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BRIEF REPORT

Reward history alters priority map based on spatial relationship, but not absolute location

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Abstract

Attention is rapidly directed to stimuli associated with rewards in past experience, independent of current task goals and physical salience of stimuli. However, despite the robust attentional priority given to reward-associated features, studies often indicate negligible priority toward previously rewarded locations. Here, we propose a relational account of value-driven attention, a mechanism that relies on spatial relationship between items to achieve value-guided selections. In three experiments ($N = 124$), participants were trained to associate specific locations with rewards (e.g., high-reward: top-left; low-reward: top-right). They then performed an orientation-discrimination task where the target's absolute location (top-left or top-right) or spatial relationship ("left of" or "right of") had previously predicted reward. Performance was superior when the target's spatial relationship matched high-reward than low-reward, irrespective of absolute locations. Conversely, the impact of reward was absent when the target matched the absolute location but not the spatial relationship associated with high reward. Our findings challenge the default assumption of location specificity in value-driven attention, demonstrating a generalizable mechanism that humans adopted to integrate value and spatial information into priority maps for adaptive behavior.

Keywords Attention · Reward · Spatial relationship · Spatial priority map

Introduction

When processing visual scenes, the brain generates spatial priority maps to allocate cognitive resources across visual fields (Fecteau & Munoz, 2006). Encountering a breathtaking view during a hike may prompt future visits to the same spot due to the positive association formed with that location. The delivery of rewards at specific locations prompts the brain to modify spatial maps in animals (Butler et al., 2019; Sosa & Giocomo, 2021). This same process may also contribute to addictive behaviors—for example, exposure to spatial contexts associated with past addictive experiences can trigger substance-seeking behaviors (Xue et al., 2012). Despite the critical role of selective attention in the acquisition of spatial information (Van der Ham et al., 2014), much less is known about how humans modify the spatial priority map to guide attention toward reward-associated locations.

Integrating reward experience into spatial priority maps is crucial for survival. However, previous studies have often reported negligible influences of reward on location-specific attention. For instance, in experiments where one quadrant of space was associated with larger monetary rewards than

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other quadrants, spatial priority was not assigned to the high-value quadrant when the target appeared equally across different quadrants (Jiang et al., 2015; Won & Leber, 2016). Other studies have shown immediate reward effects on spatial locations when the reward from the previous trial primed attention to a specific location (Hickey et al., 2014), or when participants were explicitly informed of the location–reward structure (Mine et al., 2021; Sisk et al., 2020). These prior findings suggest that the influence of reward learning on location-specific attention may be either absent, short-lived, or awareness-dependent.

While previous studies have largely assumed that the effect of reward on the spatial priority map should be location specific, in everyday life, the relative position between objects are often more critical. For example, the representation of spatial relations between entities in the environment is necessary for efficient route planning beyond mere pointing (Epstein et al., 2017). Object recognition depends on knowledge of the spatial relations between object parts (Cave & Kosslyn, 1993). Coding spatial relations not only diminishes the necessity for precise encoding of spatial information but also offers advantages for generalizing learned spatial information to new environments (Behrens et al., 2018). Therefore, it is plausible that reward may modify spatial priority maps by enhancing the representation of spatial relations between items rather than altering the representation of exact locations in physical space. This hypothesis aligns with prior demonstrations of value-driven spatial biases under certain circumstances, such as in scenarios involving two targets at a high-value and a low-value location in opposite hemifields (Chelazzi et al., 2014), or when the locations were specified in a visual scene containing a meaningful spatial arrangement of objects (e.g., a picture is to the left of the window; Anderson & Kim, 2018). Support for this hypothesis could help resolve disagreements about whether reward learning can modulate a spatial priority map. In addition, testing this relational account could reveal the generalization rule for applying learned reward contingencies to new environments.

To test whether reward learning modifies spatial priority maps based on absolute locations or spatial relationships between items, we first trained participants to learn the location–reward association (e.g., high reward: top-left; low reward: top-right). Then, we used a cued orientation-discrimination task to test performance under conditions in which either the target's absolute location (e.g., top-left or top-right) and/or its spatial relation to another item ("left of" or "right of") matched what was previously predictive of high reward. If the location-specific account holds for value-driven attention, we would expect superior performance when the target appeared at a previously highly rewarded location compared with a location associated with lesser reward. Alternatively, if the relational account holds true, superior performance would be expected when the target's spatial relationship matched high reward compared with low reward, regardless of the absolute locations (Fig. 1). Across three experiments, we show that reward

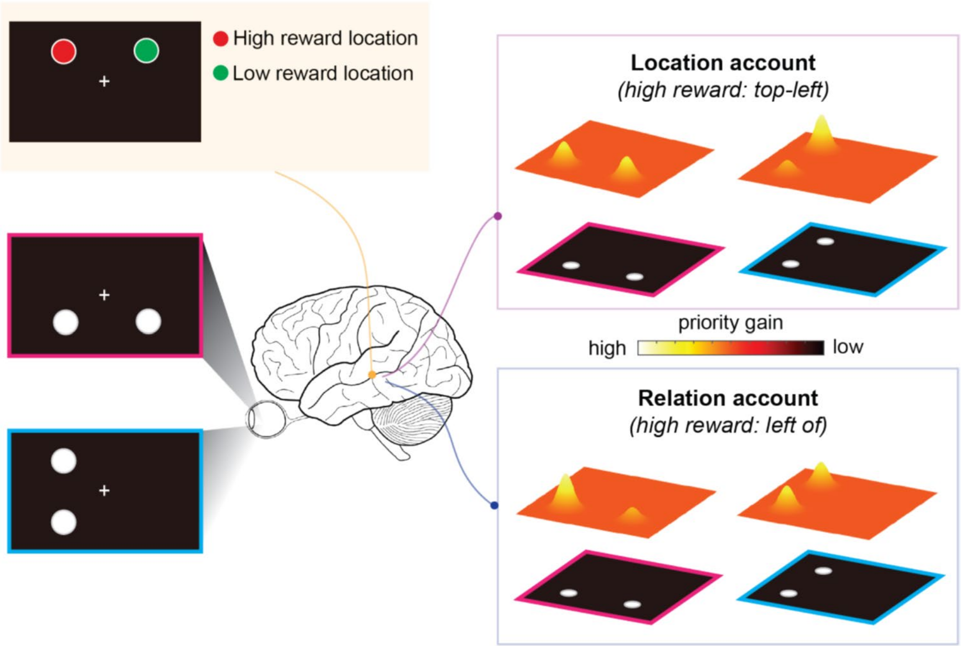

Fig. 1 Possible mechanisms underlying value-driven spatial attention

history enhanced performance when the target's spatial relationship to another item had been previously predictive of high reward, irrespective of the absolute locations of the stimuli.

This example illustrates a location–reward association, where a top-left location is associated with high reward and a top-right location is associated with low reward. According to the location account, priority is given to location matched reward history in absolute location (i.e., top-left location in the cyan boxed display). According to the relation account, priority is given to location matched reward history in spatial relationship (i.e., bottom-left location in the pink boxed display). (Color figure online).

Experiment 1

Experiment 1 aimed to examine whether attention is biased toward items that matched high reward based on absolute location or spatial relationship. To test consistency across visual fields, we trained participants in Experiment 1a to associate rewards with two locations in the upper visual field and in Experiment 1b with two locations in the lower visual field.

Method

Participants

To determine the sample size, we ran a pilot experiment with 16 participants using a similar design. We entered the estimated effect size of reward history on the trained locations ($d = 0.68$) into a simulated paired t test using G*Power (Version 3.1; Faul et al., 2007). A sample size of 30 would provide power greater than 95% ($\alpha = 0.05$) for detecting an effect of reward.

Thirty-two students (mean age = 20.84 years; 17 women and 15 men) participated in Experiment 1a. Two participants were excluded for mean response time (RT) or accuracy exceeding three standard deviations of the mean across participants. A new group of 30 students (mean age = 20.87 years; 24 women and 6 men) participated in Experiment 1b. Participants provided written informed consent approved by the Institutional Review Board (2023–007). All participants had normal or corrected-to-normal vision and were right-handed. They were paid for their participation; a portion of this payment was based on their reward-based training performance.

Stimuli and apparatus

The stimuli were oriented Gabor patches (diameter: 2°; spatial frequency: 4 cycles per degree; contrast: 8%). All stimuli were generated using Psychtoolbox (Brainard, 1997) implemented in MATLAB Version 2020b (The MathWorks, Natick, MA, USA). Stimuli were presented against a gray background (5 cd/m^2) on a 22-inch LCD monitor (resolution: 1,920 × 1,080, refresh rate: 100 Hz). Participants were tested in a dimly lit room at a viewing distance of 60 cm with a chin rest.

Experimental procedure and tasks

Participants completed a training session and a test session on two consecutive days. Using a visual search task (Fig. 2A), we first trained participants to establish the location–reward association. Then, we used a cued orientation discrimination task to test the effect of reward (Fig. 2B).

Training session

Each trial began with a cue display for 0.4–0.6 s. The cue display comprised two circles (diameter: 2°) on both sides at an eccentricity of 5° above (Experiment 1a) or below (Experiment 1b) the fixation cross against a gray background. Then, a search display showed a diagonal-oriented Gabor (left or right) and a cardinal-oriented Gabor (horizontal or vertical) within the circles for 0.5 s. Participants were asked to search for a diagonal orientation and indicate its orientation within 1.5 s. Correct responses were followed by monetary feedback shown inside the target circle for 1.5 s. Incorrect responses were followed by a blank screen. For half of the participants, the left location was associated with a high probability (80%) of a high reward (10 points) and a low probability (20%) of a low reward (1 point), while the right location was associated with a high probability (80%) of a low reward (1 point) and a low probability (20%) of a high reward (10 points). For the other half of the participants, the location–reward association was reversed. Participants were not informed about this association and aimed to maximize earnings. In a few trials (three trials per block), participants were required to indicate the reward amount using a numeric keypad (1 for 1 point, 2 for 10 points) during the intertrial interval, ensuring they recognized the rewards during the feedback display. Recognition rate was high across participants (93.8%). Each participant completed eight blocks (100 trials/block), with target orientation and locations equally probable and randomly interleaved across trials.

Test session

Each trial consisted of a cue display for 0.4–0.6 s, presenting one or two circles (diameter: 2°) at an eccentricity of 5° above or below the fixation. In double-cue trials (60% of trials), two circles appeared at four equally probable pairs of locations, followed by the sample arrays

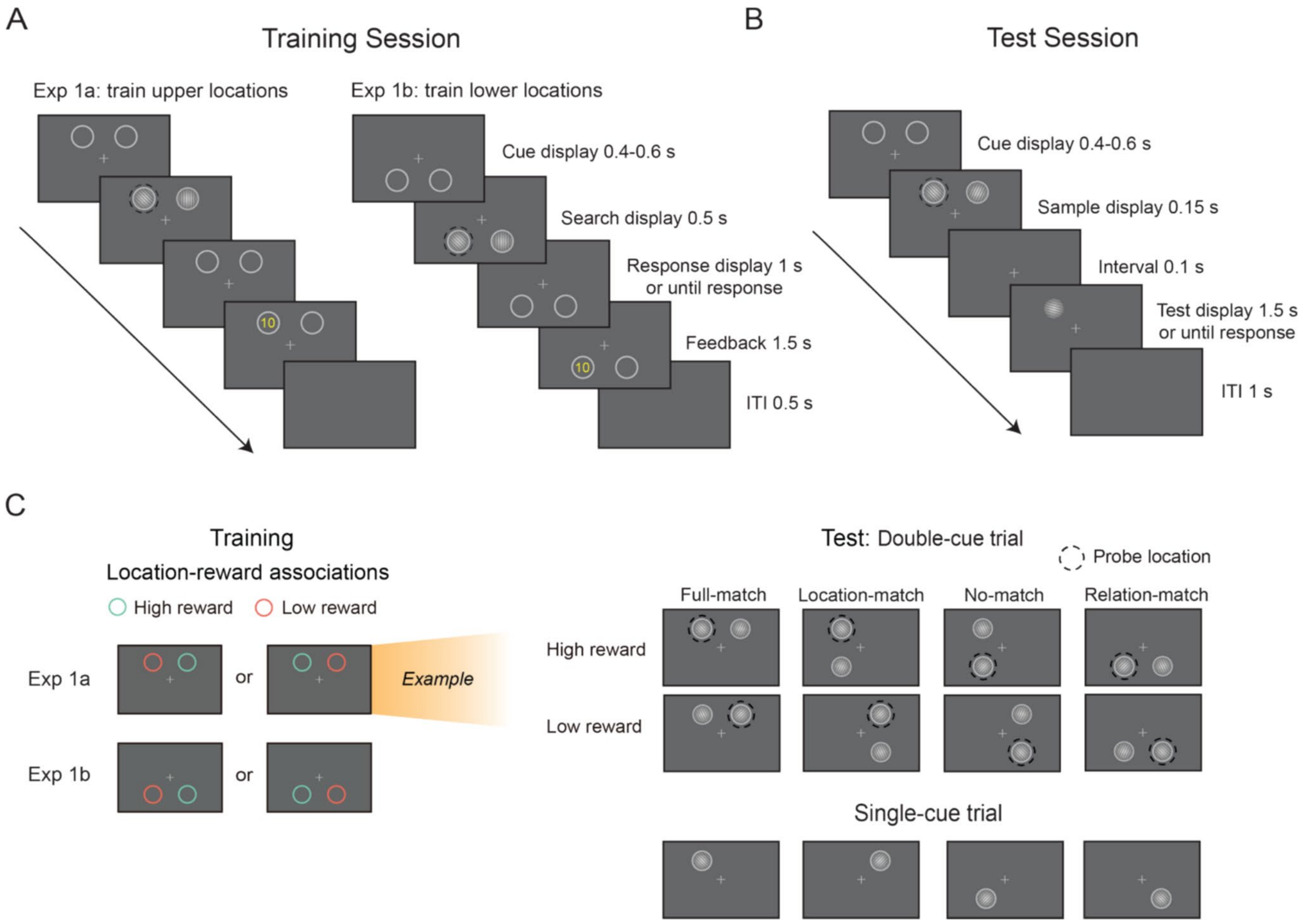

Fig. 2 Tasks and designs for Experiment 1. **A** Trial sequence of the visual search task in the training session of Experiment 1a and 1b. The task was to report the diagonally oriented Gabor target (left or right), presenting at one of the two possible locations (Experiment 1a: top-left or top-right; Experiment 1b: bottom-left or bottom-right). A correct response was followed by a high (10 points) or low reward (1 point). **B** Trial sequence of the cued orientation discrimination task in the test session. Participants were asked to report whether the test Gabor was oriented more clockwise or counterclockwise to the sample Gabor at the same location. **C** Designs of the training protocol (left panel) and experimental conditions in the test task (right panel). During training, participants were randomly assigned to one of the four location–reward associations. In Experiment 1a, half learned to associate the top-left with high reward and top-right with low reward, while the other half learned the reverse. In Experiment 1b, half associated the bottom-left with high reward and bottom-right with low reward, while the other half learned the reverse. During the test, the experimental conditions were labeled based on the probed target location (as indicated by the dashed circles) and its association with reward history. For example, consider one location–reward association (e.g., top-left: high reward; top-right: low reward), the first row shows the high-reward target across four match types, while the second row shows the low-reward target across the same four match types. These dashed circles were not shown in actual displays. (Color figure online)

comprising two randomly oriented Gabor patches within the circles for 0.15 s. After a short interval of 0.1 s, a test Gabor appeared at one of the cued locations. Participants discriminated whether the test Gabor was oriented more clockwise or counterclockwise to the sample Gabor at the same location, with angular offsets of 5°, 10° and 15°. Trials were categorized into four conditions, according to the target location and its relative location to another cued stimulus (Fig. 2C): (1) full-match condition: the target locations matched reward history in both absolute location and spatial relation (e.g., target at top-left is located *to the left* of another stimulus at top-right); (2) location-match condition: the target location matched reward history only in absolute location (e.g., target at top-left is located *above* another stimulus at bottom-left); (3) relation-match condition: the target location matched reward history only in spatial relation (e.g., target at bottom-left is located *to the left* of another stimulus at bottom-right); (4) no-match condition: the target location matched reward history neither in absolute location nor spatial relation (e.g., target at bottom-left and is located *below* another stimulus at top-left). Note that the no-match condition is similar to the location-match condition with one key difference: in the location-match condition, reward history was linked to the probed target location, whereas in the no-match condition, reward history was associated with the distractor location (nonprobed location in the cue display). As a complementary approach to examine the effect of reward history on individual locations, we included single-cue trials (40% of trials) with the same trial sequence but only one circle appearing equally probable at four locations. No feedback was provided in the test session. Each participant completed six blocks (160 trials/block), with all trial types randomly interleaved.

Data analysis

For each participant, trials with reaction times (RTs) outside the specified response window (0.2–1.5 s) or exceeding three standard deviations away from each individual's mean were excluded. RTs from incorrect trials were also excluded from further analyses. To evaluate the training performance, we used paired *t* test to compare participants' performance (accuracy and RT) between high- and low-reward conditions. To assess the effect of reward history on test session, our primary focus was on accuracy that reflects the perceptual sensitivity in the orientation-discrimination task. We also reported analysis on RT to address any potential concerns regarding the speed–accuracy trade-off.

To evaluate the strength of evidence for the lack of significant effects, we conducted parallel Bayesian analyses (Wagenmakers, 2007) using standard priors as implemented in JASP (Version 0.17.1; JASP Team, 2023). To examine the location-specific effect of reward, we performed Bayesian paired *t* tests to compare between high-reward and low-reward conditions. To examine whether the effects of reward were comparable between full-match and relation-match conditions, we performed Bayesian repeated-measures analysis of variance (ANOVA). Specifically, we specified the factors of reward history and match type (full-match vs. relation-match) was nuisance variables and constructed two models: a null model and an interaction model. The null model contained subject-related effects and the main effects of reward history and match type; whereas the interaction model contained all factors of the null model, plus an interaction term. We reported Bayes factors (BF_{01}) to quantify the evidence in favor of the null effect (or lack of interaction) if it was greater than 3.

Results

Because the results in Experiment 1a and 1b were qualitatively similar (see Supplementary Information and Fig. S1 and S2), data of Experiment 1a ($n = 30$) and 1b ($n = 30$) were pooled in the analysis. During the training session, we found significantly faster RTs for high-reward compared to low-reward condition, 497 ms vs. 515 ms: $t(59) = -3.04$, $p = 0.003$, Cohen's $d = -0.39$, 95% CI [−0.65, −0.13], but not on accuracy, 96.2% vs. 95.9%: $t(59) = 0.76$, $p = 0.451$, Cohen's $d = 0.10$, 95% CI [−0.16, 0.35], suggesting that reward facilitated the search performance.

During the test session, we analyzed the discrimination accuracy in double-cue trials (Fig. 3A). In the full-match condition, a paired *t* test on accuracy showed superior performance when the target appeared at a previously high-reward location compared to a low-reward location, $t(59) = 4.85$, $p < 0.001$, Cohen's $d = 0.63$, 95% CI [0.35, 0.90], suggesting that reward history modulated spatial attention when the target matched reward history in both absolute and relative locations. This result confirmed the acquisition of location–reward contingency, allowing us to examine the separate contributions of relative and absolute locations.

To examine whether the relational account holds for observed reward effect, we analyzed performance in the relation-match condition, where the target locations were untrained and matched reward history only in spatial relation. A paired *t* test on accuracy showed significantly superior performance for targets with a spatial relationship associated with high reward compared with low reward, $t(59) = 3.92$, $p < 0.001$, Cohen's $d = 0.51$, 95% CI [0.24, 0.77]. Further, a two-way repeated-measures ANOVA (2 reward history × 2 match type) on data from full-match and relation-match conditions revealed no interaction effect, $F(1,59) = 1.54$, $p = 0.220$, $\eta_p^2 = 0.03$, as further supported by Bayesian analysis favoring the null model over the interaction model ($BF_{01} = 2.57$). This result showed a transfer of reward effect from the trained to untrained locations, indicating that value-driven spatial bias is not location-specific but rather influenced by the relative positions between items.

To examine whether the location-specific account holds for observed reward effect, we analyzed performance in the location-match condition. Paired *t* tests on accuracy revealed no significant differences between high-reward and low-reward conditions, $t(59) = 0.26$, $p = 0.796$, Cohen's $d = 0.03$, 95% CI [−0.22, 0.29]. Although the probed location in the no-match condition was not directly linked to reward history, one might expect stronger distractions from the other nonprobed, reward-associated location in this condition. However, no such effect was observed in the no-match condition, $t(59) = -1.39$, $p = 0.169$, Cohen's $d = -0.18$, 95% CI [−0.43, 0.08]. A parallel Bayesian analysis provided evidence for the absence of a reward effect (location-match: $BF_{01} = 6.85$; no-match: $BF_{01} = 2.83$), consistent with previous studies indicating the lack of location-specific reward modulations (Jiang et al., 2015; Won & Leber, 2016). To investigate whether the results in the location-match condition

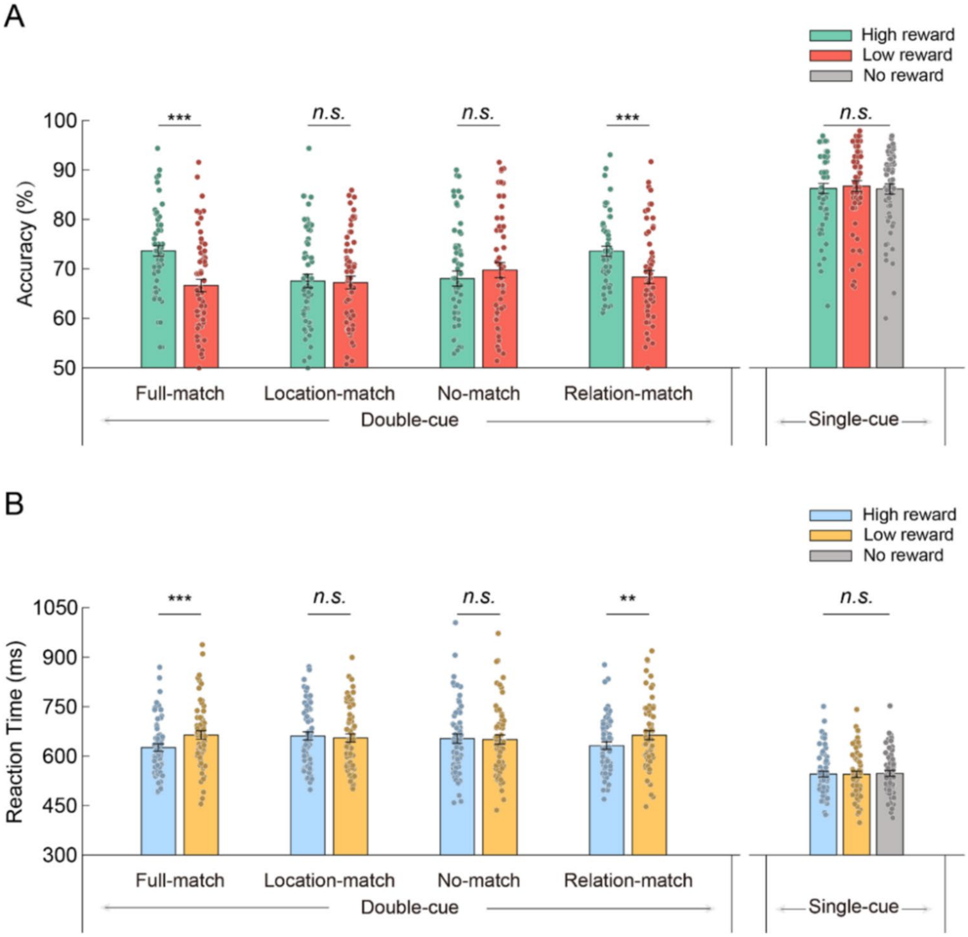

Fig. 3 Results of Experiment 1. **A** Discrimination accuracy during the test task of Experiment 1 ($n = 60$). **B** RTs during the test task of Experiment 1 ($n = 60$). Each dot represents data from one participant. Error bars reflect standard errors of the mean. $^{***}p < 0.001$, $^{**}p < 0.01$. *n.s.* = not significant. (Color figure online)

differed significantly from the full-match and relation-match conditions, we conducted a 3 (match type: full-match, location-match, relation-match) × 2 reward history (high vs. low reward) ANOVA and found a significant interaction effect, $F(2,118) = 8.94$, $p < 0.001$, $\eta_p^2 = 0.13$. The no-match condition was excluded because the probed target location was not linked to reward history.

As a complementary approach to examine location-specific reward effects, we analyzed single-cue trials, where the trial sequence remained unchanged, but only one circle appeared in the cue display. A repeated-measures ANOVA (reward history: high, low vs. no-reward location) on accuracy revealed no significant main effect, $F(2,118) = 0.55$, $p = 0.580$, $\eta_p^2 = 0.01$; $BF_{01} = 10.91$. To test whether reward conferred an advantage to the high-rewarded side in the no-reward condition, we compared high- and low-rewarded sides within this no-reward condition and found no significant difference ($p = 0.770$; $BF_{01} = 6.79$). These results suggest little influence of reward on specific locations.

To examine whether the observed impact of reward history on accuracy reflects a speed–accuracy trade-off, such as improved accuracy due to slowed response, we analyzed RTs from the double-cue trials in the test task (Fig. 3B). Paired *t* tests showed faster response when the target appeared at a high-reward compared with a low-reward location in full-match condition, $t(59) = -4.35$, $p < 0.001$, Cohen's $d = -0.56$, 95% CI $[-0.83, -0.29]$, and relation-match condition, $t(59) = -3.08$, $p = 0.003$, Cohen's $d = -0.40$, 95% CI $[-0.66, -0.13]$. No reward effects were found in location-match and no-match conditions (p values > 0.243; $BF_{01} > 3.67$). These results suggest facilitated response when the target location was relationally matched to high reward, ruling out the alternative account of speed–accuracy trade-offs. Additionally, analysis of RTs in the single-cue trials showed no evidence of reward history on specific locations (repeated-measures ANOVA: $p = 0.551$; $BF_{01} = 11.05$), nor any advantage for high-reward sides over low-reward sides in the no-reward conditions ($p = 0.363$; $BF_{01} = 4.74$).

Experiment 2

To test the generality of the reward effect on spatial relationships beyond horizontal locations (left vs. right), we trained participants in Experiment 2 to associate reward with vertical locations (upper vs. lower).

Method

Participants

Thirty-two students (mean age = 20.56 years; 24 women and 8 men) participated in this experiment. The slight variation in sample size was determined to balance four sets of location–reward associations across different visual fields (Fig. 4A). Participants provided written informed consent approved by the Institutional Review Board (2023–007). All participants had normal or corrected-to-normal vision, were right-handed, and received payment for their participation.

Stimuli, apparatus and procedure

The stimuli, apparatus and designs were largely the same as Experiment 1 (Fig. 4A), with two exceptions. First, we trained two locations along the vertical dimension. Second, to minimize the possibility that changes in retinotopic locations contributed to the reward effect in the relation-match condition (i.e., gaze shifting to intermediate locations between the two stimuli), we used an Eyelink Portable Duo system (SR Research, Ontario, Canada) to evaluate the stability of fixation during test sessions, at a sampling rate of 1000 Hz from a distance of 60 cm. The data were analyzed offline using custom MATLAB code (see Supplementary Information for detailed descriptions).

Results

During training, paired *t* tests revealed no significant difference between the target appearing at high-reward and low-reward locations (accuracy: 95.6% vs. 94.9%: $p = 0.359$; RT: 487 ms vs. 497 ms: $p = 0.124$). The variability in reward effects may be attributed to near-ceiling performance in the training tasks, limiting sensitivity to detect the reward effects, as reported in previous studies (Anderson, 2015; Gong & Liu, 2018; Gong et al., 2017).

The patterns of test performance were qualitatively similar to those reported in Experiment 1 (Fig. 4B). In the double-cue trials, planned paired *t* tests showed significant reward effects in the full-match, $t(31) = 2.43$, $p = 0.021$, Cohen's $d = 0.43$, 95% CI [0.06, 0.79], and relation-match, $t(31) = 2.60$, $p = 0.014$, Cohen's $d = 0.46$, 95% CI [0.09, 0.82], conditions. A two-way repeated-measures ANOVA (2 reward history × 2 match type) revealed no interaction effect, $F(1,31) < 0.001$, $p = 0.996$, $\eta_p^2 < 0.001$; $BF_{01} = 3.36$. Analysis of RTs ruled out speed–accuracy trade-offs as an explanation for reward effects on accuracy (*p* values > 0.078; Fig. 4C). Gaze position remained stable at fixation (mean gaze deviation = 0.25°) during the test task, with no significant difference between reward conditions (*p* values > 0.399; Fig. S3), ruling out retinotopic changes as an influence on the reward effect. To examine whether the reward effect was comparable between Experiments 1 and 2, we performed a three-way repeated-measures ANOVA (2 reward history × 2 match type × 2 experiment), which showed neither a significant Experiment × Reward History interaction nor a three-way interaction (*p* values > 0.508, $BF_{01} > 3.18$). These results support the generality of the reward effect on spatial relationships, independent of specific spatial dimensions.

Again, the results showed no evidence of location-specific reward modulation. Specifically, we found no significant reward effects in either location-match (accuracy: $p = 0.634$, $BF_{01} = 4.76$; RT: $p = 0.340$, $BF_{01} = 3.44$) or no-match conditions (accuracy: $p = 0.799$, $BF_{01} = 5.14$; RT: $p = 0.318$, $BF_{01} = 3.30$). Although a comparison of reward effects across match types (full-match, location-match, relation-match) revealed no significant interaction effect on accuracy (3 match type × 2 reward history ANOVA): $F(2,62) = 2.56$, $p = 0.086$, $\eta_p^2 = 0.03$, Bayesian analyses slightly favors the alternative hypothesis over the null effect ($BF_{01} = 0.90$). The no-match condition was excluded because the probed locations were not linked to reward history. Data from single-cue trials showed no effects of reward on specific location (accuracy: one-way ANOVA: $p = 0.782$, $BF_{01} = 8.75$; RT: $p = 0.365$, $BF_{01} = 4.75$), nor any advantage for highly-rewarded sides in the no-reward condition (accuracy: $p = 0.253$, $BF_{01} = 2.85$; RT: $p = 0.500$, $BF_{01} = 4.27$).

Experiment 3

Experiment 3 aimed to examine the scenario where the spatial relationship associated with reward contradicts the absolute locations associated with reward (i.e., a location matched with high-reward spatial relation was previously a low-reward location).

Method

Participants

Thirty-two students (mean age = 21.5 years; 23 women and 9 men) participated in this experiment. A slight adjustment to the sample size was made to balance four sets

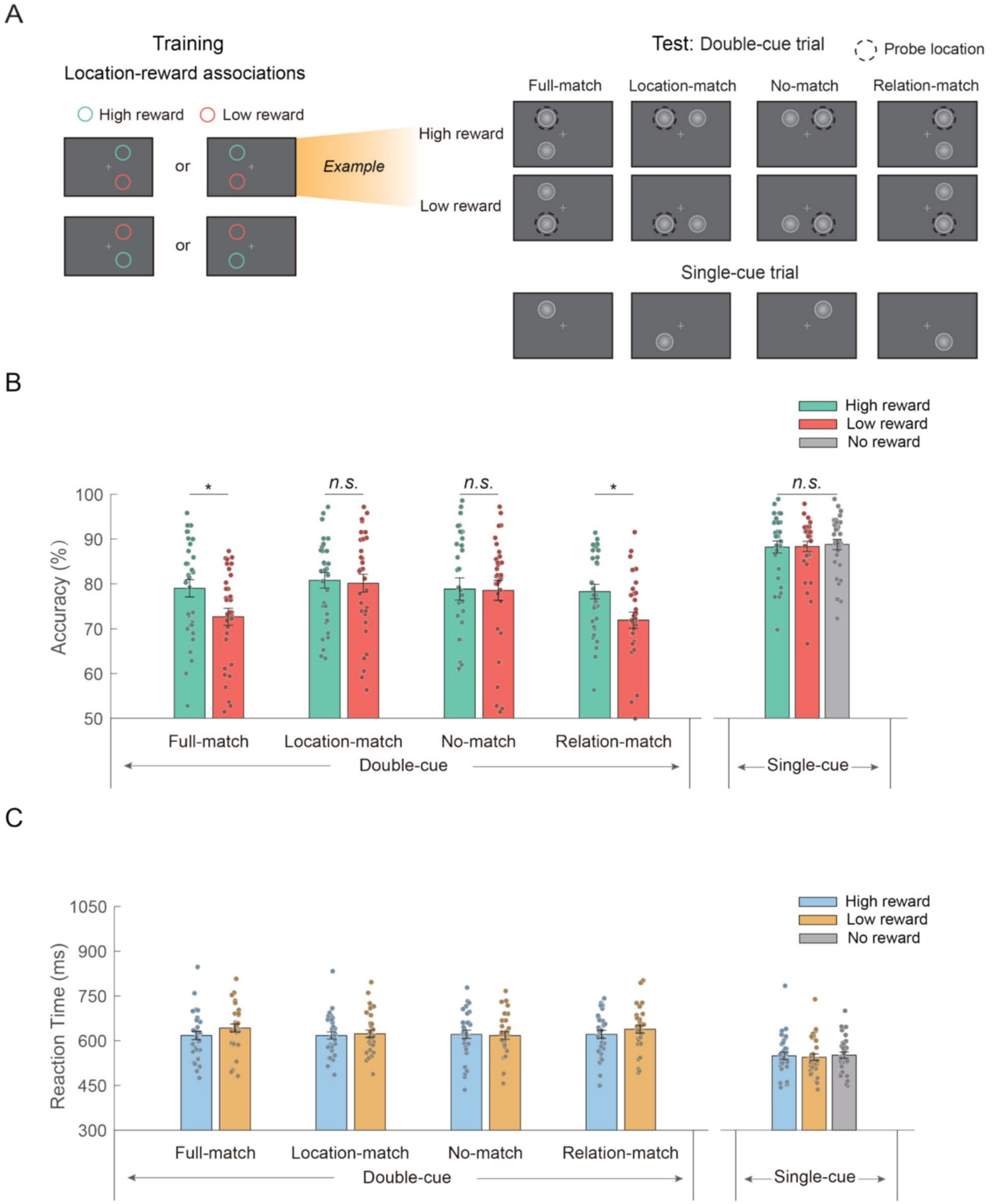

Fig. 4 Tasks and Results of Experiment 2. **A** Designs of the training protocol (left panel) and experimental conditions in the test task (right panel). Participants were randomly assigned to one of the four location–reward associations during training. During the test, the experimental conditions were labeled based on the probed target location (as indicated by the dashed circles) and its association with reward history. For example, consider one location–reward association (e.g., top-left: high reward; bottom-left: low reward), the first row shows the high-reward target across four match types, while the second row shows the low-reward target across the same four match types. These dashed circles were not shown in actual displays. **B** Discrimination accuracy during the test task of Experiment 2 ($n = 32$). **C** RTs during the test task of Experiment 2 ($n = 32$). Each dot represents data from one participant. Error bars reflect standard errors of the mean. $^*p < 0.05$. *n.s.* = not significant. (Color figure online)

of location–reward associations in different visual fields. Participants provided written informed consent approved by the Institutional Review Board (2023–007). All participants had normal or corrected-to-normal vision, were right-handed, and received payment for their participation.

Stimuli, apparatus, and procedure

The stimuli, apparatus and procedure were largely the same as Experiment 1 (Fig. 5A), except for the arrangement of double-cue trials. As shown in Fig. 5B, trials were classified into three conditions according to the target location: (1) full-match condition (see Experiment 1 for definition); (2) relation-match/location-opposite condition: the target location matched low-reward history but had opposite spatial relations with respect to what was highly rewarded (e.g., target at the *top-right near location* was previously a low-reward location but was positioned to the *left of* another stimulus, resulting in a high-reward spatial relationship); (3) relation-match condition: the target at a far location that matched reward history in spatial relations. Each participant completed six blocks (108 trials/block) with all trial types randomly interleaved. Gaze positions were recorded using an Eyelink Portable Duo system to evaluate the stability of fixation during test sessions. The analysis of gaze position showed stable fixation during the test session (mean gaze deviation = 0.27°), with no significant difference observed between reward conditions (Fig. S4).

Results

During training session, paired *t* tests revealed no significant difference between the target appearing at high-reward and low-reward locations (accuracy: 95.8% vs. 95.6%, $p = 0.795$; RT: 506 ms vs. 515 ms, $p = 0.259$).

During the test session (Fig. 5C), we found higher accuracy when the target appeared at a previously high-reward location than at a low-reward location in the full-match condition, $t(31) = 3.13$, $p = 0.004$, Cohen's $d = 0.55$, 95% CI [0.18, 0.92]. A similar effect of reward was found in the relation-match condition, $t(31) = 3.25$, $p = 0.003$, Cohen's $d = 0.57$, 95% CI [0.20, 0.95], suggesting that the effect of reward could transfer to untrained locations farther from the fixation. Importantly, when the spatial relationship associated with reward contradicted with the absolute locations associated with reward in the relation-match/location-opposite condition, we still observed superior performance for locations matching high-reward spatial relations, $t(31) = 2.64$, $p = 0.013$, Cohen's $d = 0.47$, 95% CI [0.10, 0.83]. This result suggests that the effect of reward history on spatial attention primarily relies on the spatial relationships between items. To compare the magnitudes of reward across match types, we conducted a two-way repeated-measures ANOVA (2 reward history × 3 match type) on accuracy. The analysis revealed a main effect of reward history, $F(1,31) = 16.30$, $p < 0.001$, $\eta_p^2 = 0.35$, without a significant interaction effect, $F(2,62) = 1.94$, $p = 0.152$, $\eta_p^2 = 0.06$, although Bayesian analysis provided only anecdotal evidence for the lack of interaction ($BF_{01} = 1.88$). In addition, we observed a main effect of match type, $F(2,62) = 175.32$, $p < 0.001$, $\eta_p^2 = 0.85$, indicating better performance in full-match and relation-match/location-opposite conditions compared with relation-match conditions (p values < 0.001). This result is expected, as visual sensitivity decreases with increasing eccentricity in relation-match conditions. It also explains why direct comparisons between near and far target locations within the same display were unfeasible in both the relation-match/location-opposite condition and relation-match conditions.

To address any potential concerns regarding the speed–accuracy trade-off, we applied the same analysis on RTs (Fig. 5D). A two-way repeated-measures ANOVA (2 reward history × 3 match type) showed the main effect of reward history, $F(1,31) = 4.67$, $p = 0.039$, $\eta_p^2 = 0.13$, suggesting faster response for locations matching high-reward spatial relations than low-reward spatial relations. No significant interaction effect was observed ($p = 0.289$; $BF_{01} = 3.58$). In addition, we observed a main effect of match type, $F(2,62) = 96.35$, $p < 0.001$, $\eta_p^2 = 0.76$, indicating slower response to far locations in the relation-match conditions compared to responses to near locations in the full-match and relation-match/location-opposite conditions (p values < 0.001).

Discussion

Our findings reveal a novel mechanism by which reward history shapes the spatial priority map based on spatial relationships (e.g., "left of" or "right of"), rather than based on absolute locations (e.g., top-left or top-right). Across three experiments, we observed superior discrimination performance when the target location matched previously high-reward locations in spatial relationship, even for untrained locations (Experiments 1 and 2) or when contradicting absolute reward locations (a previously low-reward location now linked to a high-reward spatial relationship; Experiment 3). In contrast, reward history had minimal influence on absolute locations, as shown by the lack of performance differences between high-reward and low-reward locations when their relative positions were unrelated to reward history, or when only one location was presented. These results support our proposed mechanism that reward history modulates the priority map based on spatial relationships. This challenges the prevailing assumption of location specificity in value-driven attention and advances the debate on whether reward

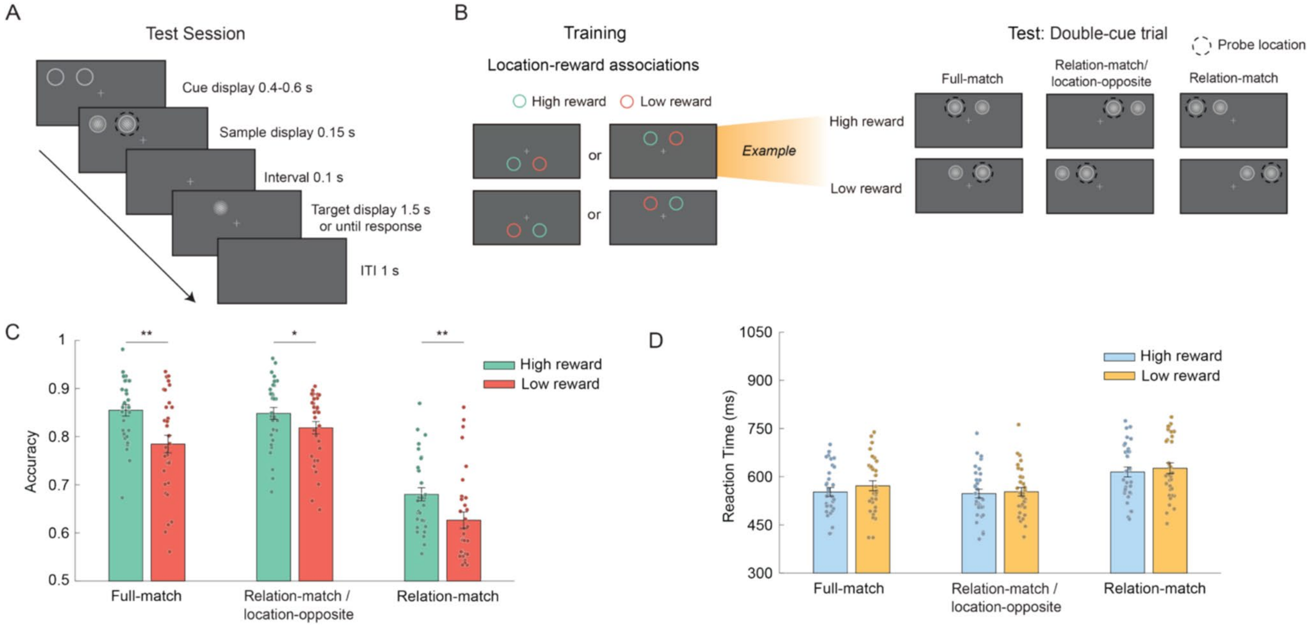

Fig. 5 Test task and results of Experiment 3. **A** Trial sequence of the orientation discrimination task in the test session. **B** Designs of the training protocol (left panel) and experimental conditions in the test task (right panel). Participants were randomly assigned to one of the four location–reward associations during training. During the test, the experimental conditions were labeled based on the probed target location (as indicated by the dashed circles) and its association with reward history. For example, consider one location–reward association (e.g., top-left at near location: high reward; top-right at near location: low reward), the first row shows the high-reward target across three match types, while the second row shows the low-reward target across the same three match types. Note that in the relation-match/location-opposite condition, the probed target location in the first row indicates a previously low-reward location (*top-right at near location*) that has a high-reward spatial relationship (*left of another stimulus*). In contrast, the probed target location in the second row indicates a previously high-reward location (*top-left at near location*) that matched a low-reward spatial relationship (*right of another stimulus*). The dashed circles were not shown in actual displays. **C** Discrimination accuracy during the test task ($n = 32$). **D** Reaction time during the test task ($n = 32$). Each dot represents data from one participant. Error bars reflect standard errors of the mean. $*p < 0.05$, $**p < 0.01$. (Color figure online)

history influences location-based attention (Chelazzi et al., 2014; Jiang et al., 2015; Won & Leber, 2016).

Our findings extend previous research implicating the impact of reward on spatial relationship. A prior study demonstrated a spatial bias toward high-value quadrant in real-world scenes, likely tied to object-based spatial relationships (Anderson & Kim, 2018). However, this location-specific effect was attributed to reinforced responses during training (i.e., the high-valued location was selected more frequently than the low-valued location), and/or object-based attentional bias (i.e., an object associated with a specific quadrant in a scene; Anderson & Kim, 2018). Here, we provide direct evidence for reward modulations based on spatial relationship between items, while equalizing selection frequency and stimulus identity. In another study (Chelazzi et al., 2014), reward history influenced location-specific attention only when two targets were presented simultaneously at high- and low-value locations, not in single-target cases. These results were attributed to cross-target competition, but could also be explained by a relational account, as high-value and low-value locations were positioned in opposite hemifields, resembling our full-match condition. However, our findings from the location-match and no-match conditions suggest that a pure competition account may not sufficiently explain our results. It remains unclear whether the reward effect on spatial relationships was influenced by selection competition during training. Future studies should eliminate competition during training (i.e., by presenting one item at a time) to isolate the role of absolute locations and further examine how reward modulates spatial attention.

The absence of reward effects on specific locations in our study appears to contradict prior findings of location-specific effects driven by statistical learning. This discrepancy likely arises from difference in the task relevance of location-specific information during training. Statistical learning enhanced attention to high-probability target locations (Chun & Jiang, 1998; Jiang et al., 2015) or suppressed high-probability distractor locations (Theeuwes et al., 2022;

van Moorselaar & Slagter, 2019), both of which directly facilitate goal-directed behavior. In contrast, during location–reward associative learning, high- and low-reward locations were equally probable as target, making attentional bias toward either location detrimental to performance. This aligns with the proposed distinction between the influences of statistical learning and reward history (Kim & Anderson, 2019). While statistical learning influences attention through habit-driven mechanism (Jiang, 2018), reward history likely modulates attention through Pavlovian mechanisms (Bucker & Theeuwes, 2017). Another possibility for the absence of reward effects on specific locations may be due to their short-lived nature, potentially diminished by the separation of training and test sessions across days in our study. However, prior single-day studies also reported no reward effects on absolute locations (e.g., Jiang et al., 2015; Won & Leber, 2016), suggesting that test timing has little impact on detecting such effects.

Previous studies have shown that spatial locations are represented using multiple reference frames, with different frames activated depending on task demands. For example, perceptual aftereffects (Afraz & Cavanagh, 2009; Knapen et al., 2010) and visuospatial memory (Golomb & Kanwisher, 2012; Shafer-Skelton & Golomb, 2018) rely on retinotopic coding, while feature-specific working memory (Ong et al., 2009) and saccade adaptation (Zimmermann et al., 2011) depend on spatiotopic coding. Particularly relevant to our study, spatial attention can involve retinotopic, spatiotopic, or both reference frames (Cavanagh et al., 2010; Golomb et al., 2008; Jiang, 2018). However, our findings of value-driven spatial attention did not align with either reference frame. Specifically, analyses of gaze positions ruled out a retinotopic account, and the location-match condition showed no spatial bias toward high-reward screen locations, ruling out a spatiotopic account. Theories of conceptual control of attention suggest that humans flexibly use spatial relation to select targets based on relative positions (Gibson & Kingstone, 2006; Gibson & Sztybel, 2014; Logan, 1995). Our findings likely align with this theory and indicate that reward prioritized the direction of attention from one location to another, following the computations of the spatial relationship between objects.

We propose that a relation-based account may provide a domain-general mechanism for value-driven attention, building upon prior findings of value-driven attention based on feature relationship (Chen et al., 2023). However, unlike feature-reward associative learning, where both feature-specific and relational-based mechanisms co-exist, our current findings indicate that reward history primarily modifies the priority map based on spatial relationship rather than absolute locations. Encoding a set of invariant spatial relationships might be well-suited for creating a stable representation to navigate a dynamic environment (Farzanfar et al., 2023) and enhance the generalization of learned value information into new contexts. Furthermore, this value-driven generalization effect persists when reward is no longer available, suggesting that reward history induces lasting changes in relational representation. These changes may involve the posterior parietal cortex, which integrates spatial (Kravitz et al., 2011), value (Anderson, 2019; Peck et al., 2009), and attentional priority signals (Bisley & Goldberg, 2010). Other regions, such as caudate tail, superior colliculus, and frontal eye field, may also contribute to learning-induced spatial priority maps (Liao et al., 2023). Future high-resolution neuroimaging studies are needed to elucidate how reward alters priority maps based on spatial relationships (Jia et al., 2021, 2023).

In conclusion, our study provides direct evidence that reward history can modulate attentional priority based on spatial relationship. This relational account might be well-suited for human brain to incorporate value and spatial information into a priority map, particularly in real-world scenarios with dynamically changing sensory inputs. Given that spatial relationships among object parts influence object recognition (Cave & Kosslyn, 1993), memory (Kaiser et al., 2015; Lovett & Franconeri, 2017), and social interactions (e.g., face-to-face or back-to-back; Adibpour et al., 2021), our findings of value-driven attentional changes in spatial relationships may extend to these domains to support adaptive behavior.

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Data availability All data and task codes have been made publicly available via the Open Science Framework (https://osf.io/u5kqc).

Code availability All analysis codes have been made publicly available via the Open Science Framework (https://osf.io/u5kqc).

Declarations

Ethics approval This study was approved by the Institutional Review Board (ref. 2023–007).

Consent to participate All participants provided written informed consent.

Consent for publication All participants gave their consent for their data to be included in scientific publications.

Open practices statement All data, analysis and task codes used in this study have been made publicly available via the Open Science Framework (https://osf.io/u5kqc). The study was not pre-registered.

Conflicts of interest/Competing interests The authors declare no competing interests.

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