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RESEARCH

Reward delays quitting in visual search

Guanlan Kang[1] · Xiaoxiao Luo[2,3] · Lihan Chen[4] · Jialiang Chen[2] · Jiahan Chen[2] · Hengsen Dai[2] · Xiaolin Zhou[2,4,5]

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Abstract

Reward motivates goal-directed behaviors, leading to faster reaction time (RT) and lower error rate in searching for a target in the reward condition than in the no-reward condition in target-discrimination tasks. However, it is unclear how reward influences target detection in which participants are required to judge whether a predesignated target is present or absent. Here, we asked participants to complete a target-detection search task in which the color of the search array indicated the reward availability of the current trial. Correct and faster (than a baseline) responses would be rewarded if the search array had the reward-related color. In Experiments 1A and 1B, the target was presented in 50% of the trials. Experiment 1B had the same design as Experiment 1A, except that different baselines were set for the target-present and target-absent conditions. In Experiment 2, the proportion of target presence was manipulated to be high (80%), moderate (50%), or low (20%) in different blocks of stimuli. Results showed that, across all the experiments, participants responded faster and made fewer errors in the reward than in the no-reward condition when the target was present. However, this facilitatory effect was reversed when the target was absent, showcasing a reward-induced interference. The signal detection analysis suggested that reward biased the report criterion to the "yes" response. These findings demonstrate that the impact of reward on goal-directed behavior can be detrimental and reward prolongs the search process by rendering participants reluctant to say "no" in visual search termination.

Introduction

Visual search is ubiquitous in daily life, by which humans and animals find a specific target (e.g., food, dangerous goods, etc.) that is important for surviving. The issues of how the salient property of a stimulus, individuals' internal goal, or selection history affect individuals' search for the target among distractors has been extensively examined in the past (e.g., Awh et al., 2012; Anderson et al., 2021; Corbetta & Shulman, 2002). A commonly used paradigm is "target-discrimination search", in which a target is always present in the search array and individuals are required to find the target and discriminate it from another possible, competing target (e.g., Kiss et al., 2009; Hickey et al., 2010). In many real-world situations, however, a target appears only occasionally, e.g., in security check or medical image screening. Unlike the "target-discrimination search", the paradigm of the "target-detection search", in which the target can be absent in the search array, is often used to investigate how individuals conduct visual search in a target-absent situation (e.g., Moher, 2020; Wolfe et al., 2005); individuals need to make a decision to quit the search at some point of time if a target is not found. The target prevalence, i.e., the probability of the target appearing in the search array, could significantly influence behavioral performance, leading to shorter reaction times (RTs) on the "absent" trials and higher miss rates and biased responses to the "present" trials in the low prevalence condition than in the high prevalence condition

Guanlan Kang and Xiaoxiao Luo contributed equally to the study.

✉ Xiaolin Zhou
xz104@psy.ecnu.edu.cn

1 School of Psychology, Laboratory of Sports Stress and Adaptation of General Administration of Sport, Beijing Sport University, Beijing, China

2 Shanghai Key Laboratory of Mental Health and Psychological Crisis Intervention, School of Psychology and Cognitive Science, East China Normal University, Shanghai 200062, China

3 Faculty of Education, Yunnan Normal University, Kunming, China

4 School of Psychological and Cognitive Sciences and Beijing Key Laboratory of Behavior and Mental Health, Peking University, Beijing, China

5 PKU-IDG/McGovern Institute for Brain Research, Peking University, Beijing, China

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(e.g., Chun & Wolfe, 1996; Godwin et al., 2015; Peltier & Becker, 2016; Wolfe & Van Wert, 2010; Wolfe et al., 2005).

Reward (or value) is a dominant factor that affects visual search (Anderson et al., 2011; Eckstein, 2011; Wolfe, 2021). For the target-discrimination search in which a target is always present, compared with the no-reward condition, when the search task is rewarded or the target is associated with reward, individuals perform more efficiently in searching for the target, with shorter RTs and lower error rates (e.g., Kiss et al., 2009; Bachman et al., 2020; Hickey et al., 2010; Hickey et al., 2015; Lee & Shomstein, 2014; Wang et al., 2013). For the target-detection search where the target could be absent, it has been theoretically assumed that the time to quit the search could be affected by reward (Wolfe, 2012), but much less effort has been made to empirically test the effect of reward on the target-detection search. Indeed, it seems there is only one study that has investigated how value (reward and punishment) affects the target-detection performance (Navalpakkam et al., 2009). In Navalpakkam et al. (2009), the reward scheme was manipulated non-linearly, e.g., increasing reward for detecting a target and penalty for missing a target in the low target prevalence condition. They found that increasing reward for the target detection would compensate for decreasing detection rate caused by target rarity when participants were in a contest. Moreover, the model that combined reward and sensory information could better describe participants' behavior. Nevertheless, a few improvements are wanted. First, Navalpakkam et al. (2009) used a paradigm in which the search display was presented briefly (50 ms). This could be quite different from a real-world search task. Second, Navalpakkam et al. (2009) used a scheme such that correct detections and rejections would be rewarded, and target misses and false alarms would get punished. This manipulation could conflate the effects of reward and punishment. In the current study, the search display was presented until a response was made or until 3000 ms elapsed with no response, and only reward was delivered (i.e., no punishment). There are at least two questions that have not been answered by Navalpakkam et al. (2009) but will be addressed by the current study.

Firstly, it is unclear how reward facilitates the performance of target-detection search in a simple reward context without punishment. Specifically, the facilitatory effect of reward on visual search could be due to (1) reward enhancing the perceptual sensitivity to the target (i.e., the ability to detect or discriminate the target); (2) reward changing the response criterion (i.e., the tendency to favor one response over another); and (3) reward affecting both the perceptual sensitivity and response criterion. On the one hand, it has been shown that reward can enhance the perception of the target (e.g., increasing *d'* in the signal detection analysis) in a cue-target paradigm in which the location of the target is pre-indicated by a cue (Engelmann et al., 2009; Pessoa & Engelmann, 2010). Using the visual-discrimination search task, Kiss et al. (2009) found that associating high reward with the target could increase the saliency of the target, leading to a larger N2pc, a neurophysiological marker of the relatively early cortical visual processing in event-related potentials (ERPs) as compared with associating low reward with the target (see also Chelazzi et al., 2013). On the other hand, by applying the signal detection analysis, some other studies showed that reward did not affect the perception of the target but the response criterion (Bowen et al., 2020; Healy & Kubovy, 1981; Maddox, 2002), although these studies did not use the visual search task. Moreover, it is also possible that reward affects both the perception and the response criterion, as we have shown in an audiovisual perception task (Luo et al., 2020). In this study, the signal detection *d'* for the McGurk perception was higher, and the response criterion *c* was lower when the audiovisual stimulus contained a reward-associated face as compared with a no-reward-associated face. It is unclear at what level of processing (i.e., perception vs. response) does reward enhance visual detection of the target.

Secondly, and more importantly to the present purpose, it is unclear how value or reward would affect search termination if a target is not present in the search array. In the target-detection search paradigm, terminating the search at the right time in target-absent situations is of great importance because it helps to save resources and to prepare for the upcoming new information. Since reward is associated with the target, when the rewarded target is not present, how does reward affect the system to make a "no" judgment? The current study is to test to what extent reward could modulate the perceptual sensitivity and/or the response criterion when the system decides to quit the visual detection search process.

The present study comprised two visual-detection search experiments in which reward expectation was manipulated by the color of the search array (e.g., the yellow indicating that a fast and correct response would be rewarded for this trial, while the cyan indicating that no reward would be given in this trial). This reward rule was suitable for the present purpose by which the target-absent trials could be differentiated into "reward" and "no-reward" conditions. Given the generally longer search time in the target-absent trials than the target-present trials, different baselines were set for the target-present condition and the target-absent condition in Experiment 1B, in contrast to Experiment 1A. Importantly, while in Experiments 1A and 1B the target appeared in 50% trials (i.e., with equal number of target-present and target-absent trials), the target prevalence in Experiment 2 was further manipulated (20%, 50%, 80%) to replicate and extend the findings of Experiment 1. The signal detection analysis was applied to the data to further examine how reward affects the perceptual sensitivity and response criterion in the visual-detection search task.

Method

Participants

Two groups of college students or graduate students took part in Experiment 1A (33 participants, 5 males, 18–26 years old) and Experiment 1B (34 participants, 10 males, 18–27 years old), and another group of 34 college students or graduate students (17 males, 18–25 years old) took part in Experiment 2 for monetary compensation. All the participants were right-handed, with normal or corrected-to-normal vision. Two participants' data were excluded due to an experimental setting problem (one for Experiment 1A, and one for Experiment 2); another participant' s data in Experiment 1A were also excluded due to his high error rates (beyond 3 *SD* of the group mean). Statistical analyses were hence conducted on 31 participants (5 males, $M_{age}=22.3$, $SD=2.6$) in Experiment 1A, 34 participants (10 males, $M_{age}=22.2$, $SD=1.7$) in Experiment 1B, and 33 participants (16 males, $M_{age}=21.9$, $SD=1.6$) in Experiment 2. All the participants provided with informed consent to participate in this study. The study protocol was conducted in accordance with the ethical research standards of the amended declaration of Helsinki.

Stimuli and procedures

Participants were tested individually in a dimly-lighted and quiet room. They were first given instructions concerning the task and procedures of the study. Experiments were run with Psychophysics Toolbox (Brainard, 1997, http://www.psychtoolbox.org/) on Matlab.

Experiment 1: target-detection search with 50% target prevalence

Both Experiments 1A and 1B had a 2 (reward vs. no-reward) by 2 (target-present vs. target-absent) factorial design comprising 4 experimental conditions (reward_target-present, reward_target-absent, no-reward_target-present, no-reward_target-absent). Each experiment had 288 trials, which were divided into 4 blocks. Each block had 72 trials with 18 trials for each of the 4 experimental conditions. Following previous studies (e.g., Kang et al., 2019; Padmala & Pessoa, 2011; Wei et al., 2016), a uniform baseline was set up in Experiment 1A, which was the mean RT of 24 practice trials covering both the target-present and -absent conditions (but only correct responses were included). Given the generally longer search times in the target-absent trials than in the target-present trials (Godwin et al., 2015; Moher, 2020; Wolfe et al., 2005), the mean RT for the target-present trials was likely to be shorter than the RT for the target-absent trials. This would lead to a situation in which the criteria of reward in the target-absent condition are hard to meet and there is a smaller proportion of rewarded trials for the target-absent condition than for the target-present condition. To address this issue, in Experiment 1B, we set up two RT baselines for reward, one based on 24 practice trials for the target-present condition and one based on 24 practice trials for the target-absent condition.

Each trial (Fig. 1) started with a fixation point (0.15° × 0.15°) presented in the center of the screen, lasting 400–600 ms. The search array consisted of 6 circles (with radius of 0.8°) presented with equal distance along an imaginary circle of a 3.5° radius at the center of the screen. Each circle included a white bar (0.5° in length) inside with a slope (selected from 15°, 30°, 45°, 60°, 75°, 90°, 105°, 120°, 135°, 145°). The color of the search array (6 circles) could be yellow or cyan. For half of the participants, the yellow array indicated a reward trial for which a correct response with the RT faster than a baseline (mean RT in practice trials for each participant) would be rewarded, while the cyan array indicated a no-reward trial for which no reward would be given. For the other half of participants, the color-reward mapping was reversed. Participants were asked to judge if there was a vertical bar (90°) in the search array by pressing "K" or "L" on the keyboard using the index or middle fingers of the right hand. The matching of response key ("K" vs. "L") and target presence (present vs. absent) was counterbalanced across participants. The target bar was presented in 50% of the trials. The search array would be presented for 3 s or until a response was given. Feedback was presented for 800 ms after the offset of the search array. If the current trial

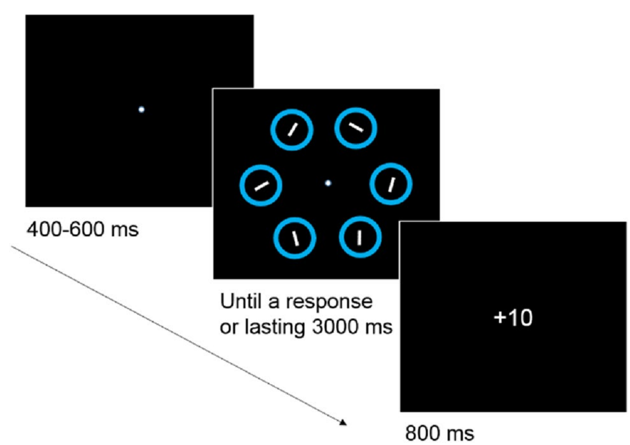

Fig. 1 An example trial of Experiment 1. The color of the search display indicated the reward availability of the current trial. The search array would be presented for 3 s or until a response was given. Feedback was presented for 800 ms after the offset of the search array

was a reward trial, a reward-feedback ("+10 points") would be presented after a correct response with the RT faster than the baseline; a correct-feedback ("correct") would be presented after a correct response with the RT slower than the baseline; an incorrect-feedback ("wrong") would be presented after an incorrect response; a slow-feedback ("too slow") would be presented if no response was given during the display of the search array. If the current trial was a no-reward trial, the reward-feedback would be removed and only a correct-feedback, incorrect-feedback, or a slow-feedback would be presented for a trial.

Before the formal experiment, participants needed to complete practice trials without reward information. Participants were asked to respond as quickly and as correctly as possible in the practice phase. For a specific participant, the RT baseline would be computed as the mean RT of all the practice trials in Experiment 1A, while the RT baselines for the target-present condition and the target-absent condition were computed separately in Experiment 1B based on responses to the target-present and the target-absent trials, respectively. Participants were informed that they would win 10 points per trial if their responses met the criterion in the reward trials and no points would be given in other situations. At the end of the experiment, the points were accumulated and exchanged for cash according to a proportion of 100:1 (i.e., for each 100 points, they earned 1 Chinese Yuan, 1 Yuan ≈ \$0.15). Participants could earn up to 14.4 Chinese Yuan as reward, which would be added to their basic payment for taking part in the experiment. Experiments 1A and 1B took approximately 20 min to complete each.

Experiment 2: target-detection task with different target prevalence conditions

The stimuli and procedure of Experiment 2 was the same as Experiment 1, except that the target prevalence was manipulated to be low (20%), moderate (50%), or high (80%). Thus, the experiment had 2 (reward vs. no-reward) by 2 (target-present vs. target-absent) by 3 (target prevalence: 20% vs. 50% vs. 80%) factorial design. Given that the reward effects in Experiments 1A and 1B were consistent regardless of baseline setting, a uniform baseline was adopted in Experiment 2, in line with the manipulations in Experiment 1 and with previous studies (e.g., Kang et al., 2019; Padmala & Pessoa, 2011; Wei et al., 2016). Specifically, the baseline was set up as the mean RT of 24 practice trials with equal number of the target-present and -absent conditions before the formal experiment. There were 900 trials in total with 300 trials in each target prevalence condition. For the low prevalence condition, there were 30 trials for the reward_target-present condition and no-reward_target-present condition, respectively, and 120 trials for the reward_target-absent and no-reward_target-absent conditions, respectively. There were 75 trials for each reward and target presence condition in the moderate (i.e., 50%) condition. For the high prevalence condition, there were 30 trials for the reward_target-absent condition and no-reward_target-absent condition, respectively, and 120 trials for the reward_target-present and no-reward_target-present conditions, respectively. All the trials were divided into 9 blocks (100 trials per block) with 3 low prevalence blocks, 3 moderate (50%) prevalence blocks and 3 high prevalence blocks. The prevalence of the target was informed to participants by a word cue, such as "high target prevalence 80%", at the beginning of each block. The order of the blocks was random between participants. Participants had a one-minute break between blocks.

Experiment 2 contained more trials and took more time (approximate 50 min) than Experiment 1. The conversion ratio of points to cash was 150:1. Participants could earn up to 30 Chinese Yuan as reward, which would be added to their basic payment (20 Chinese Yuan) for taking part in the experiment.

Statistical analysis

For the analysis of the RT, incorrect trials and trials without responses were discarded. Trials with RT beyond 3 *SD* of the mean RT of each experimental condition were also excluded. There were 88.4% trials remained for the RT analysis in Experiment 1A, 90.9% trials in Experiment 1B, and 93.8% trials in Experiment 2. Error rate was calculated as the proportion of incorrect trials and omissions. In Experiment 1A, the percentage of incorrect trials was 10.73% and the percentage of omissions was 0.02%. In Experiment 1B, the percentage of incorrect trials was 8.33%, and the percentage of omissions was 0.14%. In Experiment 2, the percentage of incorrect trials was 5.25% and the percentage of omissions was 0.06% (see the *Supplementary Materials* for more details). In Experiments 1A and 1B, 2 (reward: reward vs. no-reward) × 2 (target presence: target-present vs. target-absent) analysis of variance (ANOVA) was applied to both the RT and the error rate. Given that we observed the same pattern of effects in Experiments 1A and 1B, we conducted three-way ANOVA and reported here only the combined analyses of Experiment 1, treating the two sub-experiments as a between-participants factor. In Experiment 2, the 2 (reward: reward vs. no-reward) × 3 (target prevalence: low vs. moderate vs. high) × 2 (target presence: target-present vs. target-absent) ANOVA was conducted on the RT and error rate.

A signal detection analysis was also conducted. We calculated the response criterion (c) and the sensitivity (d') for the reward condition and the no-reward condition. Specifically, "hit" was defined by a "present" response for the target-present trials, "false alarm" was defined by a "present" response for the target-absent trials. The hit rate (P_H)

and the false alarm rate (P_{FA}) were calculated to obtain the c [-($Z_H + Z_{FA}$)/2] and the d' [Z_H-Z_{FA}] for each participant. Considering that the P_H or P_{FA} could be 0 or 1 in some conditions for some participants, we replaced 0 with 0.5/N, and 1 with 1–0.5/N, in which N was the number of target-present or -absent trials (Stanislaw & Todorov, 1999). For Experiments 1A and 1B, paired *t*-test was conducted on d' and c. Given that we observed the same pattern of effects in Experiments 1A and 1B, we conducted 2-by-2 ANOVA with Experiment (1A, 1B) as a between-participant factor, and reward as the within-participant factor, and reported here only the combined analyses of Experiment 1. In Experiment 2, the 3-by-2 ANOVA was conducted on the c and d', with reward and target prevalence as two within-participant factors.

In addition, we analyzed the proportion of rewarded trials, i.e., the proportion of trials in which participants actually gained reward in the reward condition, to explore the reward-induce behavior differences between the target-present and target-absent trials. To study the potential influence of the ways of the baselines were set up on the reward-induced behavior, we conducted 2-by-2 ANOVA combining Experiments 1A and 1B, with experiment as the between-participants factor, and target presence as the within-participant factor. In Experiment 2, 2-by-3 ANOVA was conducted on the proportion of rewarded trials.

Results

Experiment 1: target-detection search with 50% target prevalence

Reaction time

The three-way ANOVA on RTs (see Fig. 2 and Table 1), with Target presence and Reward as two within-participant factors and Experiment as a between-participants factor, showed a significant main effect of target presence, F (1, 63) = 157.897, $p < 0.001$, $\eta_p^2 = 0.715$, with shorter RT in the target-present conditions than in the target-absent conditions (860 vs. 1059 ms). Although the main effect of reward did not reach significance, F (1, 63) = 3.355, $p > 0.07$, $\eta_p^2 = 0.051$, the interaction between reward and target presence did, F (1, 63) = 36.967, $p < 0.001$, $\eta_p^2 = 0.370$. Planned *t*-tests showed that the RT was shorter in the reward condition than in the no-reward condition for the target-present trials (840 vs. 883 ms, $p < 0.001$), but the pattern was reversed for the target-absent trials (1071 vs. 1050 ms, $p = 0.027$). The main effect of experiment or interactions between experiment and other factors did not reach significance ($ps > 0.3$).

It appeared that sizes of the reward effects (i.e., RT differences between the no-reward and the reward conditions) were asymmetric, with the size of the reward effect larger for the target-present condition than for the target-absent condition (Experiments 1A: 46 vs. 18 ms; Experiment 1B: 41 vs. 21 ms). Given that the negative reward effect (reward-induced interference) appeared in the target-absent condition, we converted the negative reward effect value to a positive value by adding a negative sign. To formally test this potential asymmetry, we conducted a 2-by-2 ANOVA,

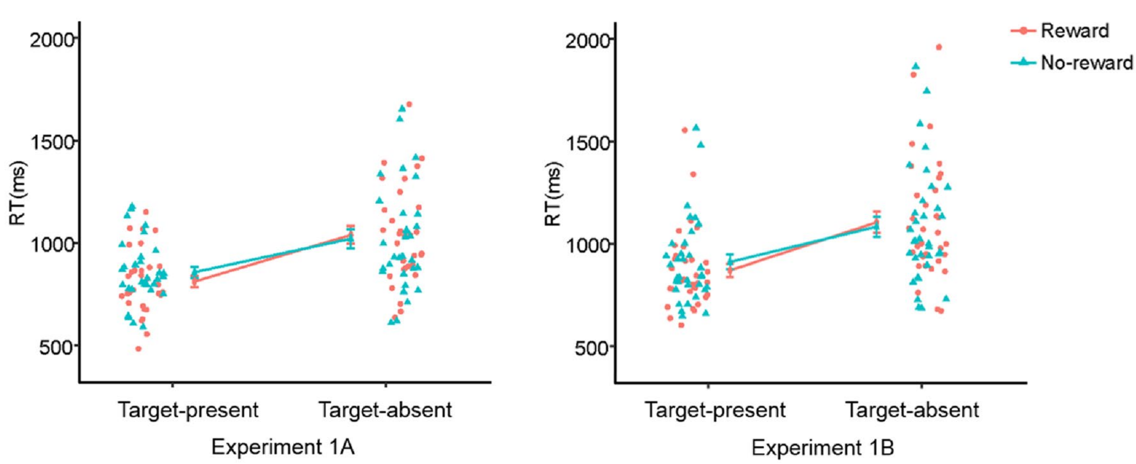

Fig. 2 Reaction times in each experimental condition in Experiments 1A and 1B. The individual data and means with standard errors are shown on the plot. Reward facilitated behavioral performance in the target-present condition, but this pattern was reversed in the target-absent condition

Table 1 Mean reaction times and error rates with standard errors in parentheses in each experimental condition for Experiments 1A, 1B and 2

	Experiment 1A	Experiment 1B	Experiment 2		
			Low	Moderate	High
Reaction time (ms)					
Present					
Reward	812 (28)	865 (33)	871 (28)	820 (26)	780 (27)
No-reward	858 (27)	906 (36)	902 (35)	850 (32)	824 (30)
Absent					
Reward	1039 (43)	1099 (51)	1002 (45)	1096 (44)	1211 (44)
No-reward	1021 (41)	1078 (49)	961 (48)	1080 (46)	1200 (45)
Error rate (%)					
Present					
Reward	14.0 (1.5)	11.0 (1.2)	16.0 (2.6)	8.8 (1.1)	3.5 (0.6)
No-reward	19.9 (2.3)	16.6 (1.6)	22.7(2.9)	11.1 (1.6)	5.5 (0.7)
Absent					
Reward	5.8 (1.2)	3.9 (0.5)	1.3 (0.2)	2.9 (0.7)	6.0 (2.0)
No-reward	3.4 (0.6)	2.4 (0.4)	1.5 (0.4)	2.3 (0.4)	4.7 (1.1)

with Target presence (target-present vs. target-absent) as a within-participant factor and Experiment (Experiment 1A vs. 1B) as a between-participant factor. Results showed only a marginal main effect of target presence, $F\ (1, 63) = 3.348$, $p = 0.072$, $\eta_p^2 = 0.050$, and no interaction between the two factors, $F\ (1, 63) = 0.083$, $p = 0.775$, $\eta_p^2 = 0.001$.

Error rate

The error rates are shown in Table 1 and Fig. 3. The three-way ANOVA found a significant main effect of target presence, $F\ (1, 63) = 195.640$, $p < 0.001$, $\eta_p^2 = 0.756$, and a main effect of reward, $F\ (1, 63) = 13.152$, $p = 0.001$, $\eta_p^2 = 0.173$. Participants made more errors in the target-present conditions than in the target-absent conditions (15.4% vs. 3.9%), and made less errors in the reward conditions than in the no-reward conditions (8.7% vs. 10.6%). In line with RT results, the interaction between reward and target presence was significant, $F\ (1, 63) = 25.304$, $p < 0.001$, $\eta_p^2 = 0.287$. Planned *t*-tests showed a lower error rate in the reward condition than in the no-reward condition for the target-present trials (12.5% vs. 18.1%, $p < 0.001$), but an opposite pattern for the target absent trials (4.8% vs. 2.9%, $p = 0.002$). The main effect of experiment or interactions between experiment and other factors did not reach significance ($ps > 0.1$).

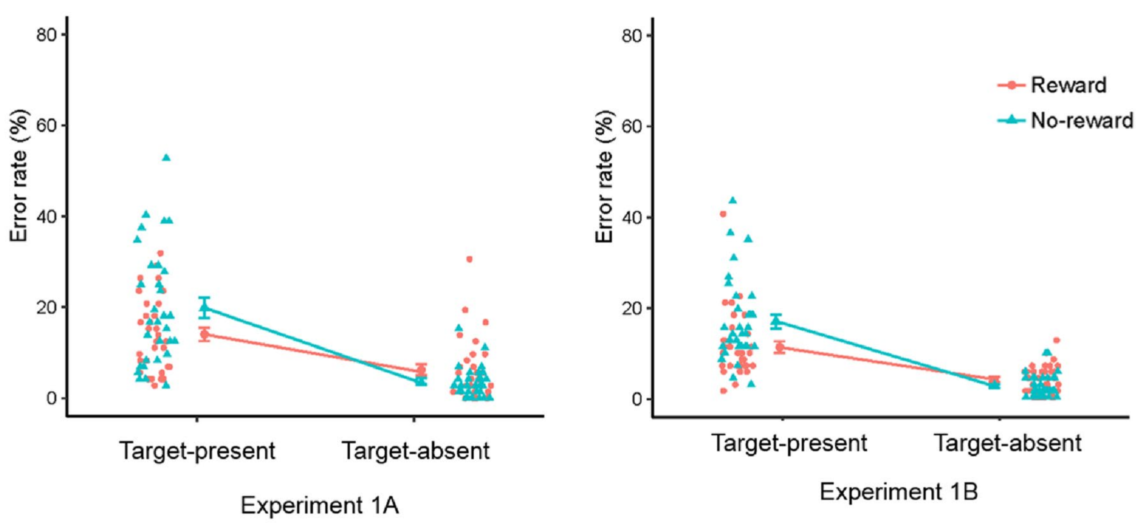

Fig. 3 Error rates in each experimental condition of Experiments 1A and 1B. The individual data and means with standard errors are shown on the plot

Signal detection analysis

The 2-by-2 ANOVA on *c*, with Reward as a within-participant factor and Experiment as a between-participant factor, showed a main effect of reward, F (1, 63) = 24.981, $p < 0.001$, $\eta_p^2 = 0.284$, with lower *c* in the reward trials than in the no-reward trials (0.30 vs. 0.51), suggesting that participants were more inclined to report "yes" in the reward condition than in the no-reward condition. The main effect of experiment or interaction between experiment and reward did not reach significance ($ps > 0.6$).

The 2-by-2 ANOVA on *d*' showed no main significant effect of either Reward or Experiment, $ps > 0.3$. These results suggested that the discriminability had no differences between the reward and no-reward conditions, and between Experiments 1A and 1B.

The proportion of rewarded trials

The 2-by-2 ANOVA showed an interaction between Experiment and Target presence, F (1, 63) = 10.358, $p = 0.002$, $\eta_p^2 = 0.141$. Planned *t*-tests showed a higher proportion of rewarded trials in the target-present condition than in the target-absent condition in Experiment 1A (76.5% vs. 69.3%), t (30) = 2.803, $p = 0.009$, but no significant difference in the Experiment 1B (80.4% vs. 77.6%), t (33) = 1.564, $p = 0.127$. Independent *t*-test also showed a significant difference between Experiments 1A and 1B for the target-absent trials, t (63) = 2.912, $p = 0.005$, suggested that the uniform baseline in Experiment 1A had led to a lower proportion of rewarded trials in the target-absent condition as compared with the specific baseline for the target-absent trials in Experiment 1B. Given that results of RT and error rate showed the same pattern in Experiments 1A and 1B, we could conclude that the difference on reward proportion would not affect the pattern of reward effect.

Experiment 2: target-detection task with different target prevalence conditions

Reaction time

The three-way ANOVA on RTs (see Fig. 4 and Table 1) found a significant main effect of target presence, F (1, 32) = 145.730, $p < 0.001$, $\eta_p^2 = 0.820$, with faster in the target-present trials than in the target-absent trials (841 vs. 1092 ms). ANOVA also obtained a significant main effect of target prevalence, F (2, 64) = 11.278, $p < 0.001$, $\eta_p^2 = 0.261$. Participants generally responded faster in the low prevalence and the moderate (50%) conditions than in the high prevalence conditions (low: 934; moderate: 962; high: 1004 ms, $ps < 0.05$), with a significant linearity over the three conditions, F (1, 32) = 20.811, $p < 0.001$, $\eta_p^2 = 0.394$. Importantly, although the main effect of reward did not reach significance ($p > 0.5$), there were significant interactions between reward and target presence, F (1, 32) = 28.772, $p < 0.001$, $\eta_p^2 = 0.473$, and between target prevalence and target presence, F (2, 64) = 130.007, $p < 0.001$, $\eta_p^2 = 0.802$. Other interactions did not reach significance ($ps > 0.09$).

To explore the interaction between reward and target presence, we merged the data across different target prevalence conditions and conducted a 2-by-2 ANOVA. Results showed a main effect of target presence (841 vs. 1092 ms), F (1, 32) = 145.669, $p < 0.001$, $\eta_p^2 = 0.820$, and an interaction between reward and target presence, F (1, 32) = 28.573, $p < 0.001$, $\eta_p^2 = 0.472$. Planned *t*-tests showed that the RT was shorter in the reward condition than in the no-reward condition for the target-present trials (823 vs. 859 ms, $p = 0.026$), but the RT was longer in the reward condition than in the no-reward condition for the target-absent trials (1103 vs. 1080 ms, $p = 0.028$).

To explore the interaction between target prevalence and target presence, we merged the data from reward and no reward conditions, and conducted a 3-by-2 ANOVA. Results

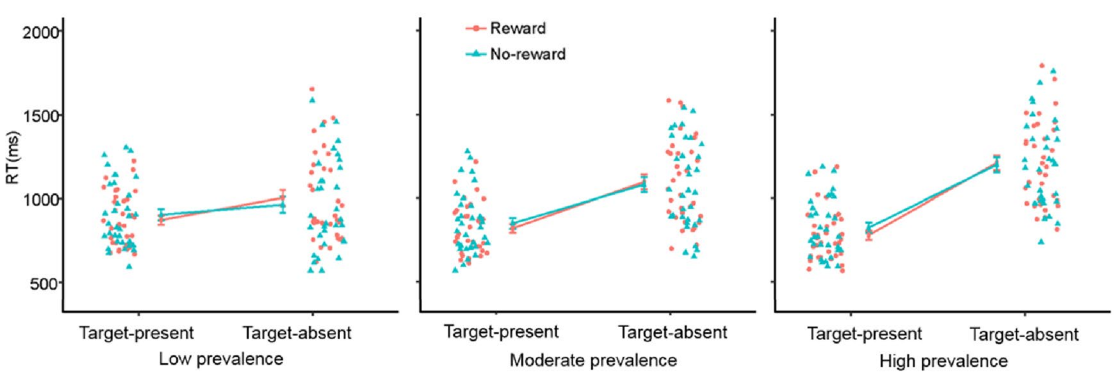

Fig. 4 Reaction times in each experimental condition in Experiment 2. The individual data and means with standard errors are shown on the plot. Reward facilitated behavioral performance in the target-present condition, but this effect was reversed in the target absent condition. The interaction pattern between reward and target presence was consistent across different target prevalence conditions

showed main effects of target prevalence, F (2, 64) = 11.285, $p < 0.001$, $\eta_p^2 = 0.261$, target presence, F (1, 32) = 145.716, $p < 0.001$, $\eta_p^2 = 0.820$, and an interaction between the two variables, F (2, 64) = 130.158, $p < 0.001$, $\eta_p^2 = 0.803$. One-way ANOVA for the target-present trials found a significant main effect, F (2, 64) = 19.325, $p < 0.001$, $\eta_p^2 = 0.377$, with the RT decreasing linearly as a function of target prevalence (low: 886, moderate: 835, high: 802, $ps < 0.05$), F (1, 32) = 30.969, $p < 0.001$, $\eta_p^2 = 0.492$. For the target-absent trials, the one-way ANOVA showed a main effect of target prevalence, F (2, 64) = 57.991, $p < 0.001$, $\eta_p^2 = 0.644$. with the RT increasing linearly as a function of target prevalence (low: 981, moderate: 1088, high: 1205 ms, $ps < 0.05$), F (1, 32) = 93.704, $p < 0.001$, $\eta_p^2 = 0.745$.

Again, the sizes of reward effects (i.e., RT differences between the no-reward and the reward conditions) appeared to be asymmetric for the moderate and high target prevalence conditions (30 vs. 16 ms, and 45 vs. 11 ms, respectively), although not for the low target prevalence condition (31 vs. 40 ms). We conducted a 2-by-2 ANOVA with target prevalence (moderate vs. high) and target presence (target-present vs. target-absent) as two within-participant factors. Results showed that the asymmetry did not reach significance, with no significant main effect of target presence, F (1, 32) = 1.196, $p = 0.282$, $\eta_p^2 = 0.036$, and no interaction between the two factors, F (1, 32) = 1.052, $p = 0.313$, $\eta_p^2 = 0.032$. It was likely that there were large individual differences in participants which had obscured the potential asymmetry. Here we will not go further on this issue although we believe that the potential asymmetry in the reward effect for target-present and target-absent conditions is worth further exploration.

Error rate

The three-way ANOVA on the error rate (see Table 1 and Fig. 5) showed main effects of prevalence, F (2, 64) = 26.303, $p < 0.001$, $\eta_p^2 = 0.451$, reward, F (1, 32) = 5.335, $p = 0.028$, $\eta_p^2 = 0.143$, and target presence, F (1, 32) = 86.729, $p < 0.001$, $\eta_p^2 = 0.730$. The error rate was higher in the low prevalence condition than in the moderate (6.3%) and high (4.9%) blocks ($ps < 0.001$), and the error rate was higher in the moderate condition than in the high prevalence condition ($p = 0.048$). The error rate for the target-present trials was higher than for the target-absent trials (11.3% vs. 3.1%). Importantly, there were significant two-way interactions between reward and target presence, F (2, 64) = 7.450, $p = 0.010$, $\eta_p^2 = 0.189$, between reward and target prevalence, F (2, 64) = 4.194, $p = 0.019$, $\eta_p^2 = 0.116$, and between target prevalence and target presence, F (2, 64) = 33.342, $p < 0.001$, $\eta_p^2 = 0.510$, although the three-way interaction did not reach significance ($p = 0.380$).

To further explore the two-way interaction between reward and target presence, we merged error rates from difference target prevalence conditions and conducted a 2-by-2 ANOVA. Results showed main effects of target presence, F (1, 32) = 86.686, $p < 0.001$, $\eta_p^2 = 0.730$, and reward, F (1, 32) = 5.338, $p = 0.027$, $\eta_p^2 = 0.143$. Importantly, the interaction between reward and target presence was significant, F (1, 32) = 7.451, $p = 0.010$, $\eta_p^2 = 0.189$. Planned t-tests showed that participants made more errors in the no-reward condition than in the reward condition for the target present trials (13.1% vs. 9.4%), t (32) = 3.116, $p = 0.004$, but not for the target absent trials (2.9% vs. 3.4%), t (32) = 0.606, $p > 0.5$.

To further explore the two-way interaction between reward and target prevalence, we merged error rates from different target presence conditions and conducted a 3-by-2 ANOVA. Results showed significant main effects of target prevalence, F (1, 32) = 23.403, $p < 0.001$, $\eta_p^2 = 0.422$, of reward, F (1, 32) = 6.503, $p = 0.016$, $\eta_p^2 = 0.169$, and a significant interaction between the two variables, F (1, 32) = 4.427, $p = 0.016$, $\eta_p^2 = 0.122$. Planned t-tests showed that participants made more errors

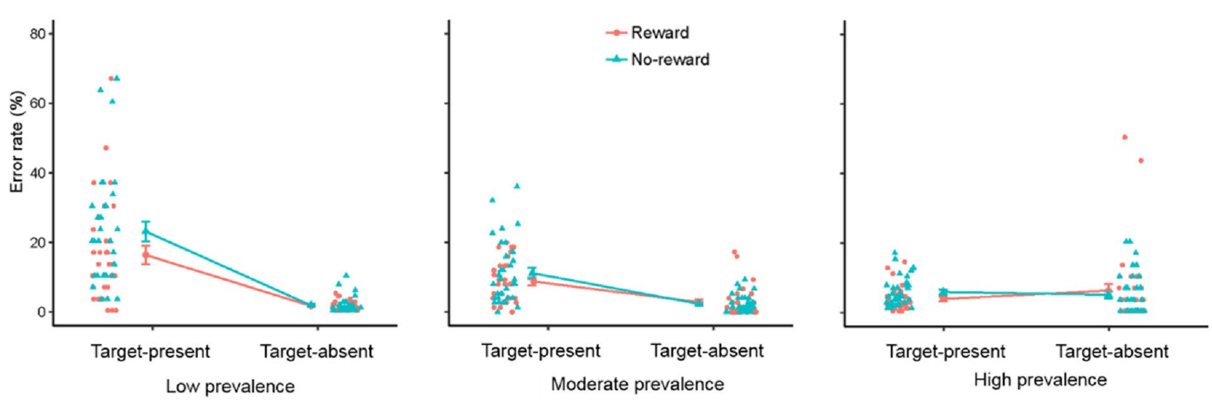

Fig. 5 Error rates in each experimental condition in Experiment 2. The individual data and means with standard errors are shown on the plot

in the no-reward condition than in the reward condition for the low prevalence condition (12.1% vs. 8.6%, $t(32) = 2.649$, $p = 0.012$), but the difference between the two conditions were significantly reduced for the moderate (7.0% vs. 5.9%) and high (5.1% vs. 4.5%) prevalence conditions ($ps > 0.07$).

To further explore the two-way interaction between target prevalence and target presence, we merged error rates from different reward conditions and conducted a 3-by-2 ANOVA. Results showed main effects of target prevalence, $F(1, 32) = 26.310$, $p < 0.001$, $\eta_p^2 = 0.451$, and target presence, $F(1, 32) = 86.716$, $p < 0.001$, $\eta_p^2 = 0.730$, and a significant interaction between the two variables, $F(1, 32) = 33.338$, $p < 0.001$, $\eta_p^2 = 0.510$. One-way ANOVA for the target-present trials found a significant main effect, $F(2, 64) = 36.484$, $p < 0.001$, $\eta_p^2 = 0.533$, with the error rate decreasing linearly as a function of target prevalence (low: 19.3%, moderate: 9.9%, high: 4.5%), $F(1, 32) = 46.141$, $p < 0.001$, $\eta_p^2 = 0.590$. For the target-absent trials, the one-way ANOVA showed a main effect of target prevalence, $F(2, 64) = 10.423$, $p < 0.001$, $\eta_p^2 = 0.246$. with the error rate increasing linearly as a function of target prevalence (low: 1.4%, moderate: 2.6%, high: 5.4%), $F(1, 32) = 11.419$, $p = 0.002$, $\eta_p^2 = 0.263$.

Signal detection analysis

The 3-by-2 ANOVA on *c* showed a main effect of target prevalence, $F(2, 64) = 30.032$, $p < 0.001$, $\eta_p^2 = 0.484$, with the *c* decreasing linearly over the target prevalence (0.56 vs. 0.32 vs. 0.087), $F(1, 32) = 36.769$, $p < 0.001$, $\eta_p^2 = 0.535$. The main effect of reward was also significant, $F(1, 32) = 6.367$, $p = 0.017$, $\eta_p^2 = 0.166$, with the *c* lower in the reward than in the no-reward condition (0.26 vs. 0.38). The interaction between target prevalence and reward did not reach significance ($p > 0.4$). These results suggested that participants were more inclined to report "yes" when the target prevalence increased, and more likely to report "yes" in the reward condition than in the no-reward condition.

The 3-by-2 ANOVA *d'* showed a main effect of target prevalence, $F(2, 64) = 20.253$, $p < 0.001$, $\eta_p^2 = 0.388$, with the *d'* increasing linearly over the target prevalence conditions (3.17 vs. 3.50 vs. 3.80), $F(1, 32) = 20.084$, $p < 0.001$, $\eta_p^2 = 0.476$. There was also a main effect of reward, $F(1, 32) = 7.357$, $p = 0.011$, $\eta_p^2 = 0.187$, with higher *d'* in the reward than in the no-reward condition (3.59 vs. 3.39). The interaction did not reach significance ($p > 0.1$). These results indicated that the discriminability between target and non-target increased over target prevalence and reward, a pattern a bit different from that in Experiment 1.

The proportion of rewarded trials

The two-way ANOVA showed a main effect of target presence, $F(1, 32) = 4.355$, $p = 0.045$, $\eta_p^2 = 0.120$, with higher proportion of rewarded trials in the target present trials than in the target absent trials. There was an interaction between target prevalence and target presence, $F(2, 64) = 36.733$, $p < 0.001$, $\eta_p^2 = 0.534$. Planned *t*-tests showed that participants obtained more reward in the target-absent trials than in the target-present trials for the low prevalence condition (88.4% vs. 80.4%), $t(32) = 2.261$, $p = 0.013$, but the difference disappeared for the moderate condition (81.7% vs. 87.4%), $t(32) = 1.784$, $p = 0.084$, and reversed for the high prevalence condition (72.2% vs. 93.4%), $t(32) = 4.844$, $p < 0.001$. It is also clear that the proportion of rewarded trials decreased linearly for the target-absent trials and increased linearly for the target-present trials over target prevalence conditions, $F(1, 32) = 27.038$, $p < 0.001$, $\eta_p^2 = 0.458$, and $F(1, 32) = 32.005$, $p < 0.001$, $\eta_p^2 = 0.500$, respectively.

Discussion

In the present study, we conducted two experiments to examine the impact of reward on target-detection search. In line with previous studies (Wolfe, 2012; Wolfe et al., 2005; Wolfe et al., 2007), the RT for the target-present condition was longer than for the target-absent condition in both experiments and there was a classic low prevalence effect in Experiment 2. Importantly, all the experiments showed a significant interaction between reward and target presence. Specifically, when the target was present, there was a facilitatory effect of reward on searching for the target, with a shorter RT and a lower error rate in the reward condition than in the no-reward condition. However, when the target was absent, the pattern of the effect of reward was reversed, with prolonged RTs and more errors in the reward condition than in the no-reward condition. Signal detection analysis showed that reward decreased the response criterion *c*, biasing the response towards the "yes" or "present" response. The reward-induced facilitatory effect for target presence and interference effect for target absence were manifested across target prevalence.

Here, we replicated the reward-induced facilitation in the target-present situation and reported a novel reward-induced interference effect in the target-absent situation, which questioned the general facilitatory effect of reward (e.g., Small et al., 2005; Kiss et al., 2009). The facilitatory effect of reward in the target-present condition was consistent with many previous studies (e.g., Kang et al., 2018; Kang et al., 2019; Kiss et al., 2009; Kristjánsson et al., 2010; Padmala & Pessoa, 2011). In the context of target-discrimination, expected reward facilitates performance when the reward information is delivered by an advanced cue (e.g., Kang et al., 2019; Padmala & Pessoa, 2011; Soutschek et al., 2015) or by the feature of the stimuli in the task phase (e.g., Kiss et al., 2009; Kristjánsson et al., 2010; Lee & Shomstein, 2014; Wang et al., 2019). In this context, gaining a reward depends on making a discrimination on the target within a predefined criterion. The expectation of monetary reward increases participants' motivation and effort to make optimal performance and maximize reward outcomes (for review, see Chelazzi et al., 2013). In the target-present condition of the current study, reward signals were indexed by the color of the search display, and correct faster detection would be rewarded (i.e., performance-contingent). This manipulation is similar to the "reactive" paradigm in the field of attentional control (Braver, 2012). Reward-induced motivation facilitates selective attention and visual search (e.g., Della Libera & Chelazzi, 2006, 2009; Hickey et al., 2010; Kiss et al., 2009; Lee & Shomstein, 2014), leading to shorter RT and lower error rates in the reward condition than in the no-reward condition when the search target was present.

However, some studies do not show robust reward facilitation on target detection (Bergmann et al., 2019; Navalpakkam et al., 2009; Tseng & Lleras, 2013). We argued that the inconsistency is due to the way of reward manipulation. For example, Navalpakkam et al. (2009) manipulated the reward/penalty schedule non-linearly and did not observe a stable reward effect on the target detection rate. They proposed that the perceived costs and benefits were not linearly related to monetary rewards, which may lead to the absence of a reward facilitation effect in their Experiment 1. In the following Experiment 2, the authors asked participants to compete to win the highest monetary payoff and did observe a reward facilitation effect on target detection (Navalpakkam et al., 2009). Studies investigating reward modulation of contextual cueing also observed inconsistent reward effects on search time (Bergmann et al., 2019; Pollmann et al., 2016; Sharifian et al., 2017; Tseng & Lleras, 2013). For example, Tseng and Lleras (2013) associated reward with different search contexts and showed shorter RTs on rewarding context trials than on penalizing context and no-outcome context trials. But Bergmann et al. (2019) associated reward with the color of context rather than with context configuration and observed no main effect of reward, although the authors found faster RT decline in repeated contexts associated with high reward as compared with repeated contexts associated with low reward or novel contexts. Thus, how the reward scheme is set up plays a crucial role in determining the appearance of a reward effect in search for a visual target.

In the target-absent situation, the reward-induced motivation and effort may interfere with the termination of search, because gaining a reward depends on quitting the search in time, which would be an "unsuccessful" search. In daily life, for the search task, the primary goal is to find a predefined target, while quitting the search without finding a target is contrary to the primary goal. Similarly, in the present target-absent condition, participants had to terminate the search and respond "the target is absent". The "primary search goal" (finding a specific target) and the "task goal" (responding "absent") were in conflict. Given that the "primary search goal" generally have higher priority over the "task goal", and given that reward-induced motivation facilitates goal-directed behaviors (for reviews, see Botvinick & Braver, 2015; Pessoa, 2009; Chelazzi et al., 2013), reward may amplify the bias to the meet the "primary search goal", such that participants spent more time searching to make sure that quitting the search is the "right" decision. This reluctant termination of search interferes with the search performance in the target-absent situation. Further studies could adopt the eye-tracking technique to examine how terminating search is achieved in the reward condition as compared to in the no-reward condition.

One might argue that the delayed responses and increased false alarms in the reward condition than in the no reward condition for the target-absent situation may reflect a strategy of maximizing reward, as the present study used a fixed reward schedule (i.e., a fixed reward for a performance that met the criterion, and no penalty for incorrect responses). Specifically, participants could have adopted a strategy to delay their search in the reward condition to maximize hits and obtain the associated reward. This strategy would increase the probability of false alarms, but such outcome was considered acceptable since they were not disincentivized with a penalty. Indeed, Navalpakkam et al. (2009) demonstrated that their participants in the search task where the display automatically terminates behaved very much like the ideal observer that maximizes the expected reward per trial. However, in the current study, participants were rewarded based on both timed and accurate responses. To maximize reward, participants needed to respond both faster and correctly and in both the target-present and target-absent conditions. Thus, the strategy of delaying responding would work against obtaining a reward for the target-absent trials in the reward condition. Moreover, although we did observed increased errors/false alarms in the reward condition in Experiment 1, this effect was absent in Experiment 2.

Importantly, the signal detection analysis showed that reward decreased the report criterion c in both experiments. It is possible that the reluctant termination of search induced by reward may be due to the change of response criterion, i.e., individuals are more likely to make a "present" response if the trial could be rewarded compared to the no-reward trial. This tendency can be explained by the confirmation bias, i.e., individuals tend to favor information that confirms their beliefs or ideas (Nickerson, 1998). The confirmation bias was also observed in visual search task (Rajsic et al., 2015): the proposition "there is a target" can be quickly verified rather than falsified because the visual search task always includes a pre-defined target and individuals may have a belief of "there is a target". This confirmation bias can affect the response criterion, evidenced by the decreased *c* (a tendency to make a "present" response) along with the increase of the target prevalence (Experiment 2). Walenchok et al. (2020) investigated the interaction between confirmation bias and target prevalence in visual search. They observed that high cue-target prevalence magnifies the confirmation bias. The authors suggested that both the confirmation and prevalence biases would encourage participants to "confirm" the more available cued target template (Walenchok et al., 2020). In the present Experiment 2, the pre-defined target may establish a specific target template in mind. In the high prevalence condition, participants were more convinced of the target presence, which was added to the confirmation bias, leading to a more liberal response criterion (i.e., decreased *c*). Moreover, reward motivation has been proved to improve goal-directed behavior in many studies (Botvinick & Braver, 2015; Kang et al., 2019; Pessoa, 2009), and earning reward is always associated with a successful "hit" action, such as detecting a specific target, i.e., making a "present" response. Therefore, it is possible that reward reinforces the belief of "there is a target" to achieve a successful "hit" action, which hinders the termination of search when there is actually no target.

For the analysis of *d'*, we did not observe consistent reward modulation between Experiments 1 (i.e., no reward effect on *d'*) and Experiment 2 (i.e., higher *d'* in the reward condition than in the no-reward condition). In previous studies that showed a reward effect on perceptual sensitivity, the reward was either associated with the target stimulus (e.g., Kiss et al., 2009; Luo et al., 2020) or was manipulated by an advance cue (e.g., Engelmann et al., 2009; Hughes et al., 2013). The former manipulation would increase the salience of the target stimulus relative to other non-target stimuli; the latter manipulation would allow participants to proactively recruit more attention for obtaining the potential reward in the upcoming task. However, in the present study, the reward information was indicated by the color of the search array, such that participants could not anticipate whether the upcoming trial was a reward trial or no-reward trial before the target was presented (i.e., a reactive reward information). In addition, Experiment 2 contained 900 trials that was more than three times of Experiment 1 (288 trials). Participants had more training on the task in Experiment 2, leading to an improved perceptual discriminability in the reward condition. Further studies are needed to investigate the influence of reactive reward on perceptual discriminability.

Noting that while the three-way interaction between reward, target prevalence, and target presence on both the RT and error rate did not reach significance in Experiment 2, there was a two-way interaction between reward and prevalence on the error rate. Specifically, for the low prevalence, participants committed fewer errors in the reward condition than in the no-reward condition; this effect was non-significant in the moderate and high prevalence conditions. Previous studies suggested that participants could abandon search prematurely, leading to a higher miss rate and shorter RT in the target-absent trials for the low prevalence condition as compared with other prevalence conditions (Wolfe, 2012; Wolfe et al., 2005). Wolfe et al. (2007) speculated that the influence of reward on rare target search would appear when the reward was higher than what was normally used in laboratory. However, Navalpakkam et al. (2009) found that increasing the target detection reward would improve the detection performance that was hindered by the target rarity. Similarly, we found that reward increased accuracy (hits and correct rejections) in the low prevalence condition. It is possible that reward and sensory priors (e.g., target prevalence) interact to impact search behaviors in general.

In addition, the proportion of rewarded trials was affected by the way of how the baseline was set up. Specifically, when the baseline was set up as the mean reaction time of target-present and -absent trials at the practice phase, participants would obtain more reward in the target-present trials than in the target-absent trials (Experiments 1A and 2); when different baselines were set up for the target-present trials (i.e., the mean RT of target-present trials on the practice phase) and target-absent trials (the mean RT of the target-absent trials on the practice phase), no significant difference appeared between the target-present and target-absent trials. Importantly for the present purpose, however, the pattern of the effects of reward on the target-detection search remained consistent across all the experiments, not affected by the way the baseline was set up.

To conclude, using a visual-detection search task, the present study replicated the classical reward-induced facilitatory effect when the target was present and revealed a reward-induced interference effect when the target was absent. These reward-related effects could be observed across situations with different target prevalence. We interpreted these effects as the change of the response criterion driven by reward, with reward strengthening the confirmation bias in visual search. Our findings may provide a new insight on how to effectively use reward to promote goal-directed behaviors.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00426-023-01860-6.

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Author contributions All authors developed the study concept and contributed to the study design. Data collection and analysis were performed by GK, JC, JC, HD, and XL. Manuscript preparation was conducted by GK, XL, LC and XZ. All authors approved the manuscript for submission.

Data availability The data generated and analyzed during this study are available at https://osf.io/rwhzm/

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

Ethical approval This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Institutional Review Board of Beijing Sport University and the Committee on Human Research Protection, East China Normal University. Informed consent was obtained from all individual participants included in the study.

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