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Stimuli that signal the availability of reward break into attentional focus

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ABSTRACT

Mounting evidence has shown that a task-irrelevant, previously reward-associated stimulus can ca
tion even when attending to this stimulus impairs the processing of the current target. Here w
whether a stimulus that merely signals the availability of reward could capture attention and in
target processing when it is located outside of attentional focus. In three experiments, a target
presented at the bottom of the lower visual field to attract focal attention. A distractor signalling
reward availability for the current trial was presented around the target with a variable distance be
This distractor was task-irrelevant; getting distracted by it could potentially result in an omission of
the high-reward condition, the distractor located adjacent to the target more severely interfered
processing than the distractor at a relatively distant location; for the low-reward condition, distra
ferent locations had the same impact upon target processing. Relative to the low-reward distracto
reward distractor impaired target processing, but only at the location adjacent to the target. Whe
location was uncertain such that attention was unable to be directed to the target in advance, the
distractor interfered with target processing at both the adjacent and distant locations. Overall,
suggest that a task-irrelevant stimulus can break into focus of attention by simply signalling the a
reward even when getting distracted by this stimulus is counterproductive to obtaining reward.

1. Introduction

Prominent models describe visual selective attention as being controlled by a voluntary top-down system and an involuntary bottom-up system (Corbetta & Shulman, 2002; Theeuwes, 2010). This theoretical dichotomy, however, is challenged by a recent notion that attentional control is also modulated by the past selection history of a stimulus (Awh, Belopolsky, & Theeuwes, 2012). A typical example is that a stimulus gains attentional priority after it has been associated with reward (Anderson, Laurent, & Yantis, 2011; Chelazzi, Perlato, Santandrea, & Della Libera, 2013; Hickey, Chelazzi, & Theeuwes, 2010). In a series of experiments, Anderson et al. (2011) asked participants to search for one of two target colours during a learning phase. High or low reward was paired with a fast and correct response to one of the two target colours. In a subsequent test phase where the task was to search for a unique shape, a stimulus having one of the two learned colours became a critical distractor among other distractors. This critical distractor impaired task performance more severely when it was associated with high reward than with low reward. Such attentional capture by reward-associated stimuli was termed reward-based (value-driven)
capture.

According to an incentive salience account, associating
with reward changes the representation of that stimulus s
becomes more salient and attention-drawing (Berridge &
1998; Hickey & Peelen, 2015; Hickey et al., 2010; Wang et
From this perspective, the association of reward with
changes the attentional processing of this stimulus at an ea
sing stage (Hickey et al., 2010; Wang, Yu, & Zhou, 2013).
with this notion, we found in our previous studies (Wa
Theeuwes, & Zhou, 2014; Wang et al., 2015) that the cente
inhibition, which originates from the sensory competition
representations in the early visual cortex (Desimone & Duncan, 1995; Luck, Girelli, McDermott, & Ford, 1997), could be modulated by reward. Moreover, we found that the anterior insula (AI) played a causal role in enabling the reward-associated distractor to break into attentional focus (Wang et al., 2015). Given that the center-surround inhibition is a consequence of sensory competition in early visual cortex (Boehler, Tsotsos, Schoenfeld, Heinze, & Hopf, 2009, 2011; Hopf et al.,

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0042-6989/

2006) and that AI is a key region in representing subjective salience (Uddin, 2015), our results suggest that reward-associated stimulus captures attention because of its increased salience.

Despite that a stimulus can gain attentional priority through an extensive reward learning phase, recent evidence suggests that such an extensive learning phase is not necessary for reward-based attentional capture to occur. Le Pelley, Pearson, Griffiths, and Beesley (2015) showed that a task-irrelevant distractor could capture attention by simply signalling the availability of reward, even though attending to this distractor impairs task performance and hence is detrimental to obtaining reward. The authors used an additional singleton task (Theeuwes, 1991a, 1992), in which participants searched for a shape singleton while the colour of an irrelevant singleton, which has a higher bottom-up perceptual salience than the shape singleton (Wang et al., 2013; Wei & Zhou, 2006), signalled the amount of reward that could be earned on that trial. That is, the amount of reward participants would receive after a correct and fast response in the current trial was predicted by the colour singleton, with one colour being predictive of high reward and the other colour being predictive of low reward. Although directing attention to the colour singleton would impair task performance and thus lower the probability of obtaining reward, the distractor that signalled a high reward nevertheless more severely interfered with target processing than the distractor that signalled a low reward. A similar pattern was observed in an oculomotor version of the task where the colour singleton signalling a high reward attracted more saccades than the colour singleton signalling a low reward, even though these eye movements resulted in reward omission (Failing, Nissens, Pearson, Le Pelley, & Theeuwes, 2015; Le Pelley et al., 2015; Pearson, Donki, Tran, Most, & Le Pelley, 2015).

Although attentional capture by reward availability shows a pattern of interference with target processing similar to the pattern observed in paradigms with reward learning, it remains unclear whether they are driven by the same mechanism. One possible account is that, like the reward association through a task-relevant learning process, the task-irrelevant information of reward availability also increases the subjective salience of the distractor. In this case, the capture effect caused by the availability of reward emerges at an early stage of sensory competition in the visual cortex. A recent study showed that the attentional capture by reward availability occurs even when the reward-associated distractor is non-salient as it does not stand out from other items in display (Failing et al., 2015) This finding is consistent with the notion that reward can enable an otherwise physically non-salient stimulus to gain reward-based salience and capture attention (Wang et al., 2013). On the other hand, classic studies on attentional capture showed that physically salient distractors are unable to cause capturing effect when attention has been directed to the target location (Theeuwes, 1991b; Yantis & Jonides, 1990). The current study was designed to investigate whether the availability of reward could capture attention and interfere with target processing when attentional focus has been directed away in advance. Based on the above-mentioned findings, we hypothesized that reward availability can increase the salience of a task-irrelevant stimulus, making the stimulus more likely to involuntarily draw attention, such that the reward-associated stimulus breaks into the current focus of attention. In three experiments, a target was always presented at the bottom of the lower visual field such that attention could be directed to the target location before the distractor appeared. A colour singleton distractor associated with high or low reward was presented at different distances from the target. Crucially, getting distracted by this distractor could delay response to the target and engender a risk of reward omission (Le Pelley et al., 2015). We expected that the high-reward distractor would be more capable of breaking into attentional focus than the low-reward distractor and causing delay of responses to the target.

Two previous studies showed that reward-associated distractor captures attention when the target location is cued in advance (MacLean, Diaz, & Giesbrecht, 2016; Munneke, Belopolsky, & Theeuwes, 2016). In these studies, attention was either endogenously cued to a certain hemisphere (MacLean et al., 2016) or an area (Munneke et al., 2016), resulting in a broadly distributed attentional window that allows capture to occur (MacLean et al., 2016; Theeuwes, 1991b). As such, it remains unclear whether the reward-based attentional capture occurs as a result of breaking into a narrowly-defined attentional focus. Moreover, in MacLean et al. (2016), the reward-based attentional capture was investigated with a reward association learning paradigm, which differed from the manipulation of reward availability in the current study. In Munneke et al. (2016), the attentional capture by reward availability was observed when there was an uncertainty of the reward delivery (i.e., the proportion of trials in which a reward could be obtained was low); the attentional capture effect might be driven by both reward availability and reward uncertainty (e.g., prediction error, Dayan, Kakade, & Montague, 2000; Gottlieb, 2012). The current study differed from these studies in at least two important aspects. First, the initial attention was narrowed down onto the exact location of the target in advance and getting distracted by the reward-associated distractor would be detrimental to obtaining reward; this would prevent the participants from strategically diffusing their initial attention. Secondly, the association between reward availability and the distractor colour was fixed (with a 100% probability), thus excluding the potential impact of reward uncertainty on distraction. These aspects of modifications would contribute to the understanding of the nature, especially the automaticity, of reward-based attentional capture. Second, initial attention was endogenously (Experiment 1) or exogenously directed to the target location (Experiments 2 and 3) in the current study, allowing us to investigate whether breaking into sustained (endogenous) or relatively transient (exogenous) attentional focus by stimuli signalling reward availability would produce different patterns of distraction (Ling & Carrasco, 2006; Nakayama & Mackeben, 1989).

2. Experiment 1

2.1. Method

2.1.1. Participants

Twenty-two students (16 females, mean age 24 years) from Vrije University Amsterdam participated in Experiment 1. They reported normal or corrected-to-normal vision and normal colour vision. They all gave written informed consent prior to the experiments in a manner approved by the Ethics Committee of the VU University, Amsterdam. Data from two participants were excluded due to relatively poor overall performance (one of them had an overall accuracy below 80% and the other one had the mean reaction time of correct responses slower than 2.5 SD above the group mean). Data of the remaining 20 participants (14 females, mean age 24 years) were analyzed; their payment ranged from €12 to €14.4 (mean payment €12.5).

2.1.2. Stimuli and design

The experiment task was similar to what reported in our previous study (Wang et al., 2014). Stimuli were presented on a Samsung SyncMaster 2233RZ monitor (1680 × 1050 resolution, 120 Hz refresh rate). Twenty items (each measured 1.2° × 1.2° in visual angle) were presented at the center of a light gray (gray scale: 204) screen. These items were located on an imaginary circle (8.5° radius) around the central fixation (a black cross, 0.5° × 0.5°), with equal distances (1.5°) between each two adjacent items.

The target was a black diamond among the other 19 distracting circles. The target diamond was always located at the bottom location of the imaginary circle. A black line segment was presented in each of the items, which was horizontal or vertical in the target diamond and titled 45° to the left or the right in the distractor circles (Fig. 1A). Participants were asked to discriminate the orientation of the line segment in the target by pressing a response button with their left and

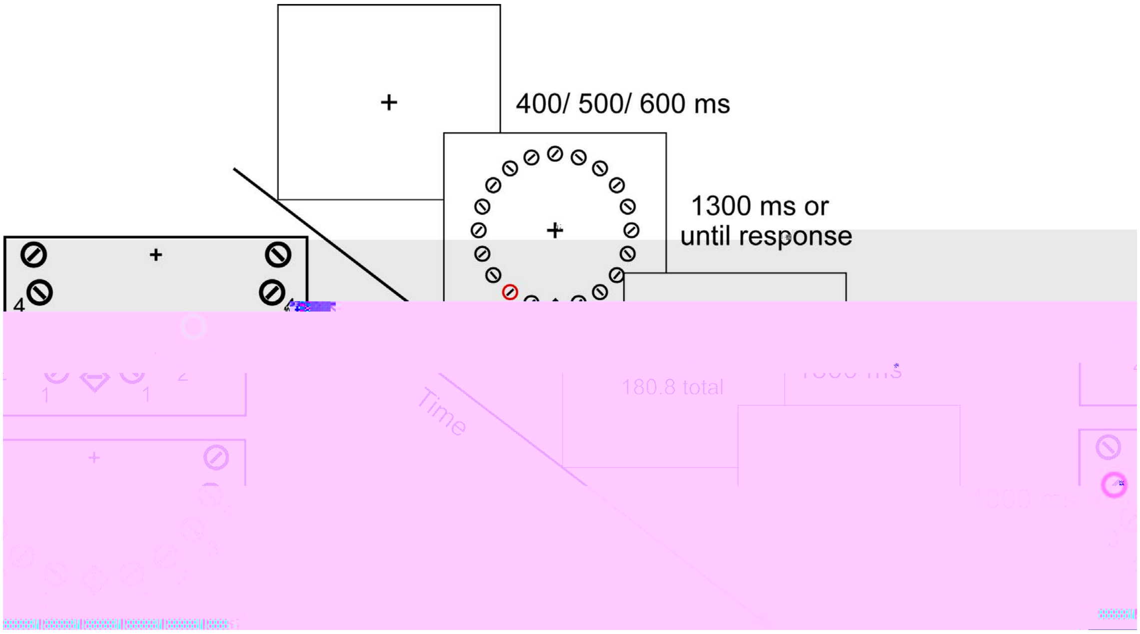

Fig. 1. Sequence of trial events in Experiment 1. The target was a diamond which was always presented at the bottom of the lower visual field. The task was to discriminate the orientation of the line segment in the target. A colour singleton distractor was presented at one of the four locations to the left or right of the target (left panel). The colour of this distractor signalled either a high or a low reward in a specific trial if a correct and fast response was given. After response, a feedback frame was presented, indicating the points the participant earned in the current trial and the total points accumulated from the first trial (right panel).

right index fingers. Each trial had a critical distractor whose colour (red or blue) was unique among the other black items and was either associated with high or low reward. For half of the participants, the red distractor was associated with high reward, and the blue distractor was associated with low reward; for the other half, the association was reversed. A feedback frame was presented after button press, indicating the points a participant earned in that trial as well as the total points accumulated up to that point. For correct responses faster than 1000 ms, the earned points in each trial were calculated as (1000 − RT) × 0.002 × bonus_multiplier. For high-reward distractor, bonus_multiplier was always 10; for low-reward distractor, bonus_multiplier was always 1 (Le Pelley et al., 2015). Errors, trials with responses slower than 1000 ms, and trials with gaze position more than 1.5° from the central fixation resulted in no points. The critical distractor was located at one of the four possible locations, with 0, 1, 2 or 3 intervening distractors between it and the target (Fig. 1, left panel). Therefore, Experiment 1 had a 2 (distractor type: high- vs. low-reward) × 4 (distractor location: 1 vs. 2 vs. 3 vs. 4) factorial design, resulting in 8 experimental conditions: high-reward distractor at location1 (H1), high-reward distractor at location 2 (H2), high-reward distractor at location 3 (H3), high-reward distractor at location 4 (H4), low-reward distractor at location 1 (L1), low-reward distractor at location 2 (L2), low-reward distractor at location 3 (L3), low-reward distractor at location 4 (L4).

2.1.3. Procedures

Participants were tested individually in a dimly lit room. They were seated in front of a screen with their head positioned on a chin rest and were required to fixate on the central cross throughout each trial. The eye-to-monitor distance was fixed at 50 cm. Stimulus presentation was controlled with Psychophysics Toolbox (Brainard, 1997; Pelli, 1997) for MATLAB (MathWorks, Inc), running on an HP Compaq 6300 Pro computer. Eye movements were monitored with an eye-movement tracking system (the Eyelink 1000 Tower mount system) at a sampling rate of 500 Hz.

Each trial began with the presentation of a central fixation sign for a varying duration of 400/500/600 ms. The task frame was then presented and remained on the screen until a response was given or until the time limit (1300 ms) was reached. The feedback frame was presented 1300 ms after button press and remained on the screen for 1300 ms. The inter-trial interval was a blank screen of 1000 ms.

There were 64 trials for each of the 8 conditions, and the total 512 trials were divided into 8 blocks of equal length. Trials of different conditions were equally distributed in each block and were presented in a random order. Participants were explicitly informed the associations between different colours and different levels of reward (e.g., red indicated a potentially high reward, while blue indicated a potentially low reward). They were also informed that the earned points in each trial were determined by both the colour of the distractor and their performance, and that the accumulated points would be proportionally exchanged for the final monetary reward (one point equals to 0.2 cents) and added to their basic payment (€ 8) for taking part in the experiment. They were instructed to respond as quickly and accurately as possible to maximize their income. Twenty-four practice trials were provided prior to the main experiment.

2.1.4. Data analysis

For each experimental condition, incorrect responses, trials in which no response was given during the response window, and trials with RTs ± 3 SDs beyond the mean RT for all the correct trials were first excluded (11.0% of all trials). Trials with gaze position more than 1.5° from the central fixation were also excluded (1.8% of all trials). Mean RT of the remaining trials in each condition was then computed. The error rate in each condition was calculated as the proportion of the number of omissions and incorrect responses against the total number of trials in the condition (Table 1). Analysis of variance (ANOVA) with distractor type (high vs. low reward) and distractor location (1, 2, 3, vs. 4) as two within-participant factors was conducted on both the mean RTs and the error rates.

2.2. Results

ANOVA on mean RTs revealed a main effect of distractor type, $F(1,19) = 5.37$, $p = 0.032$, $\eta_p^2 = 0.220$, a main effect of location, $F(3, 57) = 12.59$, $p < 0.001$, $\eta_p^2 = 0.399$, and an interaction between the two factors, $F(3, 57) = 2.84$, $p = 0.046$, $\eta_p^2 = 0.130$. Separate ANOVAs were conducted on RTs for the high-reward and low-reward distractor. For the high-reward distractor, there was a significant main effect of location, $F(3, 57) = 18.55$, $p < 0.001$, $\eta_p^2 = 0.494$. Bonferroni-corrected comparisons showed that RTs at H1 (510 ms) were slower than RTs at H2 (495 ms), H3 (495 ms) and H4 (493 ms), all $ps < 0.001$, whereas RTs at the latter three locations did not differ from each other, all $ps > 0.9$. For the low-reward distractor, there was a significant main effect of location, $F(3, 57) = 3.57$, $p = 0.020$, $\eta_p^2 = 0.158$. However, the RT difference between each two locations was not reliable enough to pass the correction of multiple comparisons, all $ps > 0.1$ (L1: 501 ms, L2: 495 ms, L3: 491 ms, L4: 491 ms). To examine whether high-reward distractor captured more attention than low-reward distractor (i.e., the reward effect), we compared the RT difference between high-reward and low-reward conditions at each location. The high-reward distractor induced slower RTs than the low-reward distractor only at Location 1, $t(19) = 3.23$, $p = 0.004$, but not at the other three locations, all $ps > 0.1$ (Fig. 2, left panel).

For the error rates, ANOVA revealed only a marginally significant interaction between distractor type and location, $F(3, 57) = 2.46$, $p = 0.072$, $\eta_p^2 = 0.115$, whereas neither the main effect of distractor type nor the main effect of location reached significance, both $F < 1$. Further ANOVAs were conducted for the high-reward and low-reward distractors, respectively. Neither the main effect of location for the high-reward (H1: 10.2%, H2: 10.2%, H3: 10.4%, H4: 9.2%), $F < 1$, nor for the low-reward distractor (L1: 10.1%, L2: 9.2%, L3: 8.4%, L4: 11.1%), $F(3, 57) = 1.84$, $p = 0.150$, reached significance. For the other direction of the interaction, there was only a trend of reward effect at Location 3, $t(19) = 1.95$, $p = 0.066$.

To examine whether the reward modulation effect changed significantly over the course of the experiment, we carried out a 2 (distractor type: high vs. low reward) × 8 (test block: 1–8) ANOVA on mean RTs at Location 1. Only a main effect of distractor type was observed, $F(1, 19) = 12.54$, $p = 0.002$, $\eta_p^2 = 0.398$, but no main effect of test block, $F(7, 133) = 1.53$, $p = 0.161$, nor interaction between distractor type and block, $F(7133) = 1.55$, $p = 0.157$, indicating equivalent reward modulation effects across different blocks (Fig. 3, left panel).

2.3. Discussion

Results of Experiment 1 showed that the high-reward distractor captured attention and interfered with target processing at the adjacent location, compared with the distractor at relatively distant location, whereas this distance effect was not observed for the low-reward distractor. More importantly, compared with the low-reward distractor, the high-reward distractor impaired target processing, but only at the adjacent location, not at other locations. This location-specific effect ruled out the possibility that attention was first directed towards the colour singleton distractor before shifting to the target location, be-

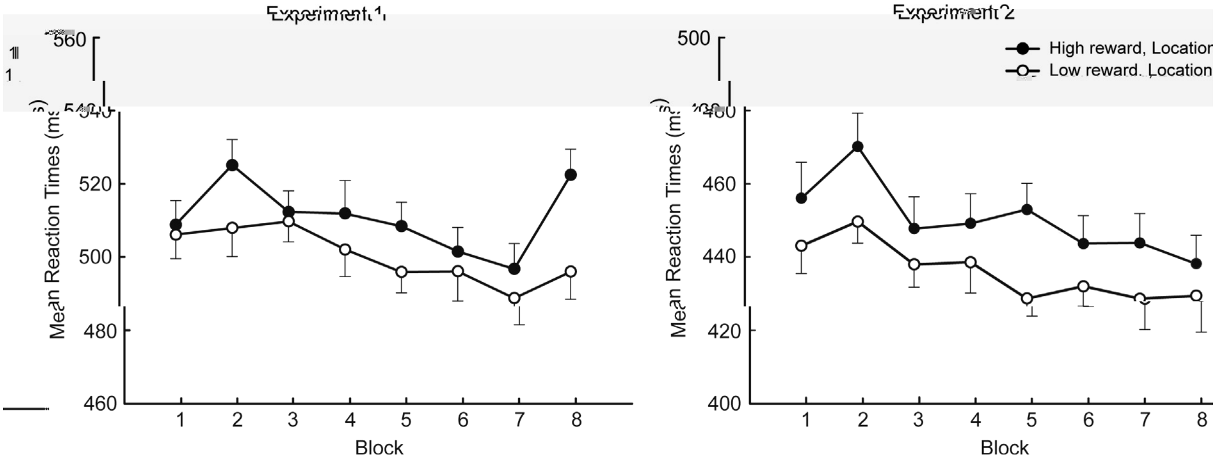

Fig. 3. Mean reaction times (ms) at the adjacent location of the target (Location 1) across blocks in Experiment 1 (A) and 2 (B).

the distractors appeared.

3.1. Method

3.1.1. Participants

Eighteen university students (12 females, mean age 25 years) with reported normal or corrected-to-normal vision and normal colour vision participated in Experiment 2. They were not tested for Experiment 1. They all provided written informed consent prior to the experiments in a manner approved by the Ethics Committee of the VU University, Amsterdam. The payments of these participants were between €12 and €15.2 (mean payment €14.3).

3.1.2. Stimuli and design

The design in Experiment 2 was the same as that in Experiment 1 except that the target diamond and distracting circles without the line segments were presented for 200 ms prior to the task frame. The target was always presented at the bottom location in the lower visual field. Specifically, in the cue frame, the diamond at the bottom location was presented together with the other black circles. After 200 ms, the colour singleton distractor replaced one of the black circles, and a line segment was presented inside each stimulus item. This task frame remained on the screen until a response was given or the time limit (1300 ms) was reached. Note here RTs were recorded relative to the onset of the task frame rather than the onset of the cue.

3.1.3. Data analysis

Data analyses in Experiment 2 were conducted in the same way as for Experiment 1. The no-response trials, incorrect responses and trials with RTs beyond 3SD of the mean RT were 10.6% of the overall data points. Trials with gaze position more than 1.5° from the central fixation were 2.7% of the overall data points.

3.2. Results

The grand mean RT collapsed over all experiment conditions in Experiment 2 (429 ms) was faster than the grand mean RT in Experiment 1 (496 ms), $t(36) = 6.25$, $p < 0.001$. ANOVA on the mean RTs, with distractor type distractor location as two within-participant factors, showed a significant main effect of distractor type, $F(1,17) = 15.76$, $p = 0.001$, $\eta_p{}^2 = 0.481$, a main effect of location, $F(3, 51) = 18.64$, $p < 0.001$, $\eta_p{}^2 = 0.523$, and an interaction between distractor type and location, $F(3, 51) = 2.86$, $p = 0.046$, $\eta_p{}^2 = 0.144$. Separate ANOVAs were then conducted for the two types of distractors. For the high-reward distractor, the main effect of location was significant, $F(3, 51) = 16.70$, $p < 0.001$, $\eta_p{}^2 = 0.496$. Further Bonferroni-corrected comparisons showed that RTs at H1 (446 ms) were slower than RTs at the other three locations (H2: 428 ms, H3: 429 ms, H4: 427 ms), $p < 0.001$, whereas RTs at the latter three locations did not differ from each other, all $ps > 0.9$. For the low-reward distractor, the main effect of location was significant, $F(3, 51) = 3.03$, $p = 0.037$, $\eta_p{}^2 = 0.151$. Further comparisons showed that only the difference between L1 (431 ms) and L3 (422 ms) reached significance, $p < 0.001$, with no statistical difference between each pair at the other locations (L2: 425 ms, L4: 424 ms), $ps > 0.2$. For the other direction of the interaction, there was a strong reward effect at Location 1, $t(17) = 4.18$, $p = 0.001$, and a trend of reward effect at Location 3, $t(17) = 1.93$, $p = 0.070$, but no effect at the other two locations, $ts < 1$ (Fig. 2, right panel).

The overall error rate in Experiment 2 (7.9%) was lower than the overall error rate in Experiment 2 (10.6%), $t(20.18) = 3.31$, $p = 0.004$. ANOVA on error rates did not reveal any main effect or interaction, all $Fs < 1$ (Table 1).

With the test block as a factor, the 2 × 8 ANOVA on mean RTs at Location 1 showed a significant main effect of distractor type, $F(1,17) = 12.06$, $p = 0.003$, $\eta_p{}^2 = 0.415$. There was also a trend of block effect, $F(7, 119) = 1.94$, $p = 0.070$, $\eta_p{}^2 = 0.102$. However, the interaction between reward and block was not significant, $F < 1$, indicating equivalent reward effects across blocks at Location 1 (Fig. 3, right panel).

3.3. Discussion

In Experiment 2, attention was involuntarily directed to the target location by an exogenous cue prior to the presentation of the target. As a result, the overall performance in Experiment 2 was better (faster responses and lower error rates) than the performance in Experiment 1, confirming the effectiveness of exogenous cueing. Crucially, however, the pattern of results was strikingly similar to what was observed in Experiment 1: the high-reward distractor caused more interference with target processing at the adjacent location than at other locations, and the effect of the low-reward distractor on target processing at the adjacent location was essentially the same as at other locations; at the adjacent location, the high-reward distractor captured attention and interfered with target processing more than the low-reward distractor. One may note that the low-reward distractor, although located outside the attentional focus (Location 1), did delay the response to the target compared with the condition in which it was more distant from the attentional focus (Location 3). This could be that the low-reward distractor occasionally broke into attentional focus because there was still a small chance for the participants to gain relatively high points in the low-reward condition (e.g., by enhancing response speed).

4. Experiment 3

To provide a direct comparison between the reward-induced attentional capture when target location is cued beforehand and when it is not cued, we manipulated the predictability of the target location in Experiment 3. In half of the trials, we presented a cue to indicate the target location to which attention could be directed in advance. In the other half, we did not present a cue, but instead presented the target at unpredictable locations. We reasoned that when the target location is uncertain, attention is likely to be firstly drawn to the colour singleton (Hickey, McDonald, & Theeuwes, 2006). As such, the reward-induced attentional capture and interference with target processing would be observed in other locations as well as at the adjacent location.

4.1. Method

4.1.1. Participants

Twenty students (13 females, mean age 21 years) from Peking University with reported normal or corrected-to-normal vision and normal colour vision participated in Experiment 3. They all provided written informed consent prior to the experiments in a manner approved by the Ethics Committee of Peking University. The payments of these participants were between ¥46 and ¥69 (mean payment ¥58.8, about €8.2).

4.1.2. Stimuli and design

The design in Experiment 3 was essentially the same as that in Experiment 2 with the following exceptions. Participants were explicitly informed that there were two kinds of blocks: cued blocks and uncued blocks. The design in the cued blocks was the same as the one in Experiment 2. In contrast, in the uncued blocks, no cue was presented prior to the task frame and the target was randomly presented at the bottom or the top location of the stimulus array. The colour singleton distractor was presented at the same visual field as the target. For example, when the target was presented at the bottom location of the stimulus array, the colour singleton distractor would be presented in the lower visual field, located at one of the four locations to the left or right of the target; when the target was presented at the top location of the stimulus array, the colour singleton distractor would be presented in the upper visual field, located at one of the four locations to the left or right of the target. Therefore, the experiment had a 2 (cueing type: cued vs. uncued) × 2 (distractor type: high reward vs. low reward) × 4 (distractor location: 1 vs. 2 vs. 3 vs. 4) within-subject design.

4.1.3. Procedures

Procedures in Experiment 3 were the same as the procedures in Experiment 2 with the following exceptions. There were 40 trials in each of the 16 conditions, and the total 640 trials were divided into 10 blocks with equal length (64 trials in each block). There were 5 cued blocks and 5 uncued blocks, and the 10 blocks were mixed and presented in a random order. At the beginning of each block, participants were instructed whether there would be a cue in the current block.

4.1.4. Data analysis

No-response trials, trials with incorrect responses and trials with RTs beyond 3SD of the mean RT (10.4% of the overall data points) were excluded from data analysis. Trials with gaze position more than 1.5° from the central fixation (2.5% of the overall data points) were also excluded.

4.2. Results

A 2 × 2 × 4 ANOVA was conducted on the mean RTs. The main effect of cueing type was significant, $F(1, 19) = 182.78$, $p < 0.001$, $\eta_p^2 = 0.906$, with slower RTs in the uncued blocks (643 ms) than in the cued blocks (490 ms). The main effect of distractor type was not significant, $F(1, 19) = 2.08$, $p = 0.166$. The main effect of location was significant, $F(3, 57) = 4.41$, $p = 0.007$, $\eta_p^2 = 0.188$. Bonferroni-corrected comparisons showed that the location effect was mainly driven by the RT difference between Location 1 (572 ms) and Location 2 (564 ms), $p = 0.025$, and the RT difference between Location 1 and Location 4 (564 ms), $p = 0.064$, while the RT difference between other locations did not reach significance, all $ps > 0.2$. Importantly, the interaction between distractor type and location was significant, $F(3, 57) = 5.20$, $p = 0.003$, $\eta_p^2 = 0.215$, so was the three-way interaction between cueing type, distractor type and location, $F(3, 57) = 6.57$, $p = 0.001$, $\eta_p^2 = 0.257$. Other two-way interactions, however, did not reach significance, $F < 1$ for the interaction between cueing type and distractor type and $F(3, 57) = 1.54$, $p = 0.213$ for the interaction between cueing type and distractor location.

Separate 2 × 4 ANOVAs were conducted for the cued blocks and the uncued blocks. For the cued blocks, while the main effect of distractor type was not significant, $F < 1$, the main effect of location was significant, $F(3, 57) = 6.16$, $p = 0.001$, $\eta_p^2 = 0.245$, so was the interaction between distractor type and location, $F(3, 57) = 3.20$, $p = 0.030$, $\eta_p^2 = 0.144$. For the high-reward distractor, the main effect of location was significant, $F(3, 57) = 10.11$, $p < 0.001$, $\eta_p^2 = 0.347$. Bonferroni-corrected comparisons showed that RTs at H1 (504 ms) was slower than RTs at the other three locations (H2: 487 ms, H3: 484 ms, H4: 490 ms), $p = 0.013$, $p = 0.001$, $p = 0.003$, respectively, whereas RTs at the latter three locations did not differ from each other, all $ps > 0.9$. For the low-reward distractor, the main effect was not significant, $F < 1$, indicating equivalent RTs at the four locations (L1: 491 ms, L2: 487 ms, L3: 487 ms, L4: 487 ms). For the other direction of the interaction, there was a reward effect only at Location 1, $t(19) = 3.44$, $p = 0.001$, but not at the other three locations, $t < 1$ (Fig. 4, left panel).

For the uncued blocks, the 2 × 4 ANOVA revealed only an interaction between distractor type and location, $F(3, 57) = 6.79$, $p = 0.001$, $\eta_p^2 = 0.263$. On the one hand, we found a significant main effect of location for the high-reward distractor, $F(3, 57) = 5.64$, $p = 0.002$, $\eta_p^2 = 0.229$. Bonferroni-corrected comparisons showed that RTs at H4 (629 ms) were significantly faster than RTs at H1 (654 ms), $p = 0.014$, and H3 (657 ms), $p = 0.023$, but not different from RTs at H2 (644 ms), $p = 0.408$. The differences between RTs at H1, H2 and H3 did not differ from each other, all $ps > 0.3$. For the low-reward distractor, the main effect of location was not significant, $F(3, 57) = 1.59$, $p = 0.201$ (L1: 640 ms, L2: 639 ms, L3: 636 ms, L4: 648 ms). On the other hand, the paired t tests showed a significant reward effect at Location 1, $t(19) = 2.58$, $p = 0.018$, and Location 3, $t(19) = 2.41$, $p = 0.027$, but a reversed effect at Location 4 (i.e., RTs at H4 were lower than RTs at L4), $t(19) = 2.57$, $p = 0.019$. RTs at H2 and at L2 did not differ from each other, $t < 1$ (Fig. 4, right panel).

The 2 × 2 × 4 ANOVA on error rates revealed a significant main effect of cueing type, $F(1, 19) = 23.95$, $p < 0.001$, $\eta_p^2 = 0.558$, with more errors in the uncued blocks (11.2%) than in the cued blocks (7.3%). There was a trend of interaction between distractor type and location, $F(3, 57) = 2.69$, $p = 0.055$, $\eta_p^2 = 0.124$. No other effects were observed.

To examine whether there was a learning effect over different test blocks, a 2 × 10 ANOVA was conducted on mean RTs at Location 1, ignoring the cueing type. The analysis showed a significant main effect of distractor type, $F(1,19) = 28.64$, $p < 0.001$, $\eta_p^2 = 0.601$, and a significant main effect of block, $F(9, 171) = 8.81$, $p < 0.001$, $\eta_p^2 = 0.371$. However, the interaction between reward and block was not significant, $F(9, 171) = 1.47$, $p = 0.162$, indicating comparable reward effects across different blocks (Fig. 5). Separating the test blocks into cued and uncued types and re-running this block sequence analysis (ignoring the actual position of the block in the randomized sequence) led us to the same conclusion.

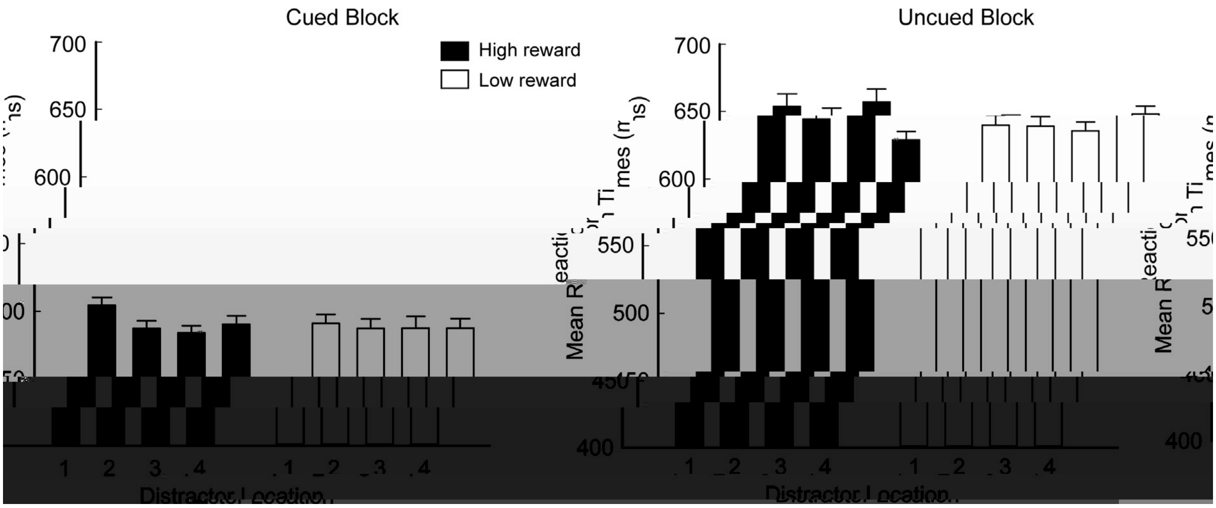

Fig. 4. Results from Experiment 3. Mean reaction times (ms) are shown as a function of different experimental conditions in the cued block (left) and in the uncued block (right).

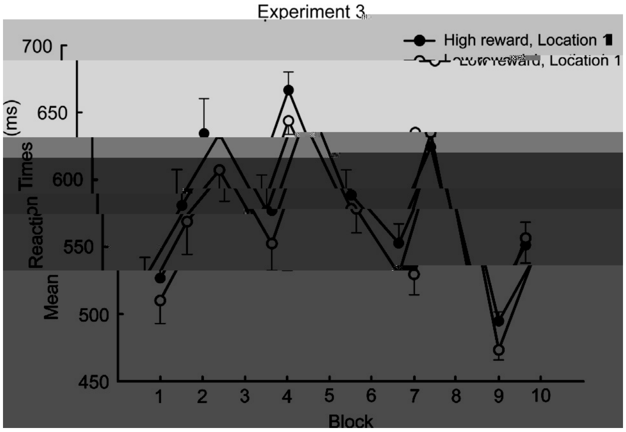

Fig. 5. Mean reaction times (ms) at the adjacent location of the target (Location 1) across blocks in Experiment 3.

4.3. Discussion

In Experiment 3, the reward modulations showed dramatically different patterns of results depending on whether the target location was cued prior to the appearance of the distractor, versus the condition in which the target location was uncued and hence unpredictable. Specifically, as in Experiment. 2, the high-reward distractor caused interference to the processing of the target when it was adjacent to the target relative to when it was far away whereas the low-reward distractor showed no effect. However, there was a reward-induced attentional capture effect at two locations (Location 1 and Location 3) near the target when the target location was not cued in advance. The reversed reward effect at Location 4 in the uncued block may indicate the active suppression of high versus low salient distractor (Geng, 2014; Sawaki, Luck, & Raymond, 2015). Given that the strength of this active suppression is determined by the representational distance between the target and the distractor (Geng, 2014), the distractor located far away from the target (Location 4) was more effectively suppressed than the distractor near the target (Locations 1, 2 and 3). According to the normalization model of attention (Herrmann, Montaser-Kouhsari, Carrasco, & Heeger, 2010; Reynolds & Heeger, 2009), distractor could be more effectively suppressed when there is spatial uncertainty than when there is no spatial uncertainty. Thus, the active suppression was observed in the uncued block (with spatial uncertainty), but not in the cued block (without spatial uncertainty) in Experiment 3.

5. General discussion

Across three experiments, we replicated the finding that a task-irrelevant stimulus captures attention and interfere with target processing by merely signalling the availability of reward even when attending to this stimulus is detrimental to gaining reward (Failing et al., 2015; Le Pelley et al., 2015; Pearson et al., 2015). In an extension, we demonstrated that the reward-associated distractor still captures attention even when it falls outside the attentional focus, regardless of whether attention is endogenously (Experiment 1) or exogenously (Experiments 2 and 3) narrowed down to the target location.

The occurrence of reward-based attentional capture when the target location is known in advance has been reported in previous studies using other paradigms (MacLean et al., 2016; Munneke et al., 2016). However, the current study provides stronger evidence for the effect for two reasons. First, we narrowed down initial attention onto the exact location of the target without any uncertainty instead of directing attention to a certain hemisphere (MacLean et al., 2016) or area (Munneke et al., 2016); the latter may result in more diffused attentional window allowing more room for capture to occur (MacLean et al., 2016). Second, the reward delivery depended only on whether a fast and accurate response was made, as paying attention to the distractor was counterproductive to gaining reward. These manipulations additively lower, if not exclude, the chance of initial attention focusing on the reward-associated distractor. Despite all this, the reward-based distractor still captured attention. The consistent observations of reward-based attentional capture across different studies, regardless of whether the target location is known in advance (MacLean et al., 2016; Munneke et al., 2016) and regardless of whether attending the distractor has been directly rewarded (Anderson et al., 2011; Le Pelley et al., 2015), pointed to a common notion that reward can enable a stimulus to gain subjective salience and *involuntarily* capture attention. The implication here is that the attentional capture by reward-associated stimuli emerges at an early stage of attentional processing.

The suggestion that reward availability modulates the early attentional processing of the distractor is consistent with oculomotor studies using similar paradigms (Failing et al., 2015; Pearson et al., 2016). For example, in an eye-movement tracking study, Failing et al. (2015) found that a larger proportion of first saccades went to the distractor that signalled availability of high reward than to the distractor that signalled availability of low reward, even though these saccades resulted in reward omissions. Critically, this reward modulation was much stronger on fast saccades (e.g., when the time interval between the central fixation and the following search array was short), compared with slow saccades (e.g., when the time interval was long), demonstrating that the influence of reward availability on oculomotor capture decreased as a function of time (see also Pearson et al., 2016). Taking together these studies and the current one, we suggest that reward association with a stimulus modulates the early selection of that stimulus, resulting in both covert and overt attentional capture.

The suggestion that reward increases stimulus salience is also in agreement with many previous studies (Anderson et al., 2011b; Failing & Theeuwes, 2014; Hickey et al., 2010; Theeuwes & Belopolsky, 2012; Wang et al., 2013). For example, Wang et al. (2013) found that the occurrence of reward-based attentional capture in the test phase was modulated by the perceptual salience of the reward-associated stimulus in the learning phase. Moreover, the account that reward increases stimulus salience and attracts attention has been suggested not only in the spatial domain but also in the temporal domain. Failing and Theeuwes (2016) showed that, relative to a stimulus signalling low or no reward, a stimulus signalling high reward gained subjective salience and attracted more attention, causing the high-reward stimulus to be perceived as expanded in time. The aforementioned evidence suggests that associating a stimulus with reward increases the subjective salience of that stimulus, which changes both the spatial and the temporal representation of that stimulus in the brain.

Although a growing body of studies has revealed that the representation of a stimulus in the early visual cortex can be enhanced by reward learning (Chelazzi et al., 2013; Hickey & Peelen, 2015; Hickey et al., 2010; Wang et al., 2015), there was no agreement on the origin of this reward-induced modulation. Some studies show that the activity in the visual cortex is modulated by the midbrain dopamine (Anderson et al., 2016; Hickey & Peelen, 2015), but it remains unknown how the reward signal is projected to the visual cortex. For example, does the midbrain projects the reward salience directly to the visual cortex, or through the attentional orienting network? With the combination of dynamic causal modelling and resting-state functional connectivity, we recently found that the salience signal is detected by AI and is projected from AI to the fronto-parietal attentional orienting network, which modulates the activity in the visual cortex (Wang et al., 2015). We also found that the functional connectivity between AI and the ventral striatum (VS) could predict the reward-induced attentional capture only after learning, but not before learning (Wang et al., 2015). Although such evidence provides a tentative framework of how reward salience is transferred from the salience network to the visual cortex, it is still unknown how the connection between VS and AI is constructed during learning. Other studies perceived the reward-based attentional capture as a direct perceptual learning effect in early visual cortex (MacLean & Giesbrecht, 2015; Seitz, Kim, & Watanabe, 2009; van Koningsbruggen, Ficarella, Battelli, & Hickey, 2016). For instance, van Koningsbruggen et al. (2016) found that the reward-based attentional effect was modulated by the stimulation over the occipital cortex, but not by the stimulation over the frontal cortex. A recent study suggested that reward might act as a teaching signal for changing the stimulus salience in early visual vision (Anderson, 2017). Further neuroimaging studies are needed to elucidate the neural mechanism of the reward-induced attentional capture.

One account related to the reward-based attentional capture, which could explain the origin of the reward-based salience, is the “arousal-biased competition” account (Mather & Sutherland, 2011). According to this account, during initial information processing, arousal influences competition between different stimuli for mental resources, increasing the processing of high priority stimuli while decreasing the processing of low priority stimuli. From this perspective, stimuli that have been exposed to arousal events such as reward and other emotional events during our past selection history (Awh et al., 2012) are capable of boosting arousal level and hence possessing higher salience relative to neutral stimuli.

Another observation in the current study was that the capture effect did not change significantly over the course of each experiment (i.e., interactions with block were not significant), suggesting that the effect emerged relatively rapidly and then remained stable. Such a fast learning effect was also observed in other studies using the same paradigm regardless of whether observers were informed about the specific association between high/low reward (Failing et al., 2015) or not (Le Pelley et al., 2015; Pearson et al., 2015). In another line of studies in which reward was delivered only during the training phase rather than the test phase, extensive training was required (e.g., at least 240 trials) when a probabilistic reward was used (e.g., high-reward colour predicted high-reward delivery in 80% of the trials, Anderson et al., 2011), whereas less training (180 trials) was required when a non-probabilistic reward was used (e.g., high-reward colour predicts high-reward delivery in all of the trials, Wang et al., 2013). Apparently, the acquisition speed of the reward-based salience depended on the extent to which the colour could predict reward delivery.

In summary, we found that a stimulus can break into the focus of attention by simply signalling the availability of reward, even though attending to this stimulus is detrimental to obtaining reward. This finding suggests that the information about the reward availability of a stimulus can increase the subjective salience of that stimulus, and the attentional capture by that stimulus emerges at an early stage of attentional processing.

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