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Reward-driven attention alters perceived salience

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Many studies have revealed that reward-associated features capture attention. Neurophysiological evidence further suggests that this reward-driven attention effect modulates visual processes by enhancing low-level visual salience. However, no behavioral study to date has directly examined whether reward-driven attention changes how people see. Combining the two-phase paradigm with a psychophysical method, the current study found that compared with nonsalient cues associated with lower reward, the nonsalient cues associated with higher reward captured more attention, and increased the perceived contrast of the subsequent stimuli. This is the first direct behavioral evidence of the effect of reward-driven attention on low-level visual perception.

Introduction

In everyday life, we are surrounded by a huge amount of visual stimuli, most of which are ignored due to our limited processing capacity. Traditionally, the physical salience of objects (Itti & Koch, 2001; Theeuwes, 1991; Theeuwes, 1992) and the current goal of participants are considered as the two major factors influencing the attentional priority for visual information processing. The physical features drive the rapid and automatic stimulus-driven (or exogenous) attention, whereas the participants' goals drive the slower and voluntary goal-driven (or endogenous) attention (Anderson, 2013; Anderson, Laurent, & Yantis, 2011; Awh, Belopolsky, & Theeuwes, 2012; Chelazzi, Perlato, Santandrea, & Della Libera, 2013; Failing & Theeuwes, 2018; Theeuwes, 2010; Theeuwes, 2019). A stimulus that is weak and/or does not meet the intention or expectation

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of the participants would not capture attention and be processed preferentially.

However, recent studies have increasingly revealed that nonsalient and goal-irrelevant visual stimuli can also receive attentional priority if they have previously been associated with reward; this phenomenon is termed reward-driven attention or reward-based selection history (Anderson, 2013; Anderson et al., 2011; Awh et al., 2012; Failing & Theeuwes, 2018). In a series of studies, Anderson and his colleagues (Anderson, 2015; Anderson & Halpern, 2017; Anderson et al., 2011; Anderson, Laurent, & Yantis, 2014) used a two-phase paradigm to study the effects of reward association on visual attention. In the initial training phase (reward learning) of this paradigm, high and low rewards are associated with specific features (e.g. different colors) of visual stimuli. In the subsequent test phase, however, the reward is no longer delivered. In previous studies, the behavioral results of the test phase showed that physically nonsalient distractors imbued with a high reward-associated feature increased the search time for the subsequent target compared with the distractors with a low reward-associated feature (Anderson et al., 2011).

The impact of the reward-driven attention on visual processing is believed to be direct, fast, and involuntary (Anderson, 2013; Anderson et al., 2011; Awh et al., 2012; Failing & Theeuwes, 2018) because studies using eye movement measurement, event-related potentials (ERPs), and functional magnetic resonance imaging (fMRI) have shown that reward-driven attention affects the early stage, low-level sensory processing of visual stimuli. For example, the reward-associated feature captures oculomotor saccades with short latencies (Failing, Nissens, Pearson, Le Pelley, & Theeuwes, 2015; Hickey & van Zoest, 2012; Preciado & Theeuwes, 2018), increases the amplitude of an early ERP P1 component (about 100 ms post-stimulus) (Hickey, Chelazzi, & Theeuwes, 2010), and enhances the activity in early visual cortex (Anderson et al., 2014; Persichetti, Aguirre, & Thompson-Schill, 2015). These results have inspired researchers to suggest that reward association might “change the (visual) salience of a stimulus” (Hickey et al., 2010; Preciado & Theeuwes, 2018), “render a feature or location subjectively more salient” (Theeuwes, 2018), and “have increased physical salience” (Anderson, 2013). These ideas are consistent with the incentive salience theory, derived from earlier animal studies, that the reward-related dopamine release would directly act on reward-conditioned stimuli and make them more salient (Oldham et al., 2018).

In behavioral studies, the impact of reward-driven attention on visual processing has been well-documented across a wide range of visual tasks, such as visual search (Bourgeois, Neveu, & Vuilleumier, 2016; Gong, Yang, & Li, 2016; Hickey, Chelazzi, & Theeuwes, 2014; Wang, Duan, Theeuwes, & Zhou, 2014; Wang, Li, Zhou, & Theeuwes, 2018), letter identification (Anderson, Laurent, & Yantis, 2012; Failing & Theeuwes, 2014), attentional blink (Raymond & O’Brien, 2009), and semantic category detection (Failing & Theeuwes, 2015). To our knowledge, most of these studies relied on response times, whereas the reward-associated feature acted as a target, distractor, or cue. So far, there is no direct behavioral evidence that reward-driven attention increases low-level salience of visual stimuli (e.g. contrast, orientation, color, or motion; Itti and Koch, 2001; Theeuwes, 1991; Theeuwes, 1992).

In this study, we used the psychophysical method to investigate whether reward-driven attention impacted perceived contrast (a basic dimension of low-level visual salience). Specifically, circles with different colors were associated with different values in the training phase. After the training, colored circles were used as cues and the perceived contrast (contrast appearance) of the visual stimuli following the cues was tested using a method modified from Carrasco et al. (2004). In Carrasco et al.’s original paradigm, each trial started with an exogenous cue appearing on one side (left or right side) of the fixation, followed by two Gabor patches presented on both sides: one was the standard stimulus with a fixed level of contrast and the other one was the test stimulus whose contrast level varied from trial to trial. Carrasco et al. (2004) then calculated the point of subjective equality (PSE; i.e. the contrast level at which the test and standard Gabor patches were equally likely to be chosen as showing higher contrast). They found that the PSE was significantly lower (i.e. a smaller contrast difference was needed for the test stimulus to match the standard stimulus) when the test stimulus was on the same side with the exogenous cue, which demonstrated the effect of stimulus-driven attention on perceived contrast. In the current study, we used two competitive reward-associated cues (a cueing pair) in each trial during the test phase. We hypothesized that the cue associated with higher reward would capture more attention than the cue with lower reward, and that the reward-driven attention would lead to a lower PSE for the test stimulus on the same side with the higher-reward cue.

Experiment 1

Methods

Participants

Experiment 1 included 24 healthy college students, a sample size comparable to similar studies on reward-driven attention (Anderson, 2015; Anderson et al., 2011; Failing & Theeuwes, 2014). All participants (right-handed, aged 19–26, mean age = 22.167 years, SD = 1.880, 11 women) had normal or corrected-to-normal vision and reported no history of neurological problems. They were naïve to the purpose of the experiment and signed the informed consent form. Experimental procedures were approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

Apparatus

Participants were asked to finish the task in a dimmed room. Stimuli were generated with Psychtoolbox (Brainard, 1997; Pelli, 1997) and presented on a gamma-corrected CRT monitor (1024 × 768 resolution at 85 Hz, mean luminance: 52 cd/m2). Before the experiment, the monitor was calibrated with a Photo Research PR-655 spectrophotometer. To improve the precision of contrast and measurements, a Bits # 14-bit video card (Cambridge Research Systems) was used. Participants viewed the stimuli at a distance of 57 cm and a head-and-chin rest was used to stabilize the head. Responses were collected using a standard keyboard.

Stimuli and procedure

General procedure

Participants performed the experiment on two successive days to avoid possible fatigue. The experiment on each day lasted for about 1.5 to 2 hours and was divided into a training phase and a test phase with a short break between them. Three colored circles were associated with high, medium, and no reward in the training phase and they were presented as cues in pair preceding target stimuli (including a test stimulus and a standard stimulus) in the test phase. Before the formal experiment (on the first day), participants were required to finish a practice session (84 trials) to familiarize themselves with the test task, whose procedure was the same as the test phase except that no reward-associated cue was provided. Participants were required to stay still and keep staring at the central point during the task.

Training phase

In each trial, two colored circles (2 degrees × 2 degrees) with black bars (a vertical bar and a horizontal bar appeared in each colored circle equally often) were placed at isoeccentric locations on the left and right sides (±8 degrees) of the fixation dot. The colors of the two circles were selected from three colors (red [R:180; G:30; B:30], green [R:0; G:70; B:30], and blue [R:30; G:30; B:180]) associated with three levels of reward: high reward (1 Chinese yuan ≈ 0.14 USD), medium reward (0.5 yuan), and no reward (0 yuan). The association between color and level of reward was counterbalanced across participants. Three types of circle pairs (high versus no reward, medium versus no reward, and high versus medium reward) were displayed in random order and each colored circle appeared in each location (left/right) with an equal frequency. Participants were required to choose one of the two colored circles by reporting the orientation of the bar inside the chosen circle. They were told that the color of the circle, not the orientation of the bar, was associated with the reward value and that the same color would always yield the same amount of reward. They were instructed to maximize reward in each trial because part of their final payment (in addition to the base pay of 20 Chinese yuan) would be determined by the earnings on one sixth of the total number of trials randomly selected from the training phase. After making the choice on each trial, participants would receive the corresponding reward of the chosen color. Although participants were informed before training that three colored circles would be associated with three reward values (0, 0.5, and 1 yuan), they did not know the exact value information of each colored circle and could only learn the reward association via the feedback from each trial. On each of the 2 days, participants completed 4 training blocks, each with 96 trials. In total, each participant finished 768 training trials, with 256 trials for each circle pair. The average reward that the participants got on the 2 days were 49.958 yuan (SD = 4.634) for the first day and 50.479 yuan (SD = 3.239) for the second day.

As shown in Figure 1, each trial began with a fixation displayed for 1 to 1.5 seconds (randomized), then two colored circles with bars were displayed for 0.08 seconds. Participants pressed the left arrow key on the keyboard if the bar in the selected circle was horizontally oriented or the up arrow key if the bar in the selected circle was vertically oriented. The fixation remained on the screen until a response was made or the allotted time elapsed. Participants were required to press the key as soon as possible. They were expected to become skilled during the task and speed up their responses over time accordingly. To maintain participants' engagement, we adapted the difficulty level of the training task by decreasing the allotted time across blocks and days. Based on the results of the pilot study, we set the allotted time as follows. On the first day, the allotted time in the four blocks was 1 second, 0.9 seconds, 0.8 seconds, and 0.7 seconds, respectively. On the second day, the allotted time in all blocks was 0.6 seconds. Responses within the allotted time were followed by a feedback display (1.5 seconds) to indicate the amount of monetary reward associated with the colored circle they had chosen. If they responded too slowly to miss the stimulus, a sign "-" was presented to indicate that no money had been earned.

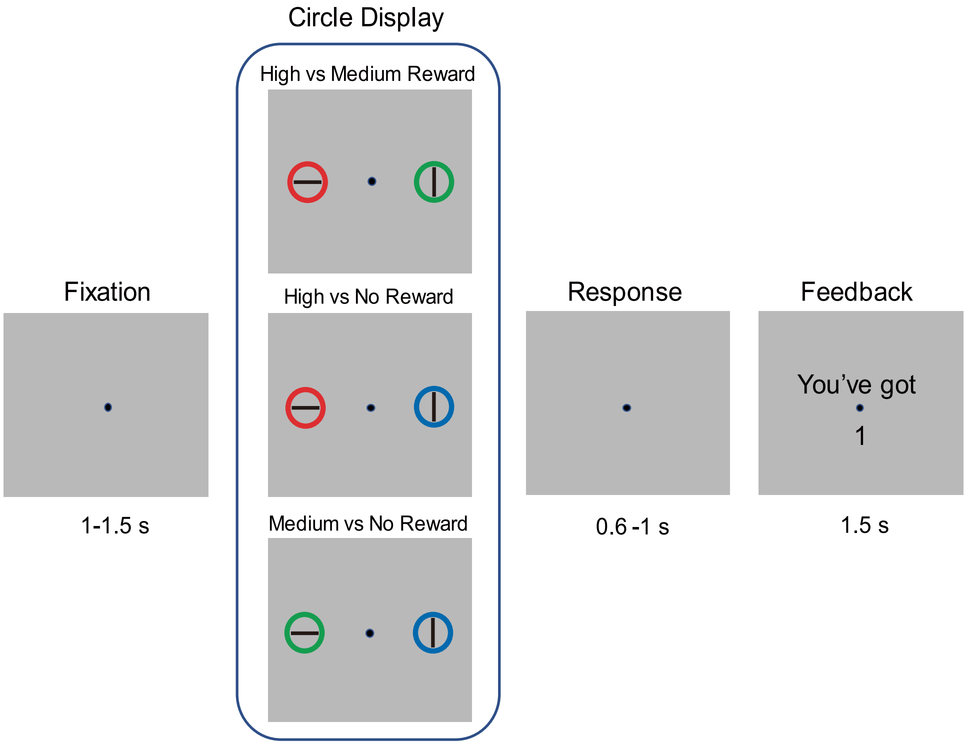

Figure 1. The stimuli and trial structure in the training phase. The reward value was associated with a specific color. In each trial, one pair of colored circles were presented and participants were asked to choose a circle and report the orientation of the bar inside the chosen circle. There were three competitive reward pairs: high versus medium reward, high versus no reward, and medium versus no reward. In this example, the red circle refers to the high reward, the green refers to the medium reward, and the blue refers to no reward.

Test phase

We adopted the paradigm developed by Carrasco et al. (2004) to test the perceived contrast. Two oriented Gabor stimuli (each enveloped by a Gaussian function) were presented as the target stimuli and the three pairs of competitive reward circles (high versus no reward, medium versus no reward, and high versus medium reward) were used as cues preceding the Gabor patches. The special frequency of Gabor patches was two cycles/degree and each of them subtended two visual degrees. One of the Gabor patches was the standard stimulus with a fixed contrast (20%) and the other was the test stimulus varying in contrast in log-space (7 contrasts: 8%–50%). The two Gabor patches were randomly tilted 45 degrees clockwise or counterclockwise in the experiment. On each of the 2 days, participants completed five test blocks of 168 trials per block. In total, each participant finished 1680 test trials (6 reward circles [3 types of cueing pairs] × 7 contrast levels × 40 trials per contrast level).

As shown in Figure 2, each trial began with a fixation display. Two colored circles, which have been associated with monetary reward in the training phase, were then presented together as a cueing pair for 0.08 seconds at isoeccentric locations on the left and right sides (±8 degrees) of the fixation, 2 degrees above the horizontal meridian. After a short stimulus onset asynchrony (SOA) of 0.12 seconds, two Gabor patches (a test stimulus and a standard stimulus) appeared for 0.04 seconds at the locations of 3 degrees under the circles to avoid spatial overlap with the cues. Participants were required to report the orientation of the Gabor with higher contrast within 5 seconds (left stimulus/hand: "Z" - counter clockwise, "X" - clockwise; right stimulus/hand: "<" - counter clockwise, and ">" - clockwise) or the trial ended. This instruction required participants to focus on the orientation of the stimuli, yet we were interested in the contrast judgment (Carrasco, Ling, & Read, 2004). No feedback was provided. Note that the colored circles (the cueing pairs) here were not followed by reward and participants were clearly informed that they would not receive any money in this phase.

Statistical analyses

Data were analyzed using MATLAB, SPSS, and JASP. As mentioned before, the perceived contrast was indexed by PSE. We therefore calculated PSE for each cue of the three cueing pairs from the data when the test

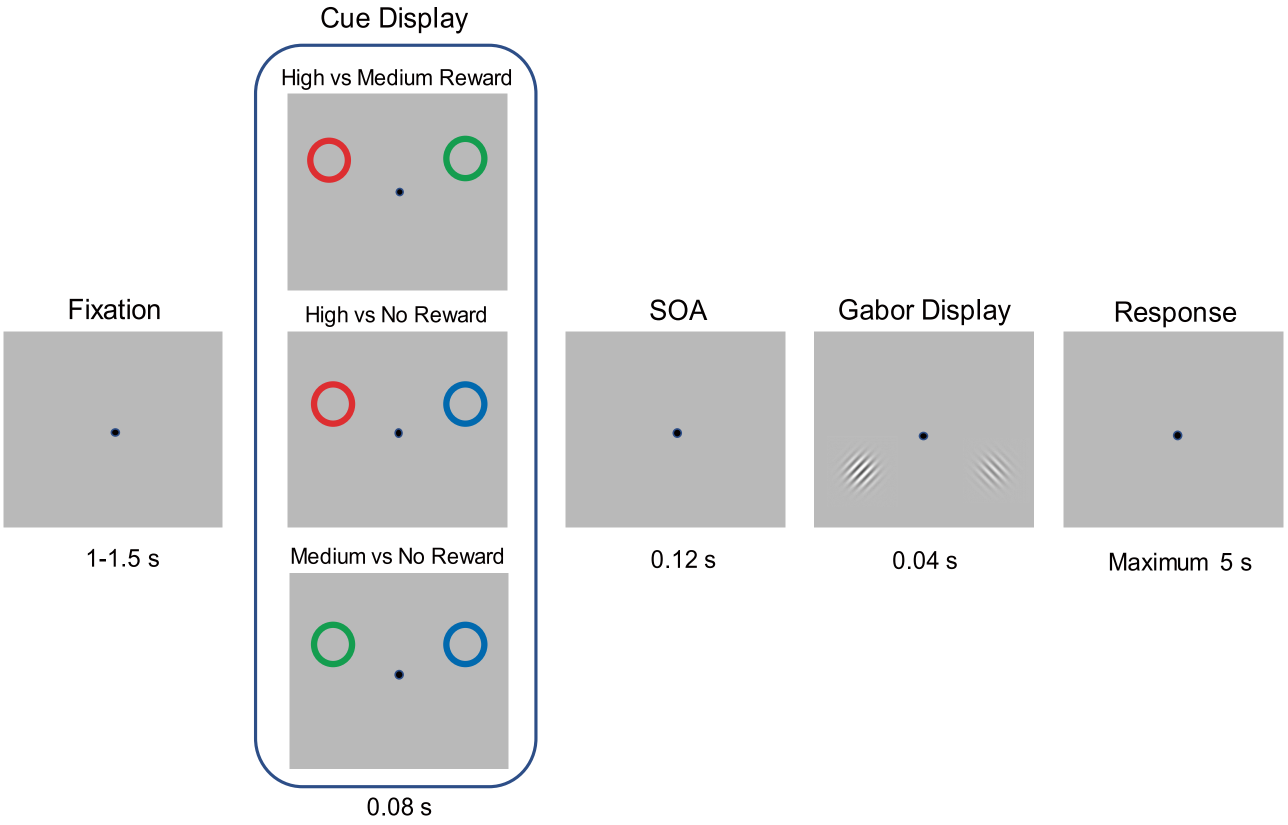

Figure 2. The stimuli and trial structure in the test phase. In each trial, one pair of colored circles were presented as the preceding cues to manipulate the allocation of spatial attention. After a short interval, two Gabor patches were presented as targets and participants were required to report the orientation of the higher contrast Gabor.

stimulus was on the same side with this cue. Specifically, for each cue, we first computed the percentage of trials in which the test stimulus was reported as showing higher contrast as a function of test log contrast when the test stimulus was on the same side as this cue. Then the data for each cue were fitted with a Weibull function using maximum likelihood procedure. The PSE was the contrast at which the test and standard stimuli were equally likely to be chosen by participants. Finally, seven PSEs were obtained for each participant for further statistical analyses.

A paired *t*-test on the PSEs of the two competitive cues in each cueing pair was conducted to test the effect of reward-associated attention and its impact on perceived contrast. In order to reduce the "type I" error caused by the three tests for the three pairs, a Bonferroni correction was used, with the p value set at $0.05/3 = 0.017$. For each cueing pair, if the higher-reward cue attracted more attention and enhanced the contrast of subsequent stimulus on its side compared with the lower-reward cue, the PSE for the higher-reward cue (e.g. when the test stimulus was on the same side as the higher-reward cue) should be lower than that for the lower-reward cue (e.g. when the test stimulus was on the same side as the lower-reward cue).

Results

Training phase

We found a significant reward-associated learning effect in the training phase, with the high-reward circle being selected more frequently than the no-reward circle in the pair of high versus no reward (mean selection rates: 93.8% vs. 4.8%), $t(23) = 52.162$, $p < 0.001$, and $d = 10.648$, the high-reward circle being selected more frequently than the medium-reward circle in the pair of high versus medium reward (mean selection rates: 91.7% vs. 5.8%), $t(23) = 46.222$, $p < 0.001$, and $d = 9.435$, and the medium-reward circle being selected more frequently than the no-reward circle in the pair of medium versus no reward (mean selection rates: 81.1% vs. 10.1%), $t(23) = 17.064$, $p < 0.001$, and $d = 3.483$.

Test phase

In the test phase (Figures 3–5), we found a significant difference in the PSEs between the high-reward and no-reward cues in the cueing pair of high versus no reward, $t(23) = -3.261$, $p = 0.003$, and $d = -0.666$,

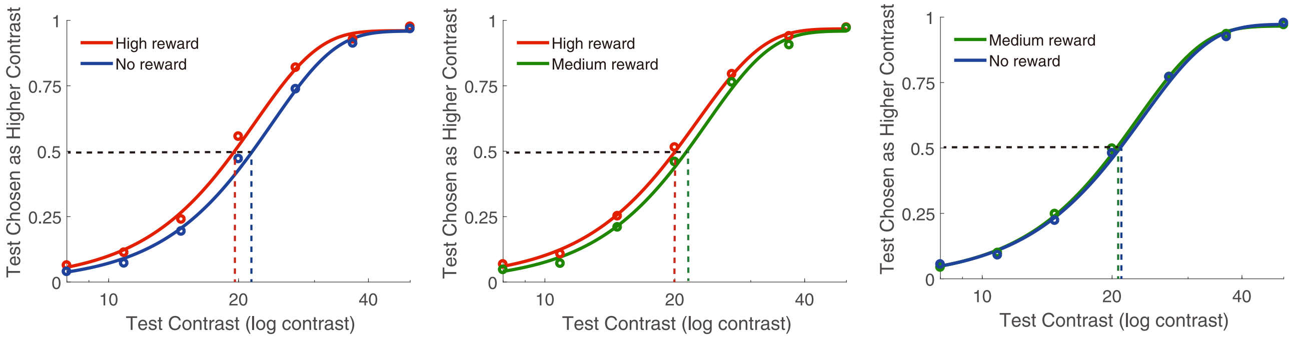

Figure 3. Fitted data for each cueing pair. Each curve represents the Weibull fit of the ratio that the test stimulus was chosen as showing higher contrast when it was on the same side as the corresponding reward circle. Dashed lines mark the PSEs, where both test stimulus and standard stimulus were equally likely to be reported as having a higher contrast.

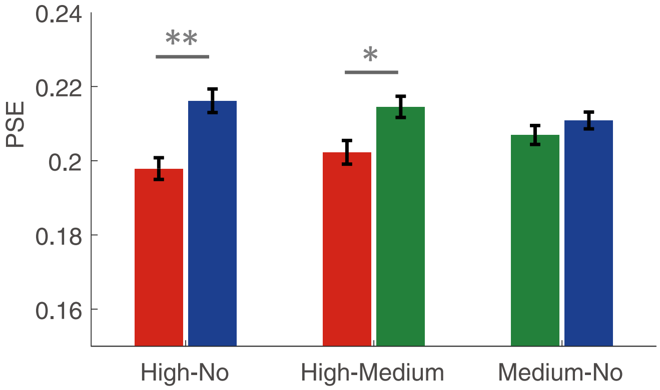

Figure 4. PSEs in each cueing pair. Each colored bar shows the PSE when the test stimulus was on the same side as the corresponding reward-associated cue. Error bars represent the standard error of the mean across participants. Asterisks indicate a significant difference in PSEs between the two cues in the cueing pair (*$p < 0.05$, **$p < 0.005$).

with a lower PSE for the high-reward cue (e.g. when the test stimulus was on the side of the high-reward cue) than for the no-reward cue (e.g. when the test stimulus was on the side of the no-reward cue). This result indicated that the contrasts of Gabor patches on the side of the high-reward cue were perceived to be higher than those on the side of the no-reward cue. There was also a significant difference in the PSEs between the high-reward and medium-reward cues in the pair of high versus medium reward, $t(23) = -2.280$, $p = 0.032$, and $d = -0.465$, with a lower PSE for the high-reward cue than for the medium-reward cue, but this significance did not survive Bonferroni correction ($p < 0.017$). No significant difference was found in the PSEs between the medium-reward and no-reward cues in the cueing pair of medium versus no reward, $t(23) = -1.116$, $p = 0.276$, and $d = -0.228$.

Discussion

The results of Experiment 1 showed that, compared with the lower-reward cue, the higher-reward cue attracted more attention and further enhanced the perceived contrast of the subsequent stimuli (high versus no reward and high versus medium reward). Our result was consistent with previous findings that reward-associated features captured attention automatically even after the reward was no longer delivered (Anderson, 2013; Anderson et al., 2011; Failing & Theeuwes, 2014; Failing & Theeuwes, 2018). More importantly, our results indicated that reward-driven attention affected early visual perception as the exogenous attention did (Carrasco et al., 2004). In addition, even though the difference in reward values between high- and medium-reward conditions was the same as that between medium-reward and no-reward conditions, there was a trend of the reward effect in the cueing pair of high versus medium reward, but not in the pair of medium versus no reward. This result indicated that the magnitude of reward might impact the perceived contrast in a nonlinear way.

Experiment 2

Experiment 1 demonstrated that higher-reward cue increased the perceived contrast of subsequent stimuli. In Experiment 1, the cueing pairs in the test phase were the same as the reward-associated circle pairs (high versus no reward, high versus medium reward, and medium versu. no reward) in the training phase. With this design, for each circle pair, participants might have developed a habit to shift attention to the higher-reward circle that had been selected more frequently throughout the training. This habit can be regarded as the effect of selection history (Anderson,

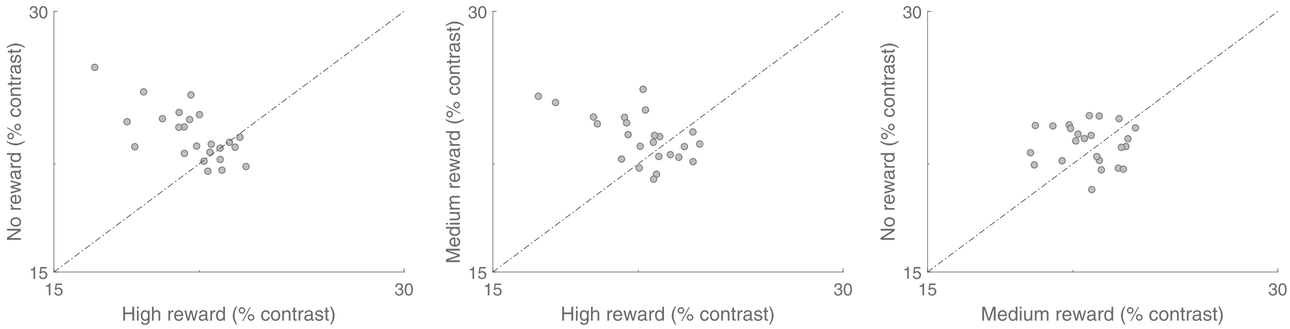

Figure 5. Attentional effects on perceived contrast at the individual level. The dashed line (a slope of 1) in each figure represents the same PSEs for the corresponding competitive rewarded cues.

2016; Awh et al., 2012; Failing & Theeuwes, 2018). That is, repeatedly selecting an item in a specific context leads to an association such that the display of that context can trigger attention shift to that item (Anderson & Kim, 2018). Hence, the effect found in the test phase of Experiment 1 might not be caused by reward, but by the selection history of one's habit/orienting response to a specific circle in that cueing pair. To rule out this possibility, we conducted Experiment 2 in which only two rewarded circle pairs (high versus no reward and low versus no reward) were shown in the training phase and a new cueing pair (high versus low reward) was introduced in the test phase. With this design, participants were expected to choose the high-reward circle in the pair of high versus no reward and the low-reward circle in the pair of low versus no reward in the training phase. Because participants were not exposed to the pair of high versus low reward during training, they were not expected to develop a habit for any specific circle.

In this experiment, we used low reward rather than the medium reward for two reasons. First, the value difference in the high versus low reward pair was large and it could help test the reward effect. Second, the value of low-reward circle (0.1 yuan) was so small that it should hardly draw participants' attention, but if the effect was still found in the pair of low versus no reward, that would be strong evidence for the selection history hypothesis.

Methods

Participants

Using the sample sizes in Anderson and Halpern's (2017) replication study as a guide, Experiment 2 included 42 healthy college students (aged 18–28, mean age = 22.643 years, SD = 2.196, 20 women). All the participants were right-handed and had normal or corrected-to-normal vision and reported no history of neurological problems. They were naïve to the purpose of the experiment and signed the informed consent form. Experimental procedures were approved by the Institutional Review Board of the Institute of Psychology, Chinese Academy of Sciences.

Apparatus, stimuli, and procedure

The apparatus, stimulus presentation, and general procedure were identical to those in Experiment 1. However, it only comprised two pairs of reward-associated circles: high versus no reward and low versus no reward (high reward: 1 yuan, low reward: 0.1 yuan), with 384 trials for each circle pair. The average amount of reward that the participants received were 60.305 yuan (SD = 6.200) for the first day and 60.657 yuan (SD = 6.130) for the second day. In the test phase, besides the two pairs in the training phase, a new pair of high versus low reward was added as a cueing pair. We focused on the difference in the PSEs for the two cues in this new pair. The test phase contained the same numbers of trials, blocks, and cueing pairs as those in Experiment 1.

Data analysis

The analytical procedure was identical to that in Experiment 1. In the three pairs of competitive cues (high versus low reward, high versus no reward, and low versus no reward), we mainly focused on the cueing pair of high versus low reward as mentioned above. In this pair, if the high-reward cue attracted more attention and enhanced the contrast of subsequent stimulus on its side compared with the low-reward cue, the PSE for the high-reward cue (e.g. when the test stimulus was on the same side as the high-reward cue) should be lower than that for the low-reward cue (e.g. when the test stimulus was on the same side as the low-reward cue).

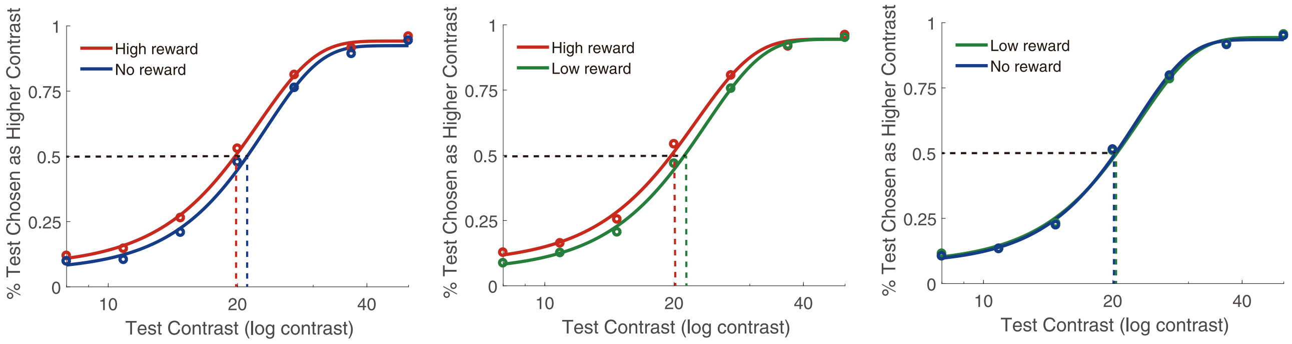

Figure 6. Fitted data for each cueing pair. Each curve represents the Weibull fit of the ratio that the test stimulus was chosen as showing a higher contrast when it was on the same side as the corresponding reward circle. Dashed lines mark the PSEs, where both test stimulus and standard stimulus were equally likely to be reported as having a higher contrast.

Results

Training phase

We found a significant reward-associated learning effect in the training phase, with the high-reward circle being selected more frequently in the pair of high versus no reward (mean selection rates: 93.8% vs. 4.6%), $t(41) = 76.446$, $p < 0.001$, and $d = 11.796$, and with the low-reward circle being selected more frequently in the pair of low versus no reward (mean selection rates: 83.9% vs. 8.5%), $t(41) = 30.111$, $p < 0.001$, and $d = 4.646$. We further compared the selection rates between high- and low-reward circles and found that the participants selected the high-reward circle in the pair of high versus no reward more frequently than the low-reward circle in the pair of low versus no reward (mean selection rates: 93.8% vs. 83.9%), $t(41) = 7.006$, $p < 0.001$, and $d = 1.081$.

Test phase

In the test phase (Figures 6–8), we found a significant difference in PSEs for the cueing pair of high versus no reward, $t(41) = -3.461$, $p = 0.001$, $d = -0.534$, with a lower PSE for the high-reward cue than for the no-reward cue, which was consistent with the finding from Experiment 1. Besides, the effect in the cueing pair of high versus low reward was also significant, $t(41) = -3.215$, $p = 0.003$, and $d = -0.496$, with a lower PSE for the high-reward cue than for the low-reward cue. That is, the contrasts of Gabor patches on the same side as the high-reward cue were perceived to be higher than those on the same side as the no-reward and low-reward cues. There was no significant effect in low versus no reward condition, $t(41) = -0.697$, $p = 0.490$, and $d = -0.108$.

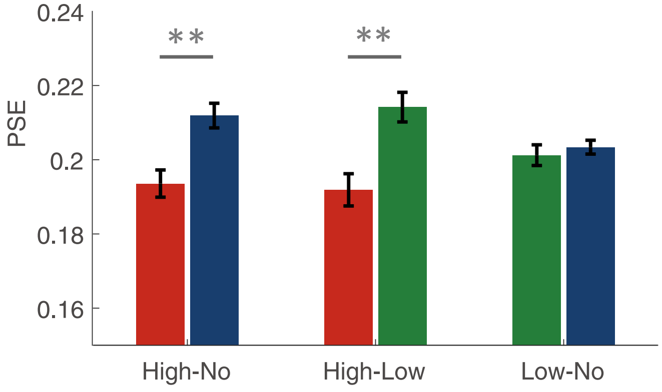

Figure 7. PSEs in each cueing pair. Each colored bar shows the PSE when the test stimulus was on the same side as the corresponding reward-associated cue. Error bars represent the standard error of the mean across participants. Asterisk indicates a significant difference in PSEs between the two cues in the cueing pair (**$p < 0.005$).

Discussion

In Experiment 2, we found a significant difference in the perceived contrast (indexed by PSE) for high versus no reward cueing pair, which replicated the effect in Experiment 1. More importantly, by testing the effect of a new cueing pair (high versus low reward) during the test phase in which both cues were selected more frequently in their own pair during the training phase (high versus no reward pair and low versus no reward pair), Experiment 2 showed that the higher-reward cue captured more attention and increased the perceived contrast of subsequent stimuli. In addition, we did not find attentional bias in the cueing pair of low versus no reward, even though during training the two cues also showed a significant difference in their selection rates. Taken together, these results indicated that the attentional effect might not be caused by

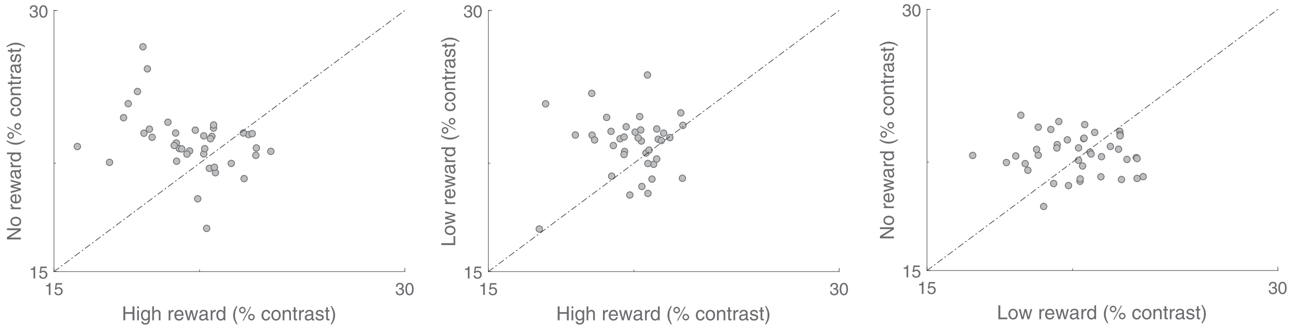

Figure 8. Attentional effects on perceived contrast at the individual level. The dashed line (a slope of 1) in each figure represents the same PSEs for the corresponding competitive rewarded cues.

a habit/orienting response or selection history of a specific stimulus in a specific context. Instead, we suggest that the results reflected a reward-driven effect on low-level visual perception.

General discussion

By using the two-phase paradigm (Anderson, 2013; Anderson et al., 2011; Failing & Theeuwes, 2014; Failing & Theeuwes, 2018) and a psychophysical method to measure the perceived contrast (Barbot & Carrasco, 2018; Carrasco et al., 2004), the current study demonstrated that reward association in the training phase changed the low-level salience of visual stimuli in the test phase and consequently increased the perceived contrast of the stimuli on the same side as the higher-reward cue compared with the lower-reward cue. This effect was also observed in a new cueing pair introduced in the test phase that was not trained before.

Our findings about the reward-driven attention on visual processing are consistent with previous studies using other tasks and paradigms (Anderson, 2013; Bucker & Theeuwes, 2018; Chelazzi et al., 2013; Failing & Theeuwes, 2018; Theeuwes, 2019). For example, Anderson and his colleagues have found that after reward association, the nonsalient stimulus would capture attention and slow down the visual search of a salient target (Anderson, 2015; Anderson, 2017; Anderson & Halpern, 2017; Anderson et al., 2011; Anderson et al., 2014). Other studies revealed that the reward-driven attention could even occur in a short term (e.g. inter-trial priming) (Della Libera & Chelazzi, 2006; Hickey et al., 2010; Hickey et al., 2014) and through Pavlovian associative reward learning in which the reward is delivered with no need for a correct response (Theeuwes, 2018). Our previous studies as well as other studies have revealed that reward could impact visual processes by enhancing attentional control in a top-down and goal-directed way (Engelmann & Pessoa, 2007; Padmala & Pessoa, 2011; Weil et al., 2010; Zhang, Tu, Dong, Chen, & Bao, 2017; Zhang et al., 2018). The reward-driven attention effect found in this study is distinct from the type of top-down modulation found in previous studies, because it is independent of intention and expectation (when the reward was no longer delivered and participants were not motivated to process the reward-associated stimulus better). The effect was also different from stimulus-driven attention because the physical salience was not changed by the reward association.

More importantly, the current study showed an increase in the low-level salience via reward-driven attention at the behavioral level. Converging results from other techniques, such as eye movement measurement, ERP, and fMRI, have revealed that the reward-driven attention would impact early sensory representation (e.g. enhancing the activity in early visual cortex and the amplitude of the early P1 component; Anderson et al., 2014; Failing et al., 2015; Hickey et al., 2010; Hickey & van Zoest, 2012; Persichetti et al., 2015; Preciado & Theeuwes, 2018). Previous research suggested that reward learning or reward-driven attention could change the salience of a visual stimulus or location (Anderson, 2013; Awh et al., 2012; Failing & Theeuwes, 2018; Theeuwes, 2019), but no study has directly demonstrated this effect with perceptual behavioral evidence. The current study for the first time provides direct evidence: people see things clearer in the presence of previously rewarded visual stimuli. This result is consistent with previous finding of the impact of reward-driven attention on the center-surround inhibition, which is also supposed to originate from the early visual stage (early sensory competition of stimulus representations; Wang et al., 2014; Wang et al., 2018).

Previous studies have also found that other types of information crucial to our survival and wellbeing (e.g. emotion) had the same influence on early vision (e.g. the perceived contrast) via attention (Barbot & Carrasco, 2018; Bocanegra & Zeelenberg, 2009; Phelps, Ling, &

Carrasco, 2006). Our study extended that conclusion about emotional stimuli to rewarding stimuli. In other words, either rewarding or emotional stimuli in the environment would quickly and automatically capture our attention and affect how we see things even if they are task-irrelevant. The impact of reward and emotion on perceptual behavior reflects the integration of different brain systems (Pessoa, 2015; Pessoa & Engelmann, 2010; Pourtois, Schettino, & Vuilleumier, 2013). Specific to the reward effect on visual processes, several previous studies indicated that it might be caused by the modulatory effect of dopamine release in the reward system, such as the midbrain and/or the striatum on the visual cortex (Anderson et al., 2014; Arsenault, Nelissen, Jarraya, & Vanduffel, 2013; Fouragnan, Retzler, & Philiastides, 2018; Gong, Jia, & Li, 2017; Noudoost & Moore, 2011; Zaldivar, Rauch, Whittingstall, Logothetis, & Goense, 2014).

In addition, in the current paradigm, we tested the relative attentional effect rather than the absolute one because two competitive reward-associated cues were presented in pair in the test phase, and selecting the stimulus on one side more frequently would inevitably lead to selecting the one on the other side less frequently. Thus, theoretically, the impact of reward-driven attention on perceived contrast would make the downward shift of the PSEs of higher-reward cues and upward shift of the PSEs of lower-reward cues from the contrast of standard stimulus (Gabor patch with fixed contrast of 20%), respectively. However, in the current study, the PSEs of higher-reward cues were not always lower than 20%. It seems that the contrast of standard stimulus was perceived higher than its real contrast (20%) and participants selected the standard stimulus (Gabor patch with fixed contrast) more frequently, which led to the systematically upwards shift. As the standard stimulus and test stimulus were randomly displayed on two sides (left/right) of the fixation, there should be no response bias to the standard stimulus. In our opinion, the long-lasting test phase might have impacted participants' contrast-transducer function and their sensitivity to the standard stimulus (e.g. visual perceptual learning of the standard stimulus) (Adini et al., 2004; Yu et al., 2004) and thus enhanced the perceived contrast of the standard stimulus. Nevertheless, the enhanced sensitivity to the standard stimulus would not impact the relative difference in perceived salience (measured by PSEs) between two competitive reward cues as the PSEs of the two cues would both shift upward. Future studies should use alternative paradigms to test the absolute effect (i.e. to figure out whether attention increases the perceived salience of higher-reward stimuli or decreases the perceived salience of lower-reward stimuli).

Finally, we should be cautious about the interpretation of the current results for several reasons. First, it is still debated whether the pure reward or the selection history produced the observed effect in the reward-driven attentional capture paradigm. On the one hand, studies on individuals with depressed symptoms who are associated with deficit in the processing of reward information found no significant priority to reward-associated stimuli, which suggested that reward processing was important for the formation of this attentional bias (Anderson et al. 2014; Anderson et al., 2017). On the other hand, many studies have revealed that sufficient training without extrinsic reward can also produce an attentional bias (Kyllingsbæk, Schneider, & Bundesen, 2001; Sha & Jiang, 2016). For example, participants who only received accuracy-based feedback during training showed an attentional capture effect in the test phase (Grubb & Li, 2018). We speculate that the experimental effect in the current study was mainly produced by reward, because in Experiment 2, the effect was found in the pair of high versus low reward in which the two cues showed a large difference in reward values but a small difference in selection rates, whereas the effect was not found in the pair of low versus no reward in which the two cues showed a small difference in reward values but a large difference in selection rates. Nevertheless, we should also note that the selection rate was not totally controlled in the pair of high versus low reward. Future studies should address the reward effect in a more direct way (i.e. totally controlling the selection rate).

Second, researchers have argued that the effect revealed by the current psychophysical paradigm developed by Carrasco et al. (2004) was not due to the attentional effect on perceived contrast but rather a cue (or response) bias (Prinzmetal et al., 2008; Schneider, 2006; Schneider & Komlos, 2008). That is, participants may bias their response towards the cued location and thus the attentional cue may not really change the stimulus perception. To rule out this explanation, Carrasco and her colleagues did a series of experiments (see the review (Carrasco & Barbot, 2019)) such as using post-cue rather than pre-cue (Fuller, Park, & Carrasco, 2009; Gobell & Carrasco, 2005), requiring participants to report the stimulus of lower contrast rather than higher contrast (Anton-Erxleben, Herrmann, & Carrasco, 2013; Carrasco et al., 2004; Ling & Carrasco, 2007) and extending the SOA between the cue and Gabor patches (Barbot & Carrasco, 2018; Carrasco et al., 2004; Fuller, Rodriguez, & Carrasco, 2008; Ling & Carrasco, 2007). These results all supported their original conclusion (attentional bias rather than response bias). Consistent with Carrasco et al.'s argument, we do not believe that cue or response bias would explain our results. The contrast of Gabor patches used in this study ranged from 8% to 50% and was suprathreshold, whereas response bias occurs only when the stimuli are at near-threshold level (Carrasco et al., 2008; Prinzmetal et al., 2008; Schneider, 2006; Schneider & Komlos, 2008). Furthermore, each trial in our experiment had two competitive circles with the same physical properties except for color as spatial cues. Therefore, participants should not bias their response to either location as a result of the preceding cues. Future studies can examine this issue by experimental manipulations such as lengthening the interval between cues and targets as Carrasco et al. did.

In conclusion, the current study found that the reward-associated stimuli captured attention and altered (mostly enhanced) the perceived contrast of subsequent stimuli. Our findings support the notion that reward-driven attention could directly and automatically impact early vision.

Keywords: reward-driven attention, low-level, visual perception, perceived contrast

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