potential preexisting biases to the left hemifield that may result from reading biases (Olson & Chun, 2002; Rinaldi, Di Luca, Henik, & Girelli, 2014). Figure 1 (left) shows a sample display from Experiment 1 with the possible reward for each sector of the screen indicated below, assuming the high-reward half is on the left.

Under most circumstances, 50-point rewards would only appear on the high-reward half of the screen, and 5-point and 0-point rewards would only appear on the other, low-reward half of the screen (e.g., Sectors 5, 6, 7, and 8). However, there were rare exceptions to this rule. Following Lucas et al. (2013), we rewarded participants for progressively lateral responses toward the rewarded side: on trials in which a response was farther to the rewarded side than any of the targets chosen in the previous six trials, participants received either 10 or 50 points, even if they chose a sector on the low-reward half of the screen. For example, suppose participants had chosen any of the low-reward Sectors 6–8 on the preceding six trials, but they chose Sector 5 on trial 7. They would receive 10 or 50 points (equally often) even though Sector 5 fell on the low-reward side. This progressive reward structure was used to make our task more similar to that of Lucas et al. (2013), which implemented this type of progressive reward. Across all experiments, progressive reward affected about 2% of trials in which participants chose a target on the low-reward side. Removing these trials did not change the results.

Interview for awareness. After participants had completed all experimental blocks, one experimenter conducted a pen-and-paper interview to probe awareness of the spatial reward structure. The questions were derived directly from the interview described by Lucas et al. (2013). The interview started out with broad questions and became progressively more specific in terms of the spatial reward structure. The interview included the following questions in the following order: (a) "Did you find the task hard?" (b) "How did you make your choices?" (c) "Did you think there was a hidden rule?" (d) "Do you think that the gains were more frequent in some conditions?" (e) "Were the gains equally distributed over the whole screen?" and (f) "Some people tested before you felt that the gains were more frequent on one side, did you have the same impression?"

Awareness classification. We classified participants into two groups. "Unaware" participants were those who revealed no knowledge about the reward-location relationship in their answers to all six questions on the awareness interview. The rest were "aware" because they indicated asymmetric spatial distribution of reward in their answers to at least one question. Analyses using more fine-grained classifications into aware, "partially aware," and unaware groups will be presented after all experiments have been described.

Results

Of the 20 participants in Experiment 1, 11 were classified as aware and 9 were unaware. We present data separately for these two groups.

Participants were highly accurate. Table 1 presents the percent of trials in which participants chose a target letter (rather than a distractor). Incorrect trials were excluded from the following analysis.

Spatial bias toward the high-reward side. Half of the participants received higher reward for targets chosen on the left side, and the other half received higher reward on the right. To perform analyses on group averages, we flipped the reward space for the latter half such that all data were plotted with the high reward on the left side (see Figure 2). To examine how choice behavior changed over time, we divided the 336 trials into 16 blocks with 21 trials per block. For all of the reported analysis of variances (ANOVAs), where the sphericity assumption was violated, we present the Greenhouse-Geisser corrected p values.

Results showed that awareness was associated with a higher magnitude of reward-based spatial biases. An ANOVA using block as a within-subject factor and awareness group as a between-subjects factor showed a significant main effect of awareness group, $F(1, 18) = 18.77$, $p < .001$, $\eta_p^2 = .51$, and a main effect of block, $F(4.12, 74.13) = 6.07$, $p < .001$, $\eta_p^2 = .25$, but also a significant interaction between awareness and block, $F(4.12,$

Table 1
Accuracy in Choosing a Target (Forward-Facing Letter) in This Study

Experiment	Accuracy
Experiment 1	98.9 (1.1)%
Experiment 2	98.8 (1.2)%
Experiment 3	98.9 (1.2)%

Note. *SD* is presented in parentheses.

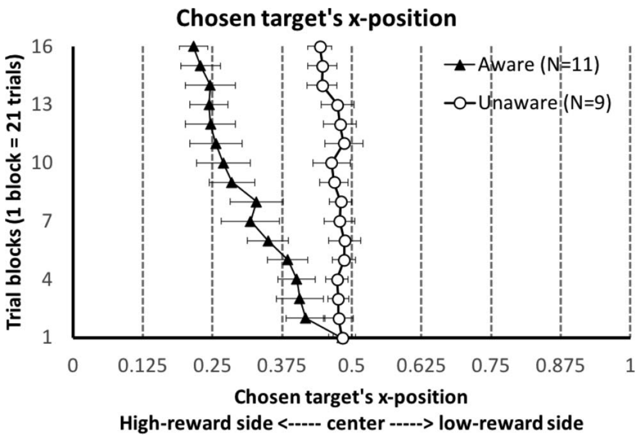

Figure 2. Chosen target's x-coordinates on the display in Experiment 1. Space is represented on the *x*-axis, with the high-reward side plotted on the left side of the graph for all participants; 0.5 on the *x*-axis is the screen middle. Time is plotted on the *y*-axis, grouped by trial blocks. Error bars show ±1 *SEM.*

74.13) = 4.04, p = .005, η_p^2 = .18. In aware participants, responses progressively shifted toward the high-reward side of the screen, producing a significant main effect of block, $F(15, 150) = 7.54$, $p < .001$, $\eta_p^2 = .43$, including a linear trend, $F(1, 10) = 20.50$, $p = .001$, $\eta_p^2 = .67$. Unaware participants, in contrast, showed no change in response across time, $F(15, 120) = .63$, $p = .85$ for the main effect of block.

T tests comparing the average x-coordinates of selected targets with the screen middle showed that aware participants significantly deviated from the screen middle. On average, they selected a target 18% away from the middle in the direction of the high-reward side, $t(10) = 6.51$, $p < .001$ (compared with screen middle). In contrast, unaware participants selected a target only 3% away from the middle in the direction of the high-reward side, not differing from screen middle, $t(8) = 1.47$, $p = .18$.

Frequency of responses. Unaware participants, on average, selected a location near the screen middle. Did they select targets in all eight sectors equally often, or did they always choose the middle sectors? Figure 3 (left) plots the proportion of responses to targets in the eight sectors. The high-reward side is plotted on the left of the graph for all participants. We also plot the reward participants received when they selected a target, plotted across the eight sectors (Figure 3, right).

Because reward was contingent on the location of the selected target, participants always received higher reward if they chose a target on the high-reward side, and low-to-zero reward if they chose a target on the low-reward side. Figure 3 (right) shows that the experienced reward is a step function, as intended by the experimental design.

Participants' response frequency across space, however, did not follow the reward values. Here, aware and unaware participants behaved differently. An ANOVA on the proportion of targets chosen in each sector including sector and awareness group as factors revealed a significant main effect of sector, $F(1.97, 35.51) = 8.89$, $p = .001$, $\eta_p^2 = .33$, no main effect of group, $F < 1$, but a significant interaction between sector and awareness group, $F(1.97, 35.51) = 11.03$, $p < .001$, $\eta_p^2 = .38$. This indicates that the number of targets chosen was not distributed equally across the sectors and that the pattern of the distribution differed between the two groups.

Unaware participants primarily showed a central bias: they favored the sectors closer to the center of the screen. In this group, an ANOVA showed a significant main effect of sector, $F(7, 56) = 10.99$, $p < .001$, $\eta_p^2 = .58$, accompanied by a significant quadratic trend, $F(1, 8) = 25.58$, $p = .001$, $\eta_p^2 = .75$. Treating screen side (high vs. low-reward) as one factor, and distance from the center as another in an ANOVA produced no effect of side, $F(1, 8) = 1.82$, $p = .21$, but a significant main effect of distance, $F(3, 24) = 21.37$, $p < .001$, $\eta_p^2 = .73$. Targets farther from the center were chosen less frequently, as shown by a significant linear trend ($p = .001$). Side and distance showed no interaction, $F < 1$.

Aware participants, on the other hand, favored locations on the high-reward side. An ANOVA on proportion of choices per sector showed a significant main effect of sector, $F(7, 70) = 11.20$, $p < .001$, $\eta_p^2 = .53$, accompanied by a strong linear trend, $F(1, 10) = 41.93$, $p < .001$, $\eta_p^2 = .81$. Treating screen side (high vs. low-reward) and distance from the center as two factors produced a

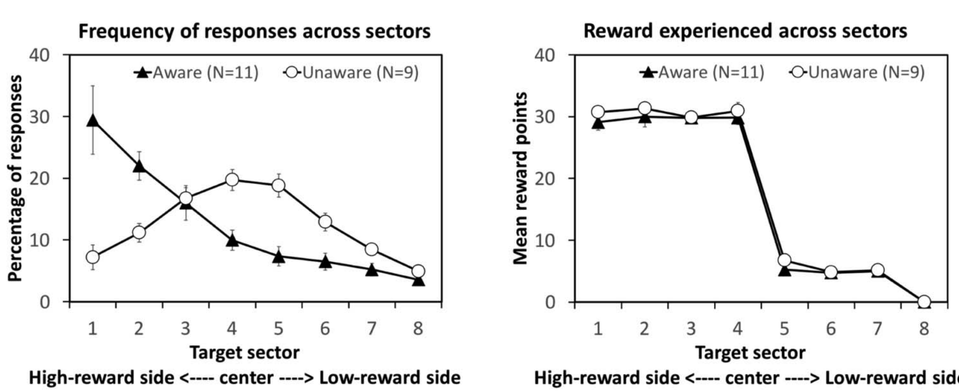

Figure 3. Data from Experiment 1. Left: Response frequency for targets displayed across the eight sectors. Out of all of a participant's responses, the percentage of responses within a given sector was calculated for each sector and averaged across participants. Right: Reward experienced when choosing a target in a specific sector. Error bars show ±1 *SEM.*

significant main effect of reward side, $F(1, 10) = 43.62$, $p < .001$, $\eta_p^2 = .81$, showing a strong preference for the high-reward side. The main effect of distance from center was marginally significant, $F(3, 30) = 2.51$, $p = .078$, qualified by a strong interaction between reward-side and distance from center, $F(3, 30) = 8.53$, $p < .001$, $\eta_p^2 = .46$. On the high-reward side, choices favored responses farther away from the center, $F(3, 30) = 4.87$, $p = .007$, $\eta_p^2 = .33$, along with a significant linear trend ($p = .02$). This was reversed on the low-reward side, where choices favored responses toward the center, $F(3, 30) = 5.47$, $p = .004$, $\eta_p^2 = .35$, along with a significant linear trend ($p = .03$). These results provided compelling evidence that choice behaviors differed qualitatively between participants with and participants without awareness of the reward structure.

Discussion

In Experiment 1, aware participants were significantly biased toward the high-reward side of the screen while unaware participants were not. In addition, examination of the pattern of responses showed a distinction in the pattern of spatial biases between unaware and aware participants. Participants who were aware showed a strong preference for the most lateral sector of the rewarded half of the screen. Unaware participants, on the other hand, showed a bias for the center of the screen, a pattern of behavior seen in previous studies on the free viewing of scenes (Wang et al., 2015).

The testing condition in Experiment 1 was favorable for uncovering reward-based spatial attention. Similar to previous two-target search tasks, Experiment 1 presented participants with multiple targets, a condition considered particularly conducive to detecting reward-guided spatial biases (Chelazzi et al., 2014). Nonetheless, in participants who did not acquire awareness of the reward-location contingency, we surprisingly found no significant evidence that reward affected spatial attention.

The lack of reward-related spatial biases in unaware participants in our study contradicts Lucas et al. (2013), who found evidence of reward learning in unaware participants. Several factors may explain this contradiction. First, participants in our study were young adults, whereas those in Lucas et al. (2013) were older adults. It is possible that reward learning differs for young and older adults, given previously observed age differences in the interaction between explicit and implicit knowledge (Twedell, Koutstaal, & Jiang, 2017). Twedell et al. (2017) found that explicit knowledge interferes with implicit guidance of attention more strongly in younger adults than in older adults, suggesting greater reliance on explicit knowledge in younger populations. Second, by using a mouse click response instead of a touch response, we may have reduced incidental motor learning. Because our aim is to examine the effects of reward on spatial attention in the absence of aid via motor habits, our task is appropriate for this purpose. Third, by using one color for all targets and a different color for all distractors, targets in our study could be easily segmented from distractors. This might differ from Lucas et al. (2013). That study did not fully describe the stimuli used, but the method section stated that "Visual similarity between the targets and distractors was increased for healthy controls, so as to make the search task more challenging for them" (p. 2619). It is possible that search was more difficult in Lucas et al. (2013) than in our Experiment 1. Thus, the next experiment will use a more difficult search task to further examine implicit, reward-based spatial attention.

Experiment 2

We removed the color cue that distinguished the targets from distractors. Each letter was assigned a random red, green, and blue value in the RGB space. This presented a challenging search task because targets were not easily distinguishable from distractors. Figure 1 (right) shows a sample search display.

Search difficulty may affect reward learning in several ways. As search becomes more difficult, there may be fewer resources left to process the location-reward contingency, reducing the overall level of reward learning and awareness. In fact, if it takes too long to find a target, participants may simply respond to the first target they see. This would render the multitarget hybrid task effectively a single-target search task, reducing sensitivity to reward learning. Alternatively, when the search task is difficult, participants may be more inclined to rely on reward information to facilitate their search. Upon finding a high-reward target, they may be incentivized to search primarily in that region. This type of reward-potentiated intertrial repetition priming is reminiscent of Hickey et al.'s (2014) findings and may yield implicit spatial biases toward high-reward regions.

Method

Participants. Twenty-seven college students (20 women; mean age = 21) participated in this study. An additional participant was tested, but their data were excluded because of a computer error.

Materials and procedure. Everything was the same as in Experiment 1, except for the colors of the stimuli. In Experiment 2, all targets and distractors were different colors (Figure 1, right). The color of each stimulus was chosen by randomly assigning RGB values (between 100 and 255 for each value) to each target and distractor. This increased the difficulty of the search task by eliminating the clear color distinction between targets and distractors.

Results

Of the 27 participants, 20 were aware of the location-reward association, and 7 were unaware. Although we tested participants until there were at least eight unaware participants, data from one of those participants was excluded because of a computer error.

Spatial bias toward the high-reward side. Figure 4 shows the average x-coordinates of the chosen target across the 16 blocks of trials. The results replicated those of Experiment 1: aware participants developed a strong spatial bias for the high-reward side, but unaware participants did not. The data from the two groups together showed significant main effects of block, $F(4.04, 101.09) = 2.79$ $p = .03$, $\eta_p^2 = .10$, awareness group, $F(1, 25) = 13.15$, $p = .001$, $\eta_p^2 = .35$, and a significant interaction between awareness group and block, $F(4.04, 101.09) = 2.73$, $p = .03$, $\eta_p^2 = .10$.

As in Experiment 1, the aware group showed a main effect of block, $F(15, 285) = 8.34$, $p < .001$, $\eta_p^2 = .31$, but the unaware group showed no such effect, $F < 1$. On average, the x-coordinate

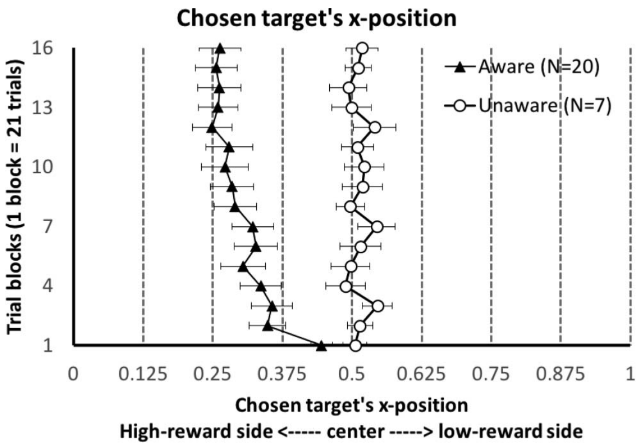

Figure 4. Chosen target's x-coordinates on the display in Experiment 2. The high-reward side is plotted on the left side of the graph for all participants; 0.5 on the *x*-axis is the screen middle. Error bars show ±1 *SEM.*

of targets chosen by the aware group was 20% away from the center in the direction of the high-reward side. This was a significant deviation from center, $t(19) = 5.98$, $p < .001$. In contrast, unaware participants chose locations near the center—mean deviation from the center was 1%, an effect not significantly different from center, $t(6) = 0.56$, $p = .59$.

Frequency of responses. Similar to Experiment 1, unaware participants more often chose targets in the middle sectors than the lateral sectors. Aware participants, on the other hand, more often chose targets toward the high-reward side (Figure 5, left). This was the case even though the groups experienced similar reward structure (Figure 5, right). In the proportion of responses, an ANOVA with awareness group and sector as variables found no effect of group, $F < 1$, or of sector, $F(1.55, 38.86) = 3.26$, $p = .06$, $\eta_p^2 = .12$, qualified by a significant interaction between awareness group and sector, $F(1.55, 38.86) = 6.77$, $p = .006$, $\eta_p^2 = .21$.

An analysis on each awareness group showed results consistent with those of Experiment 1. In the unaware group, an ANOVA using reward side (high vs. low) and distance from center showed no effect of side, $F < 1$, showing no preference for the high-reward side. The main effect of distance was significant, $F(3, 18) = 6.82$, $p = .003$, $\eta_p^2 = .53$, accompanied by a significant linear trend, $F(1, 6) = 7.90$, $p = .03$, $\eta_p^2 = .57$, demonstrating a central bias. Side and distance showed no interaction, $F < 1$. In the aware group, an ANOVA using side and distance as factors found a significant main effect of side, $F(1, 19) = 38.32$, $p < .001$, $\eta_p^2 = .67$, demonstrating a strong preference for the high-reward side. The main effect of distance was also significant, $F(3, 57) = 4.47$, $p = .007$, $\eta_p^2 = .19$, along with a significant interaction between reward side and distance from center, $F(3, 57) = 14.88$, $p < .001$, $\eta_p^2 = .44$. On the high-reward side, aware participants strongly favored lateral positions, $F(3, 57) = 8.54$, $p < .001$, $\eta_p^2 = .31$, and this was reversed on the low-reward side, where preference was given to the more medial sectors, $F(3, 57) = 7.73$, $p < .001$, $\eta_p^2 = .29$.

Discussion

As in Experiment 1, there were major differences between the response patterns of aware and unaware participants. Increasing the difficulty of search did not facilitate implicit reward-guided attention. Unaware participants showed no evidence of spatial biases for targets in more highly rewarded locations. An increase in search difficulty also did not reduce the spatial preference in aware participants. These participants strongly preferred targets in the more highly rewarded side. The strong association between awareness and reward learning casts doubt on the reliability of implicit attention driven by probabilistic reward learning.

Experiment 3

The first two experiments showed that a priority for highly rewarded locations is strongly associated with explicit awareness of the reward-location contingency. This finding differed from Lucas et al. (2013), who found evidence of learning even in unaware participants. This discrepancy motivated us to perform a conceptual replication of the first two experiments using a within-subject design. Experiment 3 was the same as Experiments 1 and 2, except that half of the trials used color as a segmenting cue for targets and distractors (as in Experiment 1) and the other half of the trials used heterogenous colors for all items (as in Experiment 2).

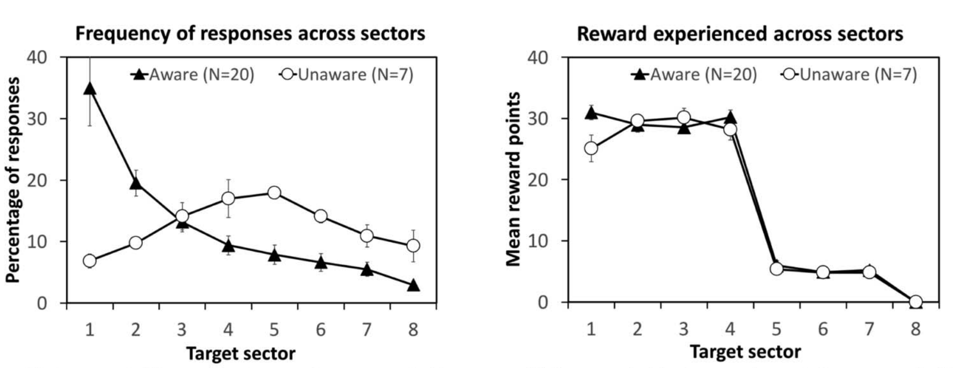

Figure 5. Data from Experiment 2. Left: Response frequency for targets displayed across the eight sectors. Right: Reward experienced when choosing a target in a specific sector. Error bars show ±1 *SEM.*

Method

Participants. Twenty-five college students (18 women; mean age = 20 years) participated in this study.

Materials and procedure. All materials and procedures were similar to Experiments 1 and 2. However, trials in which targets were a single color and distractors were a second color were intermixed with trials in which all stimuli were different colors. Half of the 336 trials were of each type.

Results and Discussion

Of the 25 participants, 17 were aware of the location-reward contingency, 8 were unaware.

Spatial bias toward the high-reward side. Figure 6 shows the average x-coordinates across the 16 blocks. The data are presented separately for easy and difficult search trials. Results fully replicated those of Experiments 1 and 2. Aware participants strongly favored locations on the more highly rewarded side; unaware participants did not. This did not differ between difficult and easy trials. An ANOVA using difficulty level and block as within-subject factors and awareness as a between-subjects factor found no main effects or interactions involving difficulty level: $F(1, 23) = 1.26$, $p = .27$ for the main effect of difficulty level, $F(1, 23) = 1.53$, $p = .23$ for the interaction with awareness, $F(15, 345) = 1.12$, $p = .34$ for the interaction with block, and $F(15, 345) = 1.12$, $p = .34$ for the three-way interaction. Thus, the data were qualitatively similar between easy and difficult search trials. As in the first two experiments, we observed significant main effects of block, $F(4.12, 94.79) = 6.04$, $p < .001$, $\eta_p^2 = .21$, awareness, $F(1, 23) = 18.17$, $p < .001$, $\eta_p^2 = .44$. and their interaction, $F(4.12, 94.79) = 4.34$, $p = .003$, $\eta_p^2 = .16$.

Because difficulty level did not influence the spatial preference for targets in different sectors, we combined easy and difficult trials in the following analysis. Aware participants developed a strong spatial bias toward the high-reward side over time, $F(15, 240) = 13.72$, $p < .001$, $\eta_p^2 = .46$ for the main effect of block, but unaware participants did not, $F(15, 105) = 0.57$, $p = .90$. Averaged across the entire experiment, aware participants' choices were 18% away from the screen middle in the direction of the high-reward side, $t(16) = -6.82$, $p < .001$. Unaware participants' choices were centered on the screen middle, $t(7) = -0.06$, $p = .96$.

Response frequency across sectors. As in Experiments 1 and 2, the two groups showed different spatial biases in terms of the proportion of responses across the eight sectors (see Figure 7). An ANOVA using difficulty level and sector as within-subject factors and awareness as a between-subjects factor found no main effect of difficulty level, $F < 1$, and no interactions between difficulty level and any other factors, $p \geq .57$. There was a significant main effect of sector, $F(2.02, 100.11) = 5.85$, $p = .005$, $\eta_p^2 = .20$, and a significant interaction between awareness group and sector, $F(2.02, 100.11) = 8.90$, $p = .001$, $\eta_p^2 = .28$. Both groups showed a bias for a certain region of space, but the distribution differed.

As in Experiments 1 and 2, unaware participants' choices exhibited a central bias. An ANOVA using difficulty level, screen side, and distance to center as factors revealed just a main effect of distance to center, $F(3, 21) = 9.90$, $p < .001$, $\eta_p^2 = .59$. Sectors closer to the center of the display were chosen more often. None of the other effects were significant, smallest $p = .32$. The same analysis showed that aware participants strongly favored the high-reward side, $F(1, 16) = 51.70$, $p < .001$, $\eta_p^2 = .76$ for the main effect of side. Distance to center interacted with reward-side, $F(3, 48) = 11.76$, $p < .001$, $\eta_p^2 = .42$. On the high-reward side, choices favored the lateral locations; the reverse was true on the low-reward side.

Experiment 3 replicated the findings from Experiments 1 and 2 using a within-subject design. We observed no difference in reward learning behavior between the difficult and easy search trial types. In both cases, aware participants acquired a spatial bias for targets on the high-reward side, while unaware participants did not.

Analyses across all experiments. Given the consistency in findings across experiments, here we combined data across all three experiments to achieve greater statistical power. Data from Experiment 3 were averaged across easy and difficult trials. We examined the following questions.

First, did the level of awareness have graded effects on performance? If so, participants who were partially aware of the reward contingency should show less learning than those fully aware and should exhibit choice behaviors that favor both the high-reward side and central locations. To this end, we reclassified participants into three groups. Unaware participants remained unaware in the new classification—they displayed no awareness on all six recognition questions ($N = 24$). Some participants previously classified

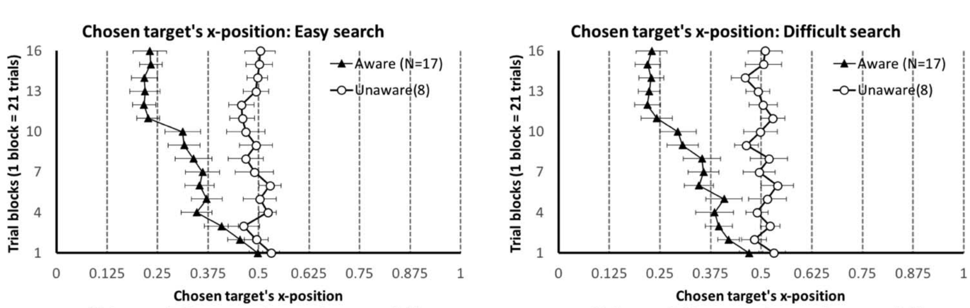

Figure 6. Chosen target's x-coordinates on the display in Experiment 3. Left: Data from easy search trials in which targets and distractors were in two different colors. Right: Data from difficult search trials in which all stimuli were different colors. The high-reward side is plotted on the left side of the graph for all participants; 0.5 on the *x*-axis is the screen middle. Error bars show ±1 *SEM*.

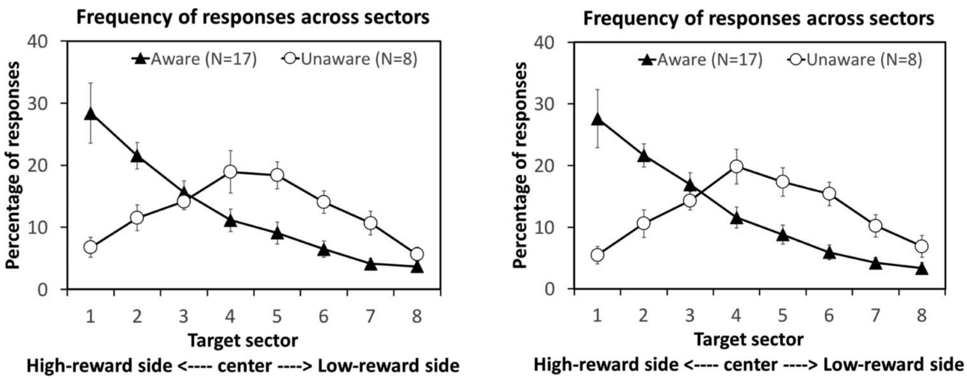

Figure 7. Data from Experiment 3: Response frequency for targets displayed across the eight sectors. Left: Easy search trials; Right: Difficult search trials. All participants experienced the same reward structure (similar to Figure 5B; figure omitted). Error bars show ±1 *SEM.*

as aware were reclassified as "partially aware." Partially aware participants were those who did not indicate awareness of the reward asymmetry in their responses to the first five questions, and only revealed awareness in response to the final question. Thus, in response to Question 5, these participants stated that the gains were equally distributed over the whole screen. However, in response to Question 6, they agreed to the impression of participants before them that gains were more frequent on one side. The contradiction between these two answers suggests that these participants were partially aware but not certain about the reward distribution (N = 9). The remaining participants (N = 39) were considered fully aware.

Figure 8 (left) shows the mean x-coordinates across the three groups. The partially aware group fell between the unaware and fully aware groups in their spatial bias—they developed a preference toward the high-reward side, but the preference was weaker than that of the fully aware participants. An ANOVA on awareness group and block showed a significant main effect of block, $F(5.21, 359.67) = 11.08$, $p < .001$, $\eta_p^2 = .14$ and an interaction between group and block, $F(10.43, 359.67) = 6.98$, $p < .001$, $\eta_p^2 = .17$. The unaware group on average selected a target 0.7% from the middle of the screen in the direction of the rewarded side, $t(23) = 0.57$, $p = .57$. The partially aware group on average selected a target 8.9% from the center of the screen in the direction of the rewarded side, $t(8) = 3.06$, $p = .016$. The fully aware group selected a target 21.1% from the center of the screen in the direction of the rewarded side, $t(38) = 11.19$, $p < .001$.

Figure 8 (right) shows the proportion of responses to targets in the eight sectors of the screen. The three awareness groups behaved differently. An ANOVA on group and sector showed a significant effect of sector, $F(1.94, 133.89) = 16.04$, $p < .001$, $\eta_p^2 = .19$, and a significant interaction between sector and awareness group, $F(3.88, 133.89) = 19.33$, $p < .001$, $\eta_p^2 = .36$. As before, the unaware participants showed just a central bias in their choices. The fully aware group favored locations at the lateral end of the high-reward side, in a largely monotonic fashion. The partially aware group exhibited both a central bias and a preference for the high-reward side. In this group, an ANOVA on screen side (high vs. low reward) and distance to center showed a significant main effect of side, $F(1, 8) = 8.49$, $p = .019$, $\eta_p^2 = .52$, as participants favored the high-reward side. The main effect of distance to center revealed a central bias, $F(3, 24) = 4.23$, $p = .016$, $\eta_p^2 = .35$. These two factors interacted, $F(3, 24) = 4.51$, $p = .012$, $\eta_p^2 = .36$. On the high-reward side, distance to center showed no main effect, $F(3, 24) = 1.84$, $p = .17$, though there was a significant quadratic trend, $F(1, 8) = 5.77$, $p = .043$, $\eta_p^2 = .42$.

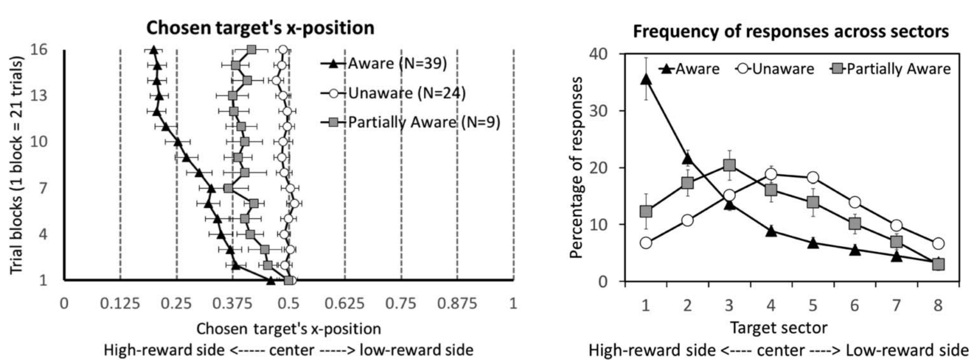

Figure 8. Results across the entire study. Participants were divided into three groups, aware, partially aware, and unaware. Left: Chosen target's x-coordinates on the display. Right: Proportion of trials in which a target in each of the eight sectors was chosen. The high-reward side is plotted on the left side of the graph for all participants. Error bars show ±1 *SEM*. Some error bars may be too small to see.

Participants favored neither the most lateral nor the most medial sector—the shift to Sector 3 was a blend of both a preference for the high-reward side and a preference for the center. On the low-reward side, there was a strong preference for the more medial locations, $F(3, 24) = 14.46$, $p < .001$, $\eta_p^2 = .64$ (linear trend $F(1, 8) = 15.64$, $p = .004$, $\eta_p^2 = .66$), as the preferences for the high-reward side and the preference for the screen center were now aligned. This fine-grained analysis on awareness again confirmed an association between awareness and spatial reward learning.

Our study shows negligible incidental reward learning in the absence of awareness. The unaware group did not show evidence of awareness in the questionnaire, and they did not show reward learning in each of the first three experiments. Across all 24 unaware participants, the mean x-coordinates chosen was 50.7% of the display. This did not significantly differ from 50% on a traditional *t* test, $t(23) = 0.57$, $p = .57$. To find out whether the results from unaware participants were more consistent with a model of null effect of reward, we combined data across all three experiments and used Bayesian statistics (Rouder & Morey, 2012; Rouder, Morey, Speckman, & Province, 2012) to evaluate the likelihood that choices were biased toward the reward side, relative to the likelihood that the choices were unbiased. A Bayes factor of 1 indicates that results are equivocal, whereas values less than 1 support the null result (i.e., it is more likely that choices were unbiased). Bayesian analysis comparing the mean x-coordinates with 50% revealed a Bayes factor of 0.302, suggesting that the absence of a reward effect was about three times more likely than its presence. Thus, our data are slightly more consistent with the null hypothesis that unaware participants show no reward learning. However, a larger sample size is needed to draw strong conclusions.

Aware versus unaware participants. To strengthen the connection between awareness and spatial reward learning, here we examined three potential alternative explanations for the differences between aware and unaware participants. One possible account for the emergence of the two distinct groups is that some participants experienced accurate reward-location feedback early on, while others experienced misleading feedback because of the randomization of the trials (i.e., receiving a 10 instead of a 50 on the high-reward side or a 10 instead of a 5 or 0 on the low-reward side). To evaluate this possibility, we compared aware and unaware participants in terms of the correlations between the reward received on the first trial and the average expected reward for targets in the chosen sector (30 for sectors on the high-reward side of the screen, 5 for the three most medial sectors on the low-reward side, and 0 for the most lateral sector on the low-reward side). The correlation was .673 in the unaware group and .715 in the aware group. These correlations did not differ, $z = 0.13$, $p = .89$, nor did the number of points received on the first trial for each side differ between groups, $t(70) = 0.39$, $p = .70$. This suggests that the two groups did not differ in the representativeness of the first experienced reward. In addition, every unaware participant received multiple 0-point rewards on the low-reward side and multiple 50-point rewards on the high-reward half of the screen, including the most lateral sector on the high-reward side of the screen. Chance factors, therefore, are unlikely to explain differences between the two groups.

A second possibility is that the unaware group represents a subset of participants who lacked sufficient motivation or effort. If this were the case, we would expect the unaware group to show lower overall accuracy. However, accuracy was just as high in the unaware group (mean 98.9%) as in the aware group (mean 98.9%). In addition, if some participants were not motivated to consider alternative target choices and instead chose the first target found to complete the experiment as quickly as possible, we would expect substantially faster RT from participants in the unaware group. This was not the case. Neither mean RT (unaware: 2,000 ms; aware: 2,365 ms, $p = .16$) nor RT variability (unaware: 1,052 ms; aware: 1,355 ms; $p = .23$) differed significantly between aware and unaware participants. RT is fairly slow, with unaware participants taking an average of 2 s to choose a target.

A third possible explanation for the difference between groups is a difference in sampling: might unaware participants be less exploratory in sampling the eight sectors? Our data showed that this was not the case. An analysis on the first two blocks and the last two blocks of data suggest, instead, that both groups sampled the display widely early in the experiment, and reduced their exploration later on. Figure 9 displays the frequency of responses across the eight target sectors. In the first two blocks, the curves were relatively flat for both groups, suggesting that they sampled all eight sectors relatively evenly. In the last two blocks, the aware group no longer explored sectors in the low-reward side. The unaware group continued to sample all sectors, though they were less likely to choose the more lateral sectors.

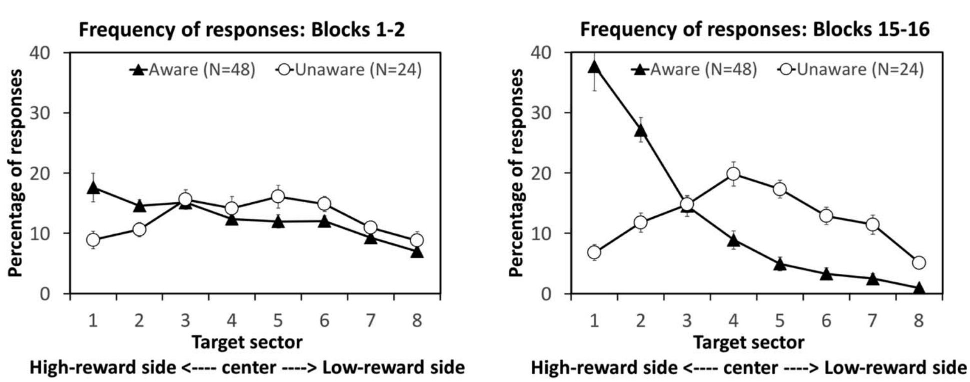

Figure 9. Change in choice behavior from the beginning (first two blocks; left) to the end (last two blocks; right) of the experiments. Error bars show ±1 *SEM*.

The presence of a small difference between the two groups in terms of the proportion of targets chosen in Sectors 1 and 2 even in the first two blocks also suggests that the aware group acquired a spatial bias early in the experiment. To ensure that this bias was not a preexisting reading bias toward the left side of the screen, we examined data from aware participants rewarded on the left and aware participants rewarded on the right. Both groups preferred the high-reward side, regardless of the side of the screen that was rewarded. Thus, the early bias results from training during the first two blocks, rather than a preexisting bias. The fact that learning would occur within the first two blocks is not surprising, given that there were 42 trials within the first two blocks combined, which is half of the number of trials in the full Lucas et al. (2013) experiment.

Thus, the lack of reward learning in unaware participants was not because of nonrepresentative experience with reward-location associations, lack of motivation, lack of exploration across the eight sectors, or a preexisting bias toward one side of space.

General Discussion

This study investigated effects of monetary reward on spatial attention. Despite slight variations in experimental design, the results across experiments are consistent—explicit awareness was associated with different reward learning behavior. In all three experiments, participants coded as unaware showed no evidence of formation of a spatial preference for locations that frequently yielded high reward. Aware participants, on the other hand, consistently showed a strong bias toward the half of the screen that yielded higher rewards. The finding holds across two levels of search difficulty—color-based easy search and shape-based difficult search. These findings establish a strong association between explicit awareness of spatial reward distribution and probabilistic spatial reward learning. This does not mean that reward cannot directly and implicitly drive attention. Rather, the findings suggest that spatial biases toward locations probabilistically associated with monetary reward are more often driven by explicit awareness of the associations. The weak—in this case negligible—implicit effects of statistical reward learning on spatial attention underscore the need for replication in future research on this topic.

Our study joins a growing list of findings to suggest that awareness and reward-guided attention are closely linked in some paradigms. Bourgeois et al. (2017) found that participants showed a larger reduction in RT in a cued search task when searching for targets that were associated with high reward in a previous task than for those associated with low reward in the previous task. Crucially, they also found greater value-driven attentional effects in participants who were aware of the underlying reward structure (i.e., the association between a certain target color and reward magnitude; Bourgeois et al., 2017).

Attentional Competition With Multiple Targets

Our study suggests that the presence of multiple targets in a reward learning task is, by itself, insufficient to yield behavior consistent with implicit guidance of attention by reward. This contrasts with previous findings: multitarget choice tasks have previously produced successful implicit spatial reward learning (Chelazzi et al., 2014; Won & Leber, 2016), whereas single-target search tasks have sometimes but not consistently done so (Jiang et al., 2015; Schlagbauer et al., 2014; Sharifian et al., 2017; Tseng & Lleras, 2013; Won & Leber, 2016). Won and Leber (2016) and Chelazzi et al. (2014) observed evidence of biases toward locations providing a higher probability of a high reward only when multiple targets were present. Furthermore, Anderson and Kim (2018) found that reward learning biased spatial attention in real-world scenes that contained landmarks to distinguish different areas of space but not in scene textures that distinguish different scenes from each other but offer no landmarks. They argue that the landmarks in real-world scenes serve to differentiate different scene areas; thus, providing participants with multiple distinct "targets." Based on these previous findings, a multitarget search task should produce reward learning if reward guides selection among multiple targets. Yet, we observed no evidence of implicit reward learning in our task involving multiple targets, suggesting that while target competition may or may not be necessary for reward-guided attention, it is not always sufficient. In other words, spatial reward learning is associated with explicit awareness even when there are multiple targets, as has previously been observed under single-target conditions.

Role of Awareness in Spatial Reward Learning

The strong association between awareness and spatial reward learning distinguishes this type of learning from other forms of attentional guidance via implicit learning. In contextual cueing, participants are presented with a set of visual search displays that occasionally repeat (Chun & Jiang, 1998). Search RT becomes faster on repeated than nonrepeated displays. In location probability learning, the search target is presented disproportionately often in one region of space. Participants learn to more quickly find the target when it appears in the high-probability than low-probability regions (Geng & Behrmann, 2002; Jiang, Swallow, & Rosenbaum, 2013). Large-sample studies or meta-analytical studies have observed higher levels of explicit awareness than expected by chance in these paradigms (Jiang, Sha, & Sisk, 2018; Vadillo et al., 2016). This seems to suggest that awareness may accompany the attentional effects of contextual or location probability learning. Yet, the crucial measure for the role of awareness is the correlation between awareness and attentional biases. Annac et al. (2019) did observe a significant correlation, but when a larger sample size was used, there was no positive correlation between awareness and the magnitude of contextual cueing ($N > 700$; Colagiuri & Livesey, 2016), or between awareness and the magnitude of location probability learning ($N > 400$; Jiang et al., 2018). The explicit awareness test used by Annac et al. (2019) asked participants to choose a target location when given a previously searched array. This differs from the awareness test used in Colagiuri and Livesey (2016), which asked participants whether or not they had previously searched a given array. Though this may contribute to the difference in findings, there is no experimental evidence to suggest that the test used in Colagiuri and Livesey (2016) should be so insensitive to explicit awareness that an analysis of a sample of over 700 participants would fail to detect an existing correlation. Thus, although explicit awareness may accompany statistical learning, the attentional biases driven by those statistical regularities function more independently of the awareness of the regularities than spatial reward learning effects, which were larger in participants with higher levels of awareness across several experiments in the present study.

Our finding cannot be easily dismissed as an artifact of testing unmotivated participants. One might argue that participants who gained explicit awareness were more motivated to find the target with the highest reward than were participants who failed to gain explicit awareness, resulting in a lack of learning. However, this is a suboptimal explanation for our findings for several reasons. First, our analyses of RT data show that aware and unaware participants spend approximately the same amount of time on the search task, and they were equally accurate. Second, incidental learning in other paradigms is not so sensitive to motivation. Even when experimental manipulations of motivation via priming of goal pursuit do improve incidental learning, the effect is short-lived, and those without goal priming still show learning (Bourgeois et al., 2017). Third, as was observed in Lucas et al. (2013), in the postexperiment questionnaire, many of our unaware participants reported alternative strategies for identifying the high-reward target. These strategies included choosing the largest or the smallest target, choosing the target by color, or even choosing targets in alphabetical order. This demonstrates that the unaware participants were motivated to identify a strategy for finding the high-reward target but either committed to an incorrect strategy or failed to identify an effective strategy. Finally, the use of motivation as an explanation for the difference between aware and unaware participants does not actually influence our conclusion. We suggest that our evidence shows that in spatial reward learning paradigms, explicit awareness is associated with qualitative and quantitative changes in behavior and may be necessary for a bias to be observed. The argument that the difference between our aware and unaware participants is a difference of motivation simply provides an explanation for how our aware participants became aware. It does not negate the crucial, potentially causal, role of awareness in probabilistic spatial reward learning.

It could also be argued that learning progresses from implicit to explicit; experience with reward asymmetry leads first to implicit learning, then, with more experience, implicit learning gives way to explicit awareness (for a similar argument in scene-based contextual cueing, see Goujon, Didierjean, & Poulet, 2014). Because awareness is tested only at the end of the visual search task, some participants may have transitioned to explicit awareness, while others still remained in the implicit stage. This is empirically challenging to test—if awareness is probed earlier, it would alert participants to the reward-location contingency and alter the subsequent learning behavior. And because we did not experimentally manipulate explicit awareness, the data cannot directly determine the direction of causality—whether an implicit learned bias led to awareness or whether awareness led to the bias. Although the possibility that implicit learning preceded awareness is difficult to rule out, we have some evidence to challenge its validity. Unaware participants were given ample evidence to acquire implicit learning. The number of trials—336—is much higher than what is needed to establish other types of implicit learning, such as contextual cueing, location probability learning, and concurrent object discrimination learning. Yet, we found no evidence of learning in unaware participants. In contrast, for people who did have awareness, learning emerged rapidly and was significant even by the second block (see Figure 9). If implicit learning precedes awareness, we might expect our unaware participants to show behavior at the end of the experiment similar to our aware participants' behavior after the first two blocks of the experiment, but this was not the case. Therefore, there is no evidence of a progressive transition from weak implicit to strong explicit biases. However, future studies that probe awareness and measure spatial biases at earlier timepoints are needed to strengthen our conclusion. In addition, future studies that experimentally vary awareness by providing or withholding accurate or inaccurate information about the spatial reward structure are needed to clarify the direction of the causal relationship between awareness and spatial biases. Regardless of remaining uncertainties, the pattern of behavior observed in this paradigm distinguishes this kind of attentional learning from other forms of implicit experience-driven attention that are less dependent on explicit knowledge.

Automatic Influences of Reward in Other Paradigms

Although we find no evidence of implicit guidance based on the reward value of spatial locations, these findings do not suggest that reward cannot influence attention in general. Evidence of implicit guidance of attention based on the reward value of object features, such as color or shape, has been observed in several different paradigms. Le Pelley et al. (2015) found that task-irrelevant stimuli displayed in a color that signaled reward captured attention even in participants who could not correctly identify the association between that color and reward. Pearson, Donkin, Tran, Most, and Le Pelley (2015) also found that awareness did not affect value-driven oculomotor capture effects. An interesting finding was that in Pearson et al. (2015), making a saccade to the distractor with the reward-indicating color would result in omission of that reward, yet explicit awareness of this policy did not reduce the effect. It is possible that the absence of implicit attentional capture by reward-associated locations, despite the presence of implicit attentional capture by reward-associated colors, exists because color is typically a more stable predictor of reward than is location (Won & Leber, 2016). Regardless, this difference calls attention to potential mechanistic differences between spatial and featural attention that ought to be considered in future research. Overall, the literature on probabilistic reward learning contains much conflicting evidence, and a greater emphasis on replication is needed to elucidate the reliability of previously observed implicit effects of reward learning. Given our own replications of findings across experiments presented here, it appears that, within this spatial probabilistic reward learning paradigm, preferences toward locations associated with high reward are driven largely by explicit awareness of those associations.

Many attention researchers subscribe to the idea of an integrated priority map that guides attention (Awh et al., 2012; Todd & Manaligod, 2018). Stimulus salience and task goals both directly influence the priority of locations within the map and in doing so modulate the likelihood that an individual will attend to that location. It remains unclear whether experience with reward directly affects the priority of locations within the map or, rather, whether awareness of location-reward associations modulates attention via the existing goal-directed pathway (see Figure 10). The results here suggest that the latter better captures the mechanisms underlying attentional biases toward locations that are probabilistically associated with reward.

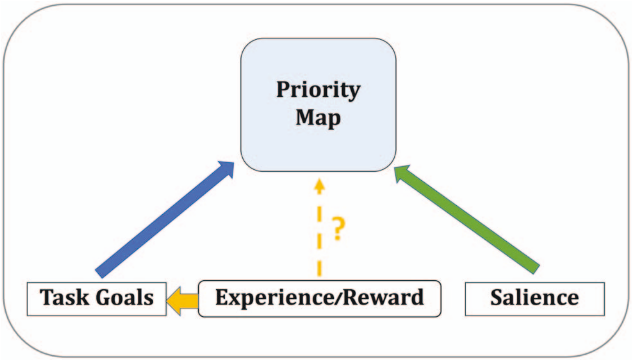

Figure 10. Visual schematic of a potential mechanism by which reward modulates attention. Our results suggest that reward strongly influences the allocation of attention by working through existing task goals when reward associations are explicitly known. Reward may also directly modulate the priority of locations within an integrated priority map, but these influences are weak compared with the influences of goal-directed control. See the online article for the color version of this figure.

Conclusion

Across several experiments, we observed consistent evidence of a close association between explicit awareness and reward-based spatial biases in a hybrid search and choice task. Regardless of search difficulty, participants displayed a bias toward locations associated with higher reward only when they were able to explicitly identify the asymmetric distribution of reward. While the lack of implicit guidance of spatial attention by reward in our paradigm is in line with many previous findings, target frequency and even reward-feature associations have been shown to induce implicit biases in the past. These apparent discrepancies come about because of the complex interaction between different, sometimes competing influences on attentional allocation. Spatial attention is guided by multiple factors, including task goals, stimulus salience, and previous experience (Awh et al., 2012; Theeuwes, 2018). Although recent years have brought an appreciation for these selection history effects in general, our findings underline the importance of recognizing the strength of top-down, explicit guidance of attention. Our study is but one example in which reward-driven selection history effects are shown to be distinct from other forms of selection history effects in terms of their association with explicit, goal-driven attention. Although it is possible that implicit reward learning can guide attention, the effects of goal-directed attention in probabilistic reward learning tasks are much stronger and drive the majority of observed biases toward reward-associated locations. Future research must delve further, both into the conditions under which implicit learning of reward can support spatial attention and into the mechanisms that drive this and other forms of attentional learning.

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Received February 8, 2019
Revision received June 13, 2019
Accepted June 15, 2019 ■