Journal of Experimental Psychology: General

Reward History Modulates Attention Based on Feature Relationship

Yilin Chen, Shikai Chen, Xiaodong Zhang, Sihan Zhang, Ke Jia, Brian A. Anderson, and Mengyuan Gong

Reward History Modulates Attention Based on Feature Relationship

Yilin Chen[1], Shikai Chen[1], Xiaodong Zhang[1], Sihan Zhang[2], Ke Jia[3, 4, 5], Brian A. Anderson[6],
and Mengyuan Gong[1]
[1] Department of Psychology and Behavioral Sciences, Zhejiang University
[2] College of Life Sciences, Zhejiang University
[3] Department of Neurobiology, Affiliated Mental Health Center & Hangzhou Seventh People's Hospital, Zhejiang University
School of Medicine
[4] Liangzhu Laboratory, MOE Frontier Science Center for Brain Science and Brain-Machine Integration, State Key Laboratory of
Brain-Machine Intelligence, Zhejiang University
[5] NHC and CAMS Key Laboratory of Medical Neurobiology, Zhejiang University
[6] Department of Psychological & Brain Sciences, Texas A&M University

Prioritizing attention to reward-predictive items is critical for survival, but challenging because these items rarely appear in the same feature or within the same environment. However, whether attention selection can be adaptively tuned to items that matched the context-dependent, relative feature of previously rewarded items remains largely unknown. In four experiments ($N = 40$ per experiment), we trained participants to learn the color-reward association and then adopted visual search tasks in which the color of a singleton distractor matched either the feature value (e.g., red or yellow) or feature relationship (i.e., redder or yellower) of previously rewarded colors. We consistently found enhanced attentional capture by a singleton distractor when it was relationally matched to the high reward compared with the low reward relationship, in addition to observing the typical effect of learned value on singletons matching the previously rewarded colors. Our findings provide novel evidence for the flexibility of value-driven attention via feature relationship, which is particularly useful given the changeable sensory inputs in real-world searches.

Keywords: reward, attentional capture, feature relationship, visual search

The real world contains a multitude of features and objects, as well as the relations among them. The human brain can rapidly extract relational information from the environment to facilitate adaptive behavior (Hafri & Firestone, 2021; Summerfield et al., 2020). For example, accurate recall of episodic memory requires binding components of an event (what, where, and when) into a relational representation (Shastri, 2002). Efficient navigation to a destination depends on cognitive maps that preserve the spatial relationship among entities (Epstein et al., 2017). The Gestalt principles focused on relative proximity, similarity, and continuity

facilitate visual perception and working memory (Peterson & Berryhill, 2013; Wagemans et al., 2012). Despite these evidences supporting the importance of relational information for flexible behavior, much less is known about how humans leverage relational information to guide the selection of reward-predictive stimuli.

The ability to use relational information to efficiently direct attention to high-value stimuli could be critical for survival in dynamically changing environments. Animals can learn to use relational rules to aid foraging choice, discriminating between food patches based on relative rather than absolute properties. For example,

hummingbirds have been observed to prefer larger over smaller flowers, as the flower size may serve as an indicator of nectar reward quantity (Ornelas et al., 2007). This natural phenomenon indicates that attention could be guided to the relative attributes of natural reward (e.g., food), enabling the organism to flexibly select valuable information. However, whether this relational-based mechanism holds for the selection of stimuli that have previously been associated with reward, as a consequence of reward history, remains elusive.

A prevalent view inferred from the literature is that reward history modulates attention to specific reward-associated feature values (Anderson et al., 2011a, 2011b; Gong & Li, 2014; Gong & Liu, 2018; Hickey et al., 2010; Itthipuripat et al., 2019; Lee & Shomstein, 2014). Such an effect can spread or transfer to stimuli that share the reward-predictive feature value (Anderson et al., 2012; Lee & Shomstein, 2014) or are perceptually similar to the reward-associated feature value (Anderson, 2017), following the feature similarity rule (Martinez-Trujillo & Treue, 2004). For instance, if participants learned the association between reward and the color red, a red-orange item could induce stronger attentional capture than a yellow item because red-orange is physically more similar to red than yellow. In contrast to this feature-specific account, the relational account proposes that attention can be tuned to the context-dependent feature relationship (Becker, 2010; Becker et al., 2013), as specified by how an item differs from the surroundings. This account provides a theoretical basis for possible attentional bias toward items sharing the same feature relationship with previously rewarded items. If this hypothesis holds true, for participants who learned the association between reward and red, a yellow-orange item in yellow contexts (i.e., redder) could induce a stronger attentional effect than a yellow-orange item in orange contexts (i.e., yellower). Testing of this hypothesis is important, as it would predict the generalizability of reward effects on the control of attention to different objects in different contexts with a common feature relationship, which is necessary for the flexible selection of valuable information in ecologically valid, real-world situations.

To test the relational-based mechanism for value-driven attention, we first trained participants to learn a feature-reward association (e.g., high reward—red; low reward—yellow). Then, using targeted visual search displays, we varied the singleton's feature to match either the reward-associated feature value (e.g., red or yellow) or feature relationship (e.g., redder or yellower). In four experiments, we show that in addition to the effect of reward on feature value, attentional capture by the singleton was stronger when its relationship to other stimuli matched the high-value compared to the low-value relationship while controlling for absolute feature value.

Experiment 1

Experiment 1 aimed to examine whether attention can be tuned to items sharing the same feature relationship with previously rewarded items. We had participants perform a visual search task with a color singleton that had a constant feature value (orange), but different feature relationships in different contexts (redder or yellower). If the relational account holds for value-driven attention, we would predict stronger attentional capture by a singleton whose feature relationship matched the relationship previously associated with high rather than low reward.

Materials and Method

Participants

To determine the sample size, we ran a pilot experiment with 18 participants using a similar design. We entered the estimated effect size of reward history ($\eta_p^2 = 0.12$) into a simulated two-way (reward history × match type) repeated-measures analysis of variance (ANOVA) using G*Power (Version 3.1, Faul et al., 2007). A sample size of 40 would provide power greater than 90% for detecting a main effect of reward.

Forty-one (26 female and 15 male; age: $M = 21.3$ years, $SD = 2.3$) undergraduate and graduate students from Zhejiang University participated in Experiment 1. The demographic information (age and gender) was provided by the participants themselves via self-report using a brief survey. We excluded data from one participant whose mean response time (RT) exceeded three standard deviations of the mean across participants. Participants provided written informed consent approved by the Institutional Review Board at Zhejiang University (2020-06-001). All participants had normal or corrected-to-normal vision and were right-handed. They were paid on average ¥61.5 for their participation, a portion of this payment was based on their reward-based training performance.

Stimuli and Apparatus

The stimuli were filled circles ($2° \times 2°$) that had one of five possible colors: red ($u' = 0.428$, $v' = 0.526$; 16.37 cd/m²), red-orange ($u' = 0.335$, $v' = 0.537$; 20.00 cd/m²), orange ($u' = 0.292$, $v' = 0.542$; 22.57 cd/m²), yellow-orange ($u' = 0.254$, $v' = 0.547$; 25.12 cd/m²), yellow ($u' = 0.209$, $v' = 0.552$; 31.20 cd/m²). Inside each circle was a black oriented bar ($1° \times 0.2°$) in four possible directions (vertical, horizontal, left diagonal or right diagonal).

All stimuli were generated using Psychtoolbox (Brainard, 1997) implemented in MATLAB Version 2020b (The MathWorks, Natick, MA). Stimuli were presented against a black background on a 17-in. CRT monitor (resolution: $1,024 \times 768$, refresh rate: 100 Hz) and viewed at a distance of 60 cm in a dim-lit room.

Experimental Procedure and Tasks
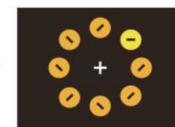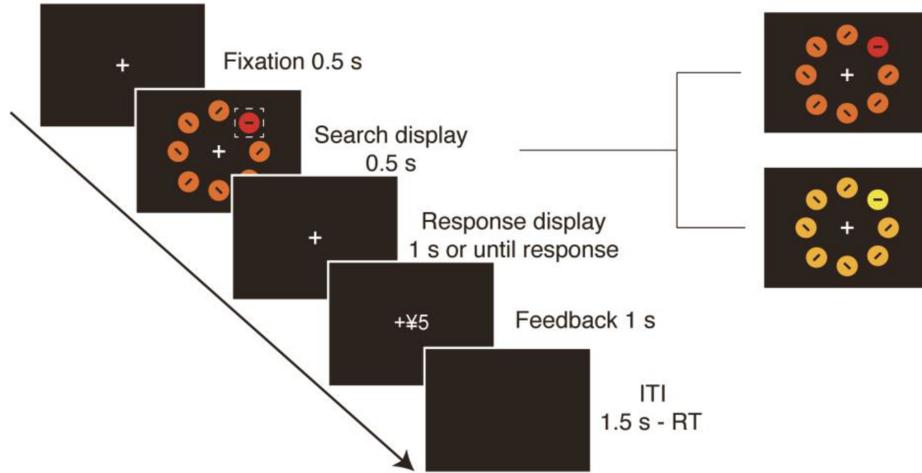
Participants completed a training session and a test session on two consecutive days. Using visual search tasks, we first trained participants to establish the reward-color association and then tested the reward effect in a separate test session.

Training Session. Each trial began with a central fixation for 0.5 s, followed by a search display for 0.5 s. The search display comprised eight oriented bars appearing inside colored circles, at an eccentricity of 5°. The search arrays comprised either a red singleton among red-orange nonsingletons or a yellow singleton among yellow-orange nonsingletons (Figure 1A). The target was defined by a uniquely oriented bar (horizontal or vertical) appearing inside the singleton color. Participants were informed to use a keypress to indicate the orientation of the target bar (horizontal or vertical). The nonsingletons contained diagonally oriented bars (45° or 135°). Participants received on-screen monetary feedback after a correct response. An incorrect response was followed by a black screen and auditory feedback. For half of the participants, red was predefined to be associated with a high probability (80%) of high

Figure 1

Tasks and Designs for Experiment 1
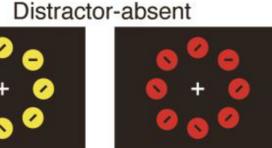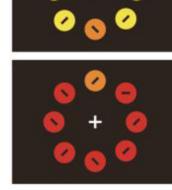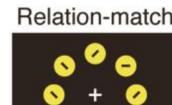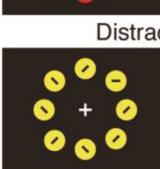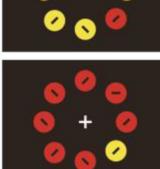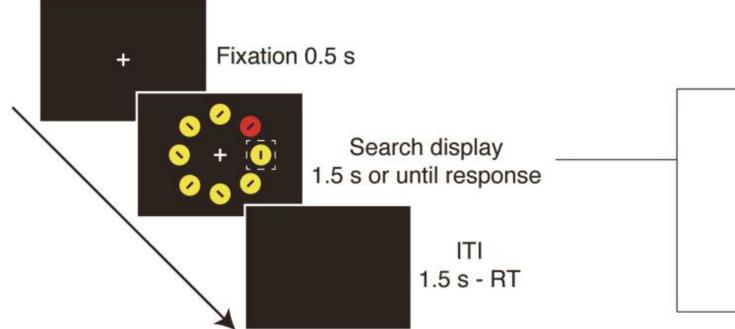
Note. Panel A: Trial sequence of the visual search task in the training session. The task was to report the orientation of the bar inside a color singleton (red or yellow). A correct response was followed by a high (+¥5) or low reward (+¥1), depending on the pre-specified color-reward associations. Panel B: Trial sequence of the visual search task in the test session. Participants were asked to find a uniquely oriented bar inside nonsingleton colors. No reward feedback was provided. The singleton distractor either matched reward history in feature value or feature relationship. The dashed box indicates the target bar (not shown in actual displays). See the online article for the color version of this figure.

reward (+¥5) and a low probability (20%) of low reward (+¥1) feedback, whereas yellow was associated with a high probability (80%) of low reward (+¥1) and a low probability (20%) of high reward (+¥5) feedback. For the other half of the participants, the color-reward association was reversed. Participants were not informed about the color-reward association and they were encouraged to perform as well as they could to maximize the total amount of earnings. They would receive a portion of their final accumulated monetary reward (up to ¥41). Each participant completed eight blocks during the training (100 trials/block).

Test Session. The trial sequence was similar to that used during the training session (Figure 1B). Each trial consisted of a fixation (0.5 s), a search display (1.5 s or until response), and a blank inter-trial interval (ITI). Different from the training task, participants were asked to find a uniquely oriented bar (horizontal or vertical) that always appeared inside nonsingleton colors. In the distractor-present trials (50% of trials), the singleton distractor either had the same color that matched the reward history, that is, *feature-match conditions* (red: red among yellows; yellow: yellow among reds) or had the same feature relation that matched the reward history, that is,

relation-match conditions (redder: orange among yellows; yellower: orange among reds). The proportion of all conditions was the same. In the distractor-absent trials (50% of trials), the search display consisted of same-colored circles that were chosen from two colors (red or yellow) with equal probability. No reward feedback was provided. All trial types were randomly interleaved. Each participant completed six blocks (160 trials/block) in this session.

Note that our main interest was the relation-match conditions with an untrained, constant feature value (orange) but different feature relations (redder and yellower). Any difference in the magnitude of attentional capture by the orange singleton as a function of color context must be attributable to the context and thus relational processing. The feature-match condition was included to confirm the acquisition of reward contingency, but because singletons in this condition had extreme feature values (i.e., reddest or yellowest), feature-specific and relational accounts do not make different predictions in this case.

Data Analysis

Correct responses were defined as appropriate keypresses within 0.2–1.5 s after the onset of the search display. Search RTs that were outside this specified window or above three standard deviations of the mean were discarded (on average 1.53% of trials for training and 2.18% of trials for test sessions).

We compared search performance between high and low reward conditions during training and test sessions, and then examined such effects under feature-match and relation-match conditions. 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 0.16.3 (JASP Team, 2022). We reported Bayes factors (BF_{01}) to provide evidence in favor of the null hypothesis if it was greater than three. All statistical analyses were performed in MATLAB and JASP software.

Transparency and Openness

All data, analysis, and task codes have been made publicly available via the Open Science Framework at https://osf.io/qvmfa/ (Gong & Chen, 2022). Data were analyzed using MATLAB, Version 2020b (The MathWorks, Natick, MA) and JASP Version 0.16.3 (JASP Team, 2022). This study was not pre-registered.

Results and Discussion

During the training session, search time was significantly faster when the target appeared in the high reward-associated color ($M = 574$ ms, $SD = 57$ ms) than in the low reward-associated color ($M = 582$ ms, $SD = 63$ ms; paired t-test: $t[39] = -2.04$, $p = .048$, Cohen's $d = -0.32$, 95% confidence interval [CI] $= [-0.64, -0.003]$), demonstrating a benefit of reward on training performance. No significant difference was observed between the two reward conditions with respect to accuracy (94.5% vs. 94.8%; $t[39] = -1.01$, $p = .320$, Cohen's $d = -0.16$, 95% CI $= [-0.47, 0.15]$).

During the test session, the search time was significantly longer in distractor-present than in distractor-absent trials, confirming a singleton-induced distraction effect (676 ms vs. 647 ms; $t[39] = 11.68$, $p < .001$, Cohen's $d = 1.85$, 95% CI $= [1.33\ 2.35]$). Planned t-tests showed stronger attentional capture when the singleton matched the high reward feature than when it matched the low reward feature
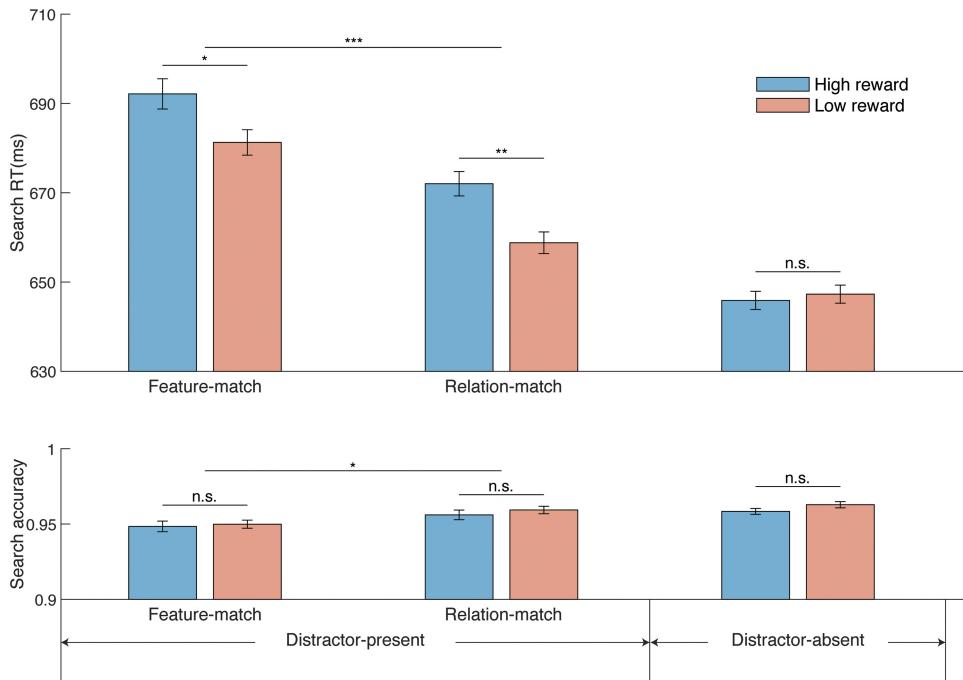
(692 ms vs. 681 ms; $t[39] = 2.12$, $p = .041$, Cohen's $d = 0.34$, 95% CI $= [0.01, 0.65]$), validating the acquisition of feature-reward contingency. Importantly, attentional capture was stronger for an orange singleton when its relationship to other stimuli matched that previously associated with high compared to low reward (672 ms vs. 659 ms; $t[39] = 3.10$, $p = .004$, Cohen's $d = 0.49$, 95% CI $= [0.16, 0.82]$), supporting our hypothesis that reward history can bias attention based on feature relationship. A two-way repeated-measures ANOVA (2 reward history × 2 match types) showed a significant main effect of reward history, $F(1, 39) = 10.07$, $p = .003$, $\eta_p^2 = 0.21$, without a significant interaction between reward history and match type, $F(1, 39) = 0.18$, $p = .678$, $\eta_p^2 < 0.01$ (Figure 2, top panel). In addition, we observed a main effect of match type, ($F(1, 39) = 57.89$, $p < .001$, $\eta_p^2 = 0.60$, showing stronger attentional capture in the feature-match than in the relation-match condition. This result was likely due to differences in the color contrast (e.g., larger color contrast between singleton and nonsingletons for feature-match than relation-match conditions; see Figure 1B) and selection history (trained color in feature-match vs. untrained color in relation-match conditions) between these two match types. To evaluate the strength of evidence for the lack of an interaction effect, we constructed two models: a null model that contained two main effects (reward history and match type) and subject-related effect; whereas the interaction model contained all factors of the null model, plus an interaction term between reward history and match type. The lack of an interaction effect was supported by moderate evidence in favor of the null model over the interaction model ($BF_{01} = 3.933$). We applied the same two-way ANOVA on search accuracy and revealed only a main effect of match type, ($F(1, 39) = 5.914$, $p = .020$, $\eta_p^2 = 0.13$ (Figure 2, bottom panel). Despite the overall highly accurate performance (>94.8%), the search accuracy was higher in the relation-match than in the feature-match conditions, reflecting more distraction by the feature-match singletons. No reward-related effects were significant for search accuracy ($ps > .494$).

A potential concern is whether longer search RTs reflected more distraction by a relationally high rewarded singleton or differential attention and/or arousal elicited by nonsingletons as a function of the reward history tied to their colors. We ruled out this possibility by showing no significant difference in search RTs between the previously high- and low reward-associated color in distractor-absent trials (646 ms vs. 647 ms; paired t-test: $t[39] = -0.62$, $p = .537$, Cohen's $d = -0.10$, 95% CI $= [-0.41, 0.21]$; Figure 2), as also indicated by moderate evidence in favor of the null hypothesis ($BF_{01} = 4.886$). Similar results were obtained for search accuracy with anecdotal evidence (95.8% vs. 96.3%; paired t-test: $t[39] = -1.56$, $p = .128$, Cohen's $d = -0.25$, 95% CI $= [-0.56, 0.07]$, $BF_{01} = 1.94$).

Experiment 2

Despite the efforts to equate the feature similarity of the singleton color (i.e., orange) between two relation-match conditions in Experiment 1, participants may subjectively perceive orange as more similar to red in a yellow context than when it is in a red context, contributing to the observed reward effect on feature relationship. To rule out this possibility and further test the robustness of value-driven attention on feature relationships, in Experiment 2, we examined whether the reward effect remained when the relational account predicts opposite patterns of results from the feature similarity account. For instance, the color of the singleton distractor could

Figure 2
Results for Experiment 1

Note. Search performance during the test session. The top panel shows the results of search RTs and the bottom panel shows search accuracy. Error bars reflect within-subject standard errors of the mean. See the online article for the color version of this figure.
*p < .05. **p < .01. ***p < .001.

be more similar to the previously high-rewarded feature value (e.g., red-orange is more *similar to red* than to yellow), but more deviated from the previously high-rewarded feature relationship (e.g., red-orange is *yellower* among reds). If the relational account remains robust for value-driven attention, we should still observe stronger attentional capture by a singleton that was relationally matched to high reward under such conditions.

Materials and Method

Participants

Forty individuals (30 female and 10 male; age: $M = 20.0$ years, $SD = 2.4$) from Zhejiang University participated in the experiment. The sample size was identical to that in Experiment 1. They provided written informed consent and all reported normal or corrected-to-normal vision. They were paid on average ¥61.2 for their participation.

Stimuli, Apparatus, and Procedure

The stimuli, apparatus, and procedure were largely the same as that in Experiment 1. We used four colors (red: $u' = 0.431$, $v' = 0.524$; red-orange: $u' = 0.350$, $v' = 0.534$; yellow-orange: $u' = 0.277$, $v' = 0.544$; yellow: $u' = 0.193$, $v' = 0.554$) that have equal luminance (17 cd/m²).

As in Experiment 1, each participant completed visual search tasks during training and test sessions. For the test session, different sets of color pairs were assigned to circles in the search arrays (Figure 3A).

The singleton distractor either had the same color that matched the reward history, that is, *feature-match conditions* (red: red among red-oranges; yellow: yellow among yellow-oranges), or the same feature relationship that matched the reward history, that is, *relation-match conditions* (redder: yellow-orange among yellows; yellower: red-orange among reds). The proportion of all conditions was the same. In distractor-absent trials, the search display consisted of the same-colored circles that were selected from four possible colors (red, red-orange, yellow-orange, yellow) with equal probability. The training session comprised eight blocks (100 trials/block) and the test session comprised five blocks (160 trials/block).
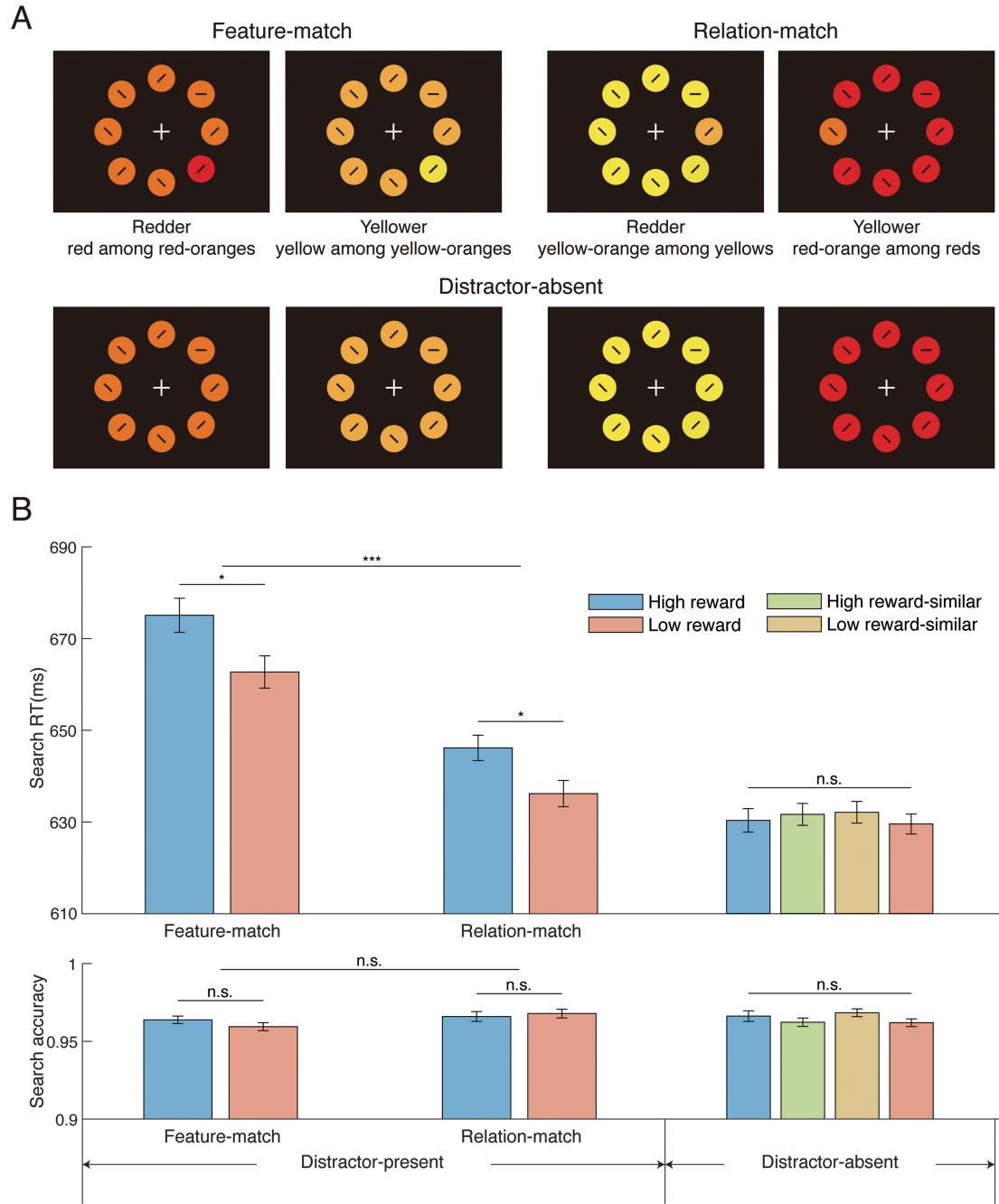
Data Analysis

We applied the same exclusion criteria as that in Experiment 1, excluding on average 1.32% of trials in the training session and 1.76% of trials in the test session. The statistical analyses on the search performance were largely the same as that reported in Experiment 1.

Results and Discussion

During the training session, search RTs did not differ significantly between the high reward-associated ($M = 580$ ms, $SD = 78$ ms) and low reward-associated ($M = 584$ ms, $SD = 96$ ms) color, $t(39) = -0.63$, $p = .532$, Cohen's $d = -0.10$, 95% CI = [−0.41, 0.21]. Similar results were obtained for search accuracy (93.9% vs. 94.1%), $t(39) = -0.67$, $p = .506$, Cohen's $d = -0.11$, 95% CI = [−0.42, 0.21]. The difference between two experiments was likely

Figure 3
Designs and Results for Experiment 2

Note. Panel A: Search arrays in the test session. Panel B: Search performance during the test session. The top panel shows the results of search RTs and the bottom panel shows search accuracy. Error bars reflect within-subject standard errors of the mean. See the online article for the color version of this figure.
*p < .05. ***p < .001.

due to the near ceiling performance of training tasks that could be insensitive to capture the effect of reward, as also reported in previous studies (Anderson, 2015; Anderson & Halpern, 2017; Gong et al., 2016, 2017; Rajsic et al., 2017).

During the test session, we found stronger attentional capture by the previously high reward-associated feature value than the previously low reward-associated feature value (675 ms vs. 663 ms; planned *t*-test: $t[39] = 2.24$, $p = .031$, Cohen's $d = 0.35$, 95% CI = [0.03, 0.67]). Critically, attentional capture was also stronger for the singleton whose color relationship was previously associated with high reward than low reward (646 ms vs. 636 ms; $t[39] = 2.52$, $p = .016$, Cohen's $d = 0.40$, 95% CI = [0.07, 0.72]),

extending the findings in Experiment 1 by showing that when the relational account predicts opposite patterns of reward effects from the feature similarity account, attention was still biased toward relationally high rewarded singletons. Consistent with Experiment 1, we ran a two-way repeated-measures ANOVA (2 reward history × 2 match type) on search RT in distractor-present trials. The analysis revealed a significant effect of reward history, $F(1, 39) = 8.80$, $p = .005$, $\eta_p^2 = 0.18$, without a significant two-factor interaction, $F(1, 39) = 0.16$, $p = .691$, $\eta_p^2 = 0.004$ (Figure 3B, top panel). We also observed a main effect of match type, $F(1, 39) = 63.43$, $p < .001$, $\eta_p^2 = 0.62$, showing stronger attention toward feature-match singletons than relation-match singletons. This effect could be ascribed to their differences in selection history, as we had equated the color difference between two match types. It is worth noting that this effect of selection history could arise from either the trained singleton's feature value or trained search arrays (including both singleton and nonsingletons); such an effect could be a result of prolonged dwell time on the feature-match singletons (Martin & Becker, 2018). Similar to the reported Bayesian analysis in Experiment 1, we confirmed the lack of interaction between reward history and match by showing moderate evidence in favor of the model without an interaction than the model with an interaction term ($BF_{01} = 4.136$). We applied the same two-way ANOVA on search accuracy and obtained no significant effects ($ps > .121$, Figure 3B, bottom panel).

In addition, we examined the possibility of value-modulated changes in attention or general arousal tied to nonsingletons. By classifying color arrays in distractor-absent trials according to their physical similarity to the previously high rewarded color (e.g., red, red-orange, yellow-orange to yellow), we found no significant difference in search RTs (one-way repeated-measures ANOVA: $F[3, 39] = 0.26$, $p = .852$, $\eta_p^2 = 0.007$; Figure 3B, bottom panel) or search accuracy across conditions, $F(3, 39) = 1.09$, $p = .355$, $\eta_p^2 = 0.027$ (Figure 3B, bottom panel), as confirmed by strong evidence for the null hypothesis (RT: $BF_{01} = 22.901$; accuracy: $BF_{01} = 8.492$).

Experiment 3

Experiment 3 aimed to address two lingering concerns from the first two experiments. First, to confirm our findings of the effect of reward history on relational-matching singletons, it would be more compelling to directly examine the possibility that reward history modulated the nonsingleton items. Second, considering that the feature-match conditions likely involve the processing of color relations, it remains to be tested if our training protocol yielded a typical effect of reward on specific feature value. Addressing these concerns requires us to separately assess the effect of reward on the nonsingleton and singleton items. To achieve these goals, we either presented a gray singleton among high or low reward-associated colors (red or yellow) to isolate the effect of reward on nonsingleton items (*color-context search task*), or presented a high or low reward-associated color singleton (red or yellow) among gray nonsingletons to isolate the effect of reward on singleton items (*gray-context search task*).

Materials and Method

Participants

Forty-two individuals (27 female and 15 male; age: $M = 20.1$ years, $SD = 2.6$) from Zhejiang University participated in this experiment. Two participants were excluded because their RT fell outside three standard deviations from the mean across participants. The sample size was the same as that in Experiments 1 and 2. They provided written informed consent and all reported normal or corrected-to-normal vision. They were paid on average ¥61.8 for their participation.

Stimuli, Apparatus, and Procedure

The stimuli, apparatus, and procedure were largely the same as in Experiment 1 and 2. We used the same set of color stimuli as that in Experiment 2 and included gray stimuli as an achromatic feature. These stimuli were of equal luminance (17 cd/m^2).

Each participant completed visual search tasks during the training session and test session. The training session was identical to Experiments 1 and 2. The test session comprised modified versions of the visual search task: a color-context search task and a gray-context search task. Participants completed five blocks of the color-context search tasks and three blocks of the gray-context search task, with the order of blocks randomized separately for each participant.

Color-Context Search Task. In distractor-present trials (50% of trials), we used an achromatic (gray) singleton that did not carry any feature value or feature relation of reward, that is, *no-match conditions* (gray among reds or gray among yellows; Figure 4A, right panel). We also kept the same feature-match conditions (red: red among yellows; yellow: yellow among reds; Figure 4A, left panel) to validate the acquisition of reward contingency. The distractor-absent trials (50% of trials) comprised the same-colored items (red or yellow).

Gray-Context Search Task. In distractor-present trials (50% of trials), we presented a singleton distractor of a previously reward-associated color (red or yellow) among gray nonsingletons (Figure 5). In doing so, the singleton differed from the context mainly by its saturation, rather than hues, thus minimizing the processing of color relations. The distractor-absent trials comprised all gray items.
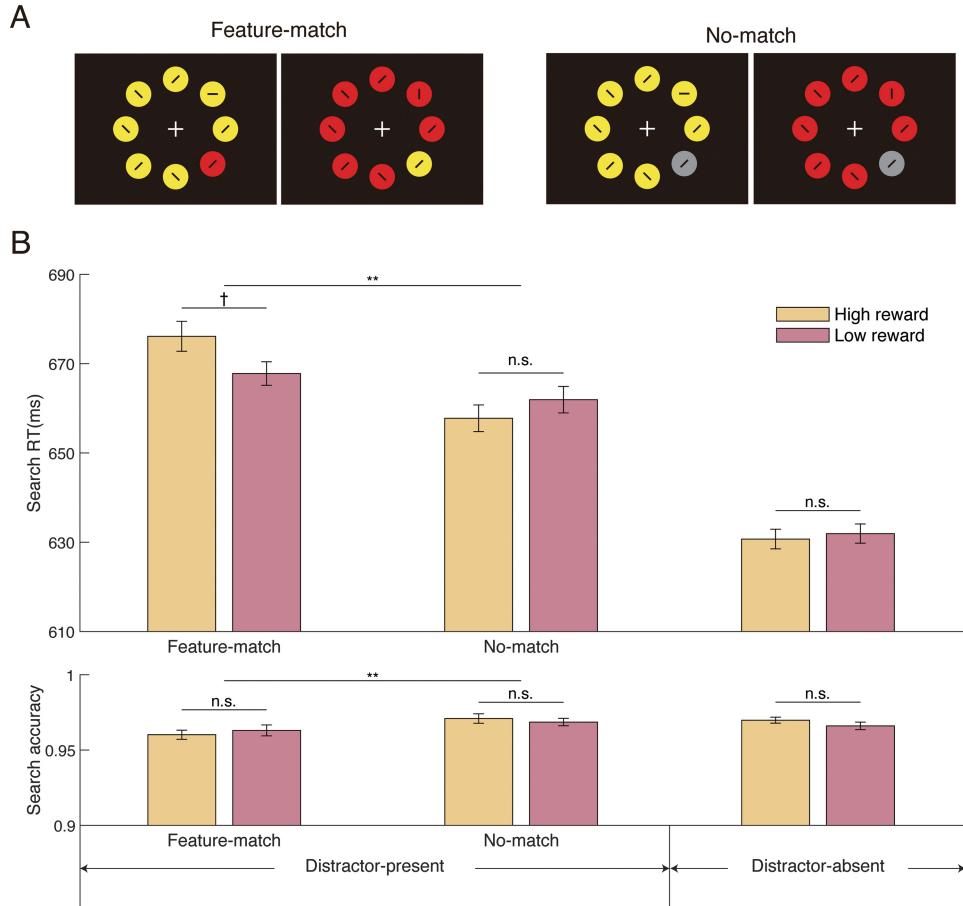
Data Analysis

We applied the same exclusion criteria as in Experiments 1 and 2, excluding 1.63% of trials in the training session and 2.03% of trials in the test session. For the color-context search task, because the gray singleton was not linked to reward, we thus classified the conditions according to the nonsingleton colors (i.e., context) and examined the effect of reward history under high reward and low reward context. For the gray-context search task, we compared search performance between the previously high reward and low reward-associated colors. Considering the fewer number of available trials for each task, we used one-tail t-tests to examine the effect of reward on trained color, as the direction of effect was clearly predicted based on our previous experiments and the literature.

Results and Discussion

During training, participants' search RTs were not significantly different between high ($M = 578$ ms, $SD = 60$ ms) and low reward ($M = 582$ ms, $SD = 59$ ms) conditions (paired t-test: $t[39] = -0.59$, $p = .560$, Cohen's $d = -0.09$, 95% CI = $[-0.40, 0.22]$). We found a small but significant difference in search accuracy (94.9% vs. 95.4%; $t[39] = -2.10$, $p = .043$, Cohen's $d = -0.33$, 95% CI = $[-0.65, -0.01]$).

Figure 4

Designs and Results for Color-Context Search Task in Experiment 3
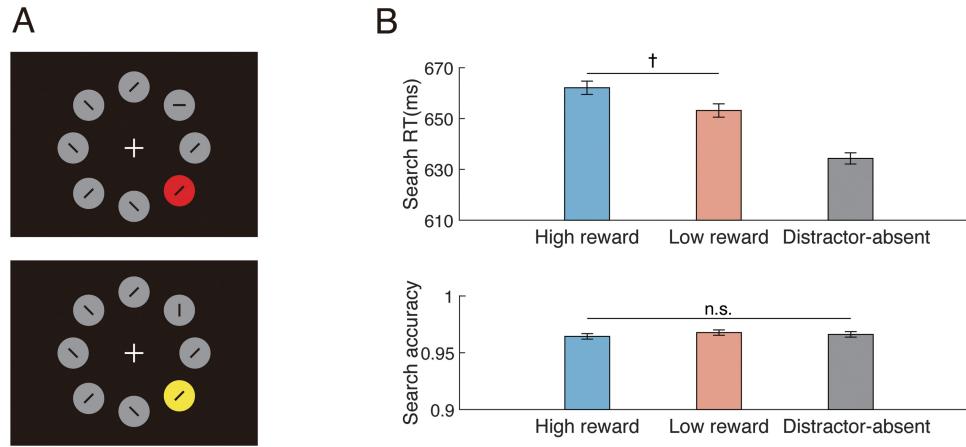
Note. Panel A: Search arrays during the test session. Panel B: Search performance during the test session. The top panel shows the results of search RTs and the bottom panel shows search accuracy. The error bar reflects within-subject standard errors of the mean. See the online article for the color version of this figure.
†$p < .05$, one tailed. **$p < .01$.

In the color-context task during the test session, a two-way repeated-measures ANOVA (2 reward history × 2 match type) on RTs in the distractor-present trials revealed no significant main effect of reward history, $F(1, 39) = 0.45$, $p = .506$, $\eta_p^2 = 0.01$, but a marginal interaction effect between reward history and match type, $F(1, 39) = 3.98$, $p = .053$, $\eta_p^2 = 0.09$. Further simple effect analysis showed stronger attentional capture by the high reward-associated singleton (surrounded by the low-reward context) than the low reward-associated singleton (surrounded by the high-reward context) in the feature-match condition (676 ms vs. 668 ms; $t(39) = 1.945$, $p = .030$, one-tailed, Cohen's $d = 0.31$, 95% CI = [0.04, ∞]), but not in the no-match condition (658 ms vs. 662 ms; $t(39) = -0.92$, $p = .818$, one-tailed, Cohen's $d = -0.15$, 95% CI = [−0.41, ∞], $BF_{01} = 3.953$), ruling out the possibility that reward modulated attentional processing of nonsingleton items. Consistent with the first two experiments, we found a significant main effect of match type, $F(1, 39) = 10.72$, $p = .002$, $\eta_p^2 = 0.22$ (Figure 4B, top panel) that likely reflected modulations by selection history (trained color in feature-match vs. untrained color in no-match conditions) and/or differences in color contrast.

We applied the same two-way ANOVA on search accuracy and also revealed a main effect of match type, $F(1, 39) = 9.70$, $p = .003$, $\eta_p^2 = 0.199$. The search accuracy was slightly higher in the no-match than in the feature-match conditions, reflecting more distraction by the feature-match singletons. No reward-related effects were significant for accuracy (ps > .511; Figure 4B, bottom panel). In addition, we found no significant difference between high- and low reward-associated colors in distractor-absent trials (RT: $t[39] = -0.44$, $p = .663$, Cohen's $d = -0.07$, 95% CI = [−0.38, 0.24], $BF_{01} = 5.353$; accuracy: $t[39] = 1.18$, $p = 0.247$, Cohen's $d = 0.19$, 95% CI = [−0.13, 0.50], $BF_{01} = 3.090$).

In the gray-context task during the test session (Figure 5), we measured search RTs and found stronger attentional capture by the previously high reward-associated color than the previous low reward-associated color (662 ms vs. 653 ms, paired t-test: $t[39] = 1.88$, $p = 0.034$, one-tailed, Cohen's $d = 0.30$, 95% CI = [0.03, ∞]). No significant difference was found in search accuracy (96.4% vs. 96.8%; $t[39] = -0.81$, $p = .210$, one-tailed, Cohen's $d = -0.13$, 95% CI = [−∞, 0.13], $BF_{01} = 4.299$). This result replicated the typical effect of reward learning on specific feature values,

Figure 5

Designs and Results for Gray-Context Search Task in Experiment 3

Note. Panel A: Search arrays during the test session. Panel B: Search performance during the test session. The top panel shows the results of search RTs and the bottom panel shows search accuracy. The error bar reflects within-subject standard errors of the mean. See the online article for the color version of this figure.
†$p < .05$, one tailed.

suggesting that our training protocols yielded similar changes in the processing of previously reward-associated feature values, in line with the literature. However, one may argue that hue is only one dimension of the colored stimuli and that a red or yellow item could still be perceived as "redder" or "yellower" in a gray context in terms of saturation, mixing possible reward effects dependent upon feature and relational information. Thus, we conducted Experiment 4, aiming to more directly decouple the value-driven effects on these two mechanisms.

Experiment 4

Previous experiments have demonstrated a value-driven effect based on feature relationship. However, the exact role of feature value in this effect remains unclear because feature value cannot be separated from feature relationship in these experiments. To more directly decouple the value-driven effects on feature-specific and relational-based attention, we tested the capture of attention by a singleton distractor whose feature value and feature relationship were oppositely associated with reward. For instance, participants were highly rewarded with the search arrays comprising red-orange among reds (i.e., red-orange is high-valued and yellower in the context), and they received smaller rewards with the search arrays comprising yellow-orange among yellows (i.e., yellow-orange is low-valued and redder in the context). We can then test the attentional capture by a color singleton when it matched the highly-rewarded feature value (e.g., red-orange), but at the same time shared the lower-rewarded feature relationship (e.g., red-orange is redder among yellow-oranges). If one of the mechanisms (feature-specific or relation-based) predominates value-driven attention, we should observe stronger attentional capture by a singleton that was either feature-matching or relation-matching to high reward. Otherwise, if both mechanisms play a role, we might observe an absence of reward modulation due to the counteracting effect between feature-specific and relation-based mechanisms.

## Materials and Method

Participants

Forty individuals (30 female and 10 male; age: $M = 20.0$ years, $SD = 2.3$) from Zhejiang University participated in this experiment. The sample size was the same as that in above-mentioned experiments. They provided written informed consent and all reported normal or corrected-to-normal vision. They were paid on average ¥61.8 for their participation.
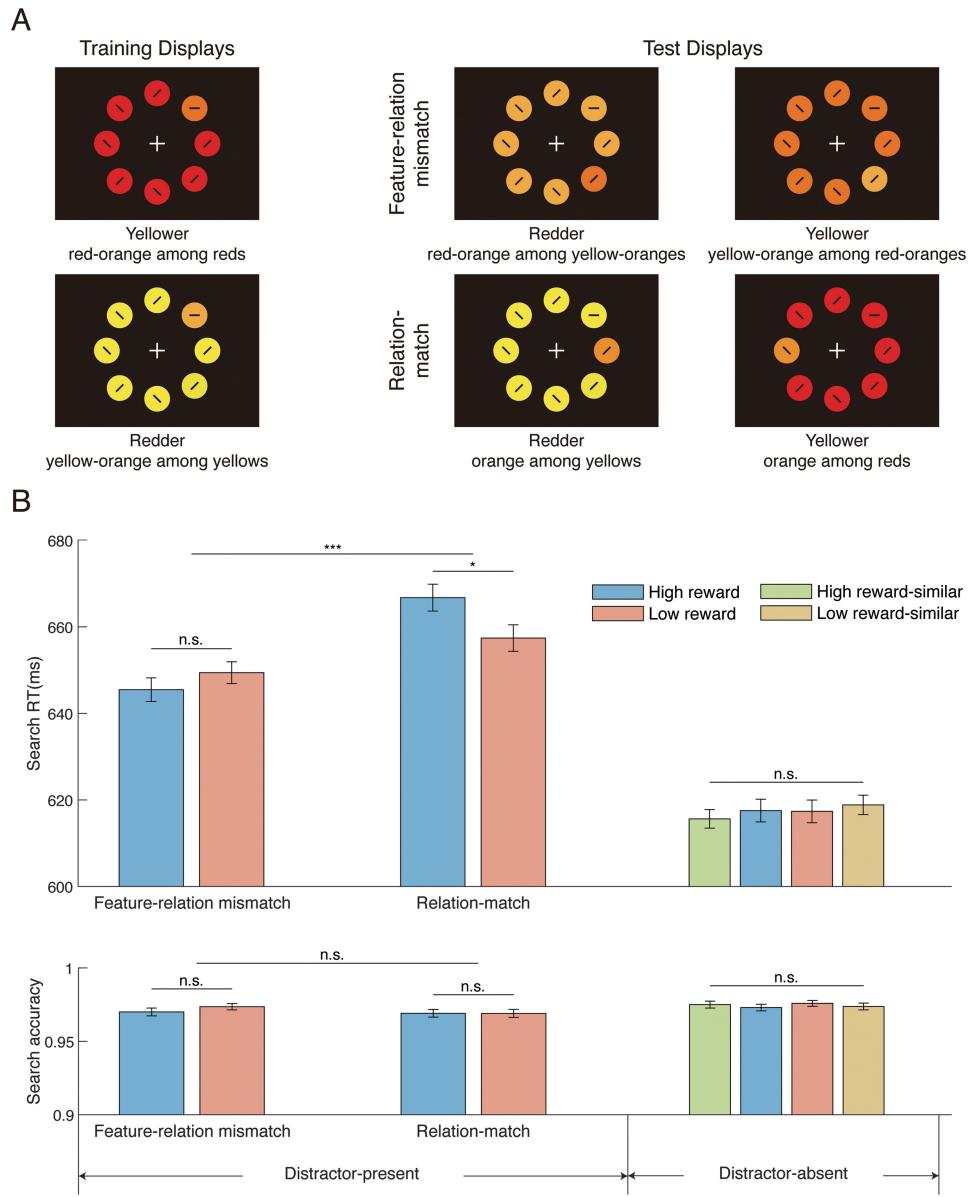
Stimuli, Apparatus, and Procedure

The stimuli, apparatus, and procedure were largely the same as above-mentioned experiments. We used a similar set of five color stimuli as that in Experiment 1 with equal luminance (17 cd/m^2).

Each participant completed visual search tasks during the training session and test session. For the training session, the task and reward settings were identical to previous experiments, but different sets of color pairs were assigned to the circles in the search arrays (Figure 6A, left panel). For half the participants, high reward was associated with the search arrays comprising red-orange among reds (i.e., red-orange is high-valued and yellower in the context), and low reward was associated with the search arrays comprising yellow-orange among yellows (i.e., yellow-orange is low-valued and redder in the context). For the other half of the participants, the association between reward and search arrays was reversed.

For the test session (Figure 6A, right panel), in distractor-present trials (50% of trials), the singleton distractor either had the same feature value but opposite feature relation with respect to what was highly rewarded, that is, feature-relation mismatch conditions (e.g., red-orange among yellow-oranges; red-orange was previously high rewarded but a redder relation was previously low rewarded) or had the same feature relation and identical feature value, that is, relation-match conditions (orange among yellows; orange among reds). Note that if any differences exist in subjectively perceived

Figure 6

Designs and Results for Experiment 4

Note. Panel A: Search arrays in the training and the test session. Panel B: Search performance during the test session. The top panel shows the results of search RTs and the bottom panel shows search accuracy. Error bars reflect within-subject standard errors of the mean. See the online article for the color version of this figure.
*$p < .05$. ***$p < .001$.

colors between two relation-match conditions (e.g., participants may *subjectively* perceive orange as more similar to red-orange in a yellow context than when it is in a red context), it could not contribute to the effect of reward on feature relation, as the singleton that is more similar to high-rewarded feature value always had low-rewarded feature relationship. The proportion of all conditions was the same. In distractor-absent trials, the search display consisted of the same-colored circles that were selected from four possible colors (red, red-orange, yellow-orange, yellow) with equal probability. The training session comprised eight blocks (100 trials/block) and the test session comprised six blocks (160 trials/block).

Data Analysis

We applied the same exclusion criteria as in prior experiments, excluding 1.54% of trials in the training session and 2.05% of trials in the test session. The statistical analyses on the search performance were largely the same as that reported in Experiment 2.

Results and Discussion

During training, participants' search RTs were not significantly different between high ($M = 572$ ms, $SD = 61$ ms) and low reward

($M = 570$ ms, $SD = 61$ ms) conditions (paired t-test: $t[39] = 0.53$, $p = .599$, Cohen's $d = 0.08$, 95% CI = [−0.23, 0.39]). Similar results were obtained on search accuracy (94.9% vs. 95.3%; $t[39] = −1.59$, $p = .120$, Cohen's $d = −0.25$, 95% CI = [−0.57, 0.07]).

During the test session, we found stronger attentional capture for the singleton whose color relationship was previously associated with high reward than low reward in the relation-match condition (667 ms vs. 657 ms; planned t-test: $t[39] = 2.30$, $p = .027$, Cohen's $d = 0.36$, 95% CI = [0.04, 0.68]), replicating the effect of reward history on feature relationship. In contrast, when feature value and feature relationship of a singleton distractor were oppositely associated with reward, we found no significant effect of reward history (645 ms vs. 649 ms; $t[39] = −1.05$, $p = .300$, Cohen's $d = −0.17$, 95% CI = [−0.48, 0.15], $BF_{01} = 3.508$), which was likely due to the counteracting effects of feature value and feature relationship in value-driven attention. Consistent with these results, a two-way repeated-measures ANOVA (2 reward history × 2 match type) on search RT revealed no significant main effect of reward history, $F(1, 39) = 1.37$, $p = .249$, $\eta_p^2 = 0.03$, but a significant two-factor interaction, $F(1, 39) = 4.46$, $p = .041$, $\eta_p^2 = 0.103$ (Figure 6B, top panel) that supports the differential pattern of reward effects between the two match types. These results suggest that both feature-specific and relational-based mechanisms may have played a role in the value-driven attention. In addition, we observed a main effect of match type, $F(1, 39) = 29.10$, $p < .001$, $\eta_p^2 = 0.43$) that showed stronger attentional capture toward relation-match singletons than feature-relation mismatch singletons. This effect could be attributed to their difference in selection history, as the trained search arrays were more similar to the relation-match condition than to the feature-relation mismatch condition. No reward-related effects were significant for search accuracy (ps > .301; Figure 6B, bottom panel).

Consistent with all previous experiments, no significant differences in search RT, $F(3, 39) = 0.40$, $p = .754$, $\eta_p^2 = 0.01$, $BF_{01} = 19.512$, or accuracy, $F(3, 39) = 0.31$, $p = .820$, $\eta_p^2 = 0.01$, $BF_{01} = 21.543$, were observed in distractor-absent trials when classifying color arrays according to their physical similarity to the previously high rewarded color (e.g., red, red-orange, yellow-orange to yellow), ruling out the possibility of value-driven changes in general arousal tied to nonsingletons.

General Discussion

Extending the prevalent view of feature-specific, value-driven attention (Anderson et al., 2021; Awh et al., 2012; Failing & Theeuwes, 2018), we provide evidence that reward history can modulate attention based on feature relationship, irrespective of the exact feature value. In four experiments, we trained participants to associate the high reward with a particular feature value (red or yellow), then used a visual search task to examine whether attention was biased toward a singleton distractor that matched the feature value (red or yellow) or the feature relationship (redder or yellower) of previously rewarded items. As expected, we observed enhanced capture by the previously reward-associated feature value, in line with prior studies showing feature-specific reward modulation (Anderson et al., 2011a, 2011b; Gong & Li, 2014; Gong & Liu, 2018; Hickey et al., 2010; Itthipuripat et al., 2019; Lee & Shomstein, 2014) and confirmed the acquisition of reward contingency. More importantly, we showed that capture by a singleton distractor was modulated by

whether the singleton was relationally matched to previously high reward-associated items, even under conditions in which a feature-specific bias would predict the opposite pattern of results. Furthermore, we eliminated the alternative account that reward enhanced attention toward nonsingleton colors or that nonsingletons evoked different levels of arousal as a function of the reward history tied to their color. These results jointly support our hypothesis that reward history can modulate attention depending on the feature relationship and provide theoretical implications for understanding the multifaceted mechanism of value-driven attention.

Our findings provide evidence for two possible mechanisms underlying value-driven attention and suggest that feature similarity may not be the only account for value-based selection. In addition to the typical effect of learned value on previously rewarded feature value, we found the increased attentional capture by the relationally high-value singleton, which contradicts the feature similarity model that would predict increased attentional capture by high reward-similar singletons. Particularly in Experiment 2, when the feature value of the singleton (e.g., red-orange is *physically more similar to red* than to yellow) was shifted toward the opposing direction from its feature relationship (e.g., red-orange is *relatively yellower* among reds), the magnitude of value-driven attentional capture was primarily modulated by feature relation over feature similarity. However, when we tested the capture effect by a singleton distractor whose feature value and feature relationship were oppositely associated with reward during training (Experiment 4), the value-driven attention was abolished. According to some recent studies using eye-tracking, relation-based and feature-specific mechanisms may operate in a division of labor during visual search: a relation-matching distractor is more likely to capture overt attention, suggesting a relational bias in early selection, whereas a feature-matching distractor tends to increase dwell time, reflecting a later-stage process (Hamblin-Frohman & Becker, 2021; Yu et al., 2022); these two sources of effect were found to exert approximately equal influences on search RTs (Martin & Becker, 2018). In the present study, the learning-dependent effects we observed in search RT do not allow us to distinguish between attentional biases at the stage of initial selection versus post-selection dwell time, although this is something that could be done in future research utilizing eye tracking technology. Overall, our findings suggest that feature-specific and relational-based mechanisms could both play a role in value-driven attention, but their effects potentially took place at different processing stages.

To be cautious, we acknowledge that a purely relational account is not impossible in explaining our data in Experiment 4 if the effect of learned value on feature relationship relied on the relational difference (as indexed by the color contrast between singleton and nonsingleton colors). Despite our efforts to balance the color contrast between the relation-match (e.g., orange among reds) and the feature-relation mismatch (e.g., red-orange among yellow-oranges) condition, participants may have subjectively perceived higher color contrast (thus maybe more pronounced relational difference) in the relation-match than in the feature-relation mismatch condition, causing observable effects only in the relation-match, but not in the feature-relation mismatch condition. However, whether the potential differences in perceived color contrast necessarily lead to relational differences is unclear. According to a prior study (Hamblin-Frohman & Becker, 2021), attention can be potentially attracted to the relational matching distractor independent of the color contrast

of the distractor. In this regard, the relational difference may be comparable between the relation-match and the feature-relation mismatch condition. Distinguishing between these two accounts is beyond the sensitivity of our methods, future work with more detailed manipulations of relational difference may help differentiate between multiple mechanisms.

Previous studies have indicated the influence of reward on contextual information. When pairing a specific feature with a specific context (e.g., background scenes) during reward-based associative learning, the effect of reward on feature value was evident only when presented along with a specific context (Anderson, 2015; Anderson & Britton, 2019; see Grégoire et al., 2021, for a parallel finding in the case of associations between features and aversive outcomes). In contrast to these findings that demonstrated the specificity of reward effect on trained stimuli (including feature and context), our findings offer evidence for a flexible mechanism that reflected the generalization of reward effect to untrained stimuli via a stable feature-context relationship. However, in order to manipulate feature relationship, the current findings were based on a special case of visual search in contexts comprising a singleton among nonsingletons; the observed value-driven attentional effects occurred on top of singleton-induced salience effects, as also reported by previous studies (Anderson et al., 2011a; Pearson et al., 2016). The generalizability of our findings should be further tested in more naturalistic situations to determine whether the reward modulations on relational-based attention preserves as a general mechanism of visual search in real-world scenes.

We provide evidence for value-driven relational attention, which might be well suited for rapid stimulus prioritization under noisy conditions, especially in perceptually demanding situations where multiple objects appear simultaneously and are perceptually similar. A recent study showed that animals applied relational rules when foraging, choosing flowers that matched the relative size, rather than the absolute size of a previously rewarded flower (Brown et al., 2022). These findings indicate the prevalent use of relational information across species that could be advantageous for living in dynamic and complex environments. Moreover, our findings showed that humans can readily assimilate new relational information via reward-based associative learning. Apart from the feature-reward association, previous studies have demonstrated that locations (Anderson & Kim, 2018a, 2018b; Chelazzi et al., 2014), objects (Hickey et al., 2015), and semantic categories of natural scenes (Failing & Theeuwes, 2015) paired with reward can capture attention. Our results may generalize to these other stimulus domains to benefit human behavior. For instance, navigation to a destination may be faster if it shares a previously rewarded spatial relationship, and viewpoint-invariant recognition of objects and scenes may be enhanced when they match a high-value categorical relationship.

Importantly, our findings suggest that this learning generalizes across different contexts even when reward is no longer available, suggesting value-driven plastic changes of relational representation in the human brain. Although few, some neurophysiological studies raised the possible existence of "relational neurons" that can be tuned to relative features. For instance, rather than responding to a specific color, the firing of color-opponent cells in early visual cortices depends on whether they receive inputs from the cone in the center and the surrounds (Conway, 2001; De Valois et al., 2000). A recent human fMRI study provided evidence for the representation of relational information in visual areas (Becker et al., 2019).

Alternatively, it has also been proposed that the posterior parietal cortex could be a candidate region for representing relational information, as it is involved in the coding of space and object in a low-dimensional format, allowing for better generalization (Summerfield et al., 2020). Relating to neural evidence for value-driven attention, it has been suggested that reward evokes dopamine that propagates to the visual system (Anderson, 2019). It is thus possible that the appearance of relationally high reward-associated stimuli may trigger the dopaminergic system to exert influence on sensory and/or parietal neurons that encode relational information. Future work is necessary to determine the exact mechanisms by which reward history modulates the representation of feature relationship.

It is worth noting that the observed effect of reward history via feature relationship reflected modulations of singleton-driven bottom-up attention, rather than task-related top-down factors (Becker, 2010; Becker et al., 2019; Yu et al., 2022). These results suggest that reward history is capable of guiding early attentional selection to relational matching items and highlight the importance of past experience in determining attentional selection in new situations. Relatedly, a recent study showed involuntary attentional capture by a relation-matching distractor when it shared a relative attribute with the previous targets (Liao et al., 2020), demonstrating the modulation of selection history on feature relations. However, their findings did not reveal similar modulations of reward history based on feature relations. The seeming contradiction could be reconciled by a key difference between their study and ours. In Liao's study, the feature-matching, trained color (e.g., orange), and relation-matching color (e.g., red) were shown in the same search display to compete for attention; prioritizing the processing of the feature-matching color may inevitably weaken the processing of the relation-matching color, as indicated by our data showing stronger attentional capture by feature-matching than relation-matching singletons. By contrast, we tested the effect of reward on feature-matching and relation-matching colors in separate trials, which enabled us to isolate the effect of reward on feature relationship. It was also the case that the target in the present study was physically non-salient while the distractor was physically salient, whereas in Liao et al. (2020), the target was a shape singleton and the distractors were nonsalient, with the present study perhaps providing a more sensitive test of value-based attentional guidance more broadly.

In conclusion, our study provides the first evidence that reward history can modulate attention based on feature relationships, irrespective of absolute feature values. This novel mechanism that operates on relational information might be well suited for maintaining the stability of value-driven selection under different situations with different objects, especially considering the changeable sensory inputs in real-world sceneries. Furthermore, it is suggested that the degree of value-driven attention is linked to a variety of clinical syndromes (Anderson, 2016, 2021), yet whether and how value-driven relational selection is associated with these disorders remains unclear. As previous studies have demonstrated a key role for dopamine in controlling stimulus generalization (Kahnt & Tobler, 2016) and in the learning and expression of value-driven attentional biases (Anderson, 2019; Anderson et al., 2016, 2017), our findings of the generalization of value-driven effect based on relational information may have diagnostic and treatment implications concerning neuropsychiatric disorders associated with aberrant generalization, such as drug abuse (Lucantonio et al., 2015), depression (Gotlib & Joormann, 2010), and schizophrenia (Shohamy et al., 2010).

References

Anderson, B. A. (2015). Value-driven attentional priority is context specific. *Psychonomic Bulletin & Review*, *22*(3), 750–756. https://doi.org/10.3758/s13423-014-0724-0

Anderson, B. A. (2016). What is abnormal about addiction-related attentional biases? *Drug and Alcohol Dependence*, *167*, 8–14. https://doi.org/10.1016/j.drugalcdep.2016.08.002

Anderson, B. A. (2017). On the feature specificity of value-driven attention. *PLoS ONE*, *12*(5), Article e0177491. https://doi.org/10.1371/journal.pone.0177491

Anderson, B. A. (2019). Neurobiology of value-driven attention. *Current Opinion in Psychology*, *29*, 27–33. https://doi.org/10.1016/j.copsyc.2018.11.004

Anderson, B. A. (2021). Relating value-driven attention to psychopathology. *Current Opinion in Psychology*, *39*, 48–54. https://doi.org/10.1016/j.copsyc.2020.07.010

Anderson, B. A., & Britton, M. K. (2019). Selection history in context: Evidence for the role of reinforcement learning in biasing attention. *Attention, Perception, & Psychophysics*, *81*(8), 2666–2672. https://doi.org/10.3758/s13414-019-01817-1

Anderson, B. A., & Halpern, M. (2017). On the value-dependence of value-driven attentional capture. *Attention, Perception, & Psychophysics*, *79*(4), 1001–1011. https://doi.org/10.3758/s13414-017-1289-6

Anderson, B. A., & Kim, H. (2018a). Mechanisms of value-learning in the guidance of spatial attention. *Cognition*, *178*, 26–36. https://doi.org/10.1016/j.cognition.2018.05.005

Anderson, B. A., & Kim, H. (2018b). On the representational nature of value-driven spatial attentional biases. *Journal of Neurophysiology*, *120*(5), 2654–2658. https://doi.org/10.1152/jn.00489.2018

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

Anderson, B. A., Kuwabara, H., Wong, D. F., Gean, E. G., Rahmim, A., Brasic, J. R., George, N., Frolov, B., Courtney, S. M., & Yantis, S. (2016). The role of dopamine in value-based attentional orienting. *Current Biology*, *26*(4), 550–555. https://doi.org/10.1016/j.cub.2015.12.062

Anderson, B. A., Kuwabara, H., Wong, D. F., Roberts, J., Rahmim, A., Brasic, J. R., & Courtney, S. M. (2017). Linking dopaminergic reward signals to the development of attentional bias: A positron emission tomographic study. *NeuroImage*, *157*, 27–33. https://doi.org/10.1016/j.neuroimage.2017.05.062

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011a). Learned value magnifies salience-based attentional capture. *PLoS ONE*, *6*(11), Article e27926. https://doi.org/10.1371/journal.pone.0027926

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011b). Value-driven attentional capture. *Proceedings of the National Academy of Sciences*, *108*(25), 10367–10371. https://doi.org/10.1073/pnas.1104047108

Anderson, B. A., Laurent, P. A., & Yantis, S. (2012). Generalization of value-based attentional priority. *Visual Cognition*, *20*(6), 647–658. https://doi.org/10.1080/13506285.2012.679711

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

Becker, S. I. (2010). The role of target–distractor relationships in guiding attention and the eyes in visual search. *Journal of Experimental Psychology: General*, *139*(2), 247–265. https://doi.org/10.1037/a0018808

Becker, S. I., Folk, C. L., & Remington, R. W. (2013). Attentional capture does not depend on feature similarity, but on target-nontarget relations. *Psychological Science*, *24*(5), 634–647. https://doi.org/10.1177/0956797612458528

Becker, S. I., Martin, A., & Finlayson, N. J. (2019). At what stage of the visual processing hierarchy is visual search relational and context-dependent vs. feature-specific? *Journal of Vision*, *19*(10), Article 132b. https://doi.org/10.1167/19.10.132b

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision*, *10*(4), 433436. https://doi.org/10.1163/156856897X00357

Brown, T., Hurly, T. A., Healy, S. D., & Tello-Ramos, M. C. (2022). Size is relative: Use of relational concepts by wild hummingbirds. *Proceedings of the Royal Society B: Biological Sciences*, *289*(1971), Article 20212508. https://doi.org/10.1098/rspb.2021.2508

Chelazzi, L., Eštočinová, J., Calletti, R., Lo Gerfo, E., Sani, I., Della Libera, C., & Santandrea, E. (2014). Altering spatial priority maps via reward-based learning. *The Journal of Neuroscience*, *34*(25), 8594–8604. https://doi.org/10.1523/JNEUROSCI.0277-14.2014

Conway, B. R. (2001). Spatial structure of cone inputs to color cells in alert macaque primary visual cortex (V-1). *The Journal of Neuroscience*, *21*(8), 2768–2783. https://doi.org/10.1523/JNEUROSCI.21-08-02768.2001

De Valois, R. L., Cottaris, N. P., Elfar, S. D., Mahon, L. E., & Wilson, J. A. (2000). Some transformations of color information from lateral geniculate nucleus to striate cortex. *Proceedings of the National Academy of Sciences*, *97*(9), 4997–5002. https://doi.org/10.1073/pnas.97.9.4997

Epstein, R. A., Patai, E. Z., Julian, J. B., & Spiers, H. J. (2017). The cognitive map in humans: Spatial navigation and beyond. *Nature Neuroscience*, *20*(11), 1504–1513. https://doi.org/10.1038/nn.4656

Failing, M. F., & Theeuwes, J. (2015). Nonspatial attentional capture by previously rewarded scene semantics. *Visual Cognition*, *23*(1–2), 82–104. https://doi.org/10.1080/13506285.2014.990546

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

Faul, F., Erdfelder, E., Lang, A. G., & Buchner, A. (2007). G*Power 3: A flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behavior Research Methods*, *39*(2), 175–191. https://doi.org/10.3758/BF03193146

Gong, M., & Chen, Y. (2022, April 27). *Reward history modulates attention based on feature relationship*. Open Science Framework. https://osf.io/qvmfa/

Gong, M., Jia, K., & Li, S. (2017). Perceptual competition promotes suppression of reward salience in behavioral selection and neural representation. *The Journal of Neuroscience*, *37*(26), 6242–6252. https://doi.org/10.1523/JNEUROSCI.0217-17.2017

Gong, M., & Li, S. (2014). Learned reward association improves visual working memory. *Journal of Experimental Psychology: Human Perception and Performance*, *40*(2), 841–856. https://doi.org/10.1037/a0035131

Gong, M., & Liu, T. (2018). Reward differentially interacts with physical salience in feature-based attention. *Journal of Vision*, *18*(11), Article 12. https://doi.org/10.1167/18.11.12

Gong, M., Yang, F., & Li, S. (2016). Reward association facilitates distractor suppression in human visual search. *European Journal of Neuroscience*, *43*(7), 942–953. https://doi.org/10.1111/ejn.13174

Gotlib, I. H., & Joormann, J. (2010). Cognition and depression: Current status and future directions. *Annual Review of Clinical Psychology*, *6*(1), 285–312. https://doi.org/10.1146/annurev.clinpsy.121208.131305

Grégoire, L., Kim, A. J., & Anderson, B. A. (2021). Semantic generalization of punishment-related attentional priority. *Visual Cognition*, *29*(5), 310–317. https://doi.org/10.1080/13506285.2021.1914796

Hafri, A., & Firestone, C. (2021). The perception of relations. *Trends in Cognitive Sciences*, *25*(6), 475–492. https://doi.org/10.1016/j.tics.2021.01.006

Hamblin-Frohman, Z., & Becker, S. I. (2021). The attentional template in high and low similarity search: Optimal tuning or tuning to relations? *Cognition*, *212*, Article 104732. https://doi.org/10.1016/j.cognition.2021.104732

Hickey, C., Chelazzi, L., & Theeuwes, J. (2010). Reward changes salience in human vision via the anterior cingulate. *Journal of Neuroscience*, *30*(33), 11096–11103. https://doi.org/10.1523/JNEUROSCI.1026-10.2010

Hickey, C., Kaiser, D., & Peelen, M. V. (2015). Reward guides attention to object categories in real-world scenes. *Journal of Experimental Psychology: General*, *144*(2), 264–273. https://doi.org/10.1037/a0038627

Itthipuripat, S., Vo, V. A., Sprague, T. C., & Serences, J. T. (2019). Value-driven attentional capture enhances distractor representations in early visual cortex. *PLOS Biology*, *17*(8), Article e3000186. https://doi.org/10.1371/journal.pbio.3000186

JASP Team (2022). *JASP* (Version 0.16.3) [Computer software].

Kahnt, T., & Tobler, P. N. (2016). Dopamine regulates stimulus generalization in the human hippocampus. *eLife*, *5*, Article e12678. https://doi.org/10.7554/eLife.12678

Lee, J., & Shomstein, S. (2014). Reward-based transfer from bottom-up to top-down search tasks. *Psychological Science*, *25*(2), 466–475. https://doi.org/10.1177/0956797613509284

Liao, M. R., Britton, M. K., & Anderson, B. A. (2020). Selection history is relative. *Vision Research*, *175*, 23–31. https://doi.org/10.1016/j.visres.2020.06.004

Lucantonio, F., Kambhampati, S., Haney, R. Z., Atalayer, D., Rowland, N. E., Shaham, Y., & Schoenbaum, G. (2015). Effects of prior cocaine versus morphine or heroin self-administration on extinction learning driven by overexpectation versus omission of reward. *Biological Psychiatry*, *77*(10), 912–920. https://doi.org/10.1016/j.biopsych.2014.11.017

Martin, A., & Becker, S. I. (2018). How feature relationships influence attention and awareness: Evidence from eye movements and EEG. *Journal of Experimental Psychology: Human Perception and Performance*, *44*(12), 1865–1883. https://doi.org/10.1037/xhp0000574

Martinez-Trujillo, J. C., & Treue, S. (2004). Feature-based attention increases the selectivity of population responses in primate visual cortex. *Current Biology*, *14*(9), 744–751. https://doi.org/10.1016/j.cub.2004.04.028

Ornelas, J. F., Ordano, M., De-Nova, A. J., Quintero, M. E., & Garland, T. (2007). Phylogenetic analysis of interspecific variation in nectar of hummingbird-visited plants. *Journal of Evolutionary Biology*, *20*(5), 1904–1917. https://doi.org/10.1111/j.1420-9101.2007.01374.x

Pearson, D., Osborn, R., Whitford, T. J., Failing, M., Theeuwes, J., & Le Pelley, M. E. (2016). Value-modulated oculomotor capture by task-irrelevant stimuli is a consequence of early competition on the saccade map. *Attention, Perception, & Psychophysics*, *78*(7), 2226–2240. https://doi.org/10.3758/s13414-016-1135-2

Peterson, D. J., & Berryhill, M. E. (2013). The Gestalt principle of similarity benefits visual working memory. *Psychonomic Bulletin & Review*, *20*(6), 1282–1289. https://doi.org/10.3758/s13423-013-0460-x

Rajsic, J., Perera, H., & Pratt, J. (2017). Learned value and object perception: Accelerated perception or biased decisions? *Attention, Perception, & Psychophysics*, *79*(2), 603–613. https://doi.org/10.3758/s13414-016-1242-0

Shastri, L. (2002). Episodic memory and cortico-hippocampal interactions. *Trends in Cognitive Sciences*, *6*(4), 162–168. https://doi.org/10.1016/s1364-6613(02)01868-5

Shohamy, D., Mihalakos, P., Chin, R., Thomas, B., Wagner, A. D., & Tamminga, C. (2010). Learning and generalization in schizophrenia: Effects of disease and antipsychotic drug treatment. *Biological Psychiatry*, *67*(10), 926–932. https://doi.org/10.1016/j.biopsych.2009.10.025

Summerfield, C., Luyckx, F., & Sheahan, H. (2020). Structure learning and the posterior parietal cortex. *Progress in Neurobiology*, *184*, Article 101717. https://doi.org/10.1016/j.pneurobio.2019.101717

Wagemans, J., Feldman, J., Gepshtein, S., Kimchi, R., Pomerantz, J. R., van der Helm, P. A., & van Leeuwen, C. (2012). A century of Gestalt psychology in visual perception: II. Conceptual and theoretical foundations. *Psychological Bulletin*, *138*(6), 1218–1252. https://doi.org/10.1037/a0029334

Wagenmakers, E.-J. (2007). A practical solution to the pervasive problems of p values. *Psychonomic Bulletin & Review*, *14*(5), 779–804. https://doi.org/10.3758/BF03194105

Yu, X., Hanks, T. D., & Geng, J. J. (2022). Attentional guidance and match decisions rely on different template information during visual search. *Psychological Science*, *33*(1), 105–120. https://doi.org/10.1177/09567976211032225