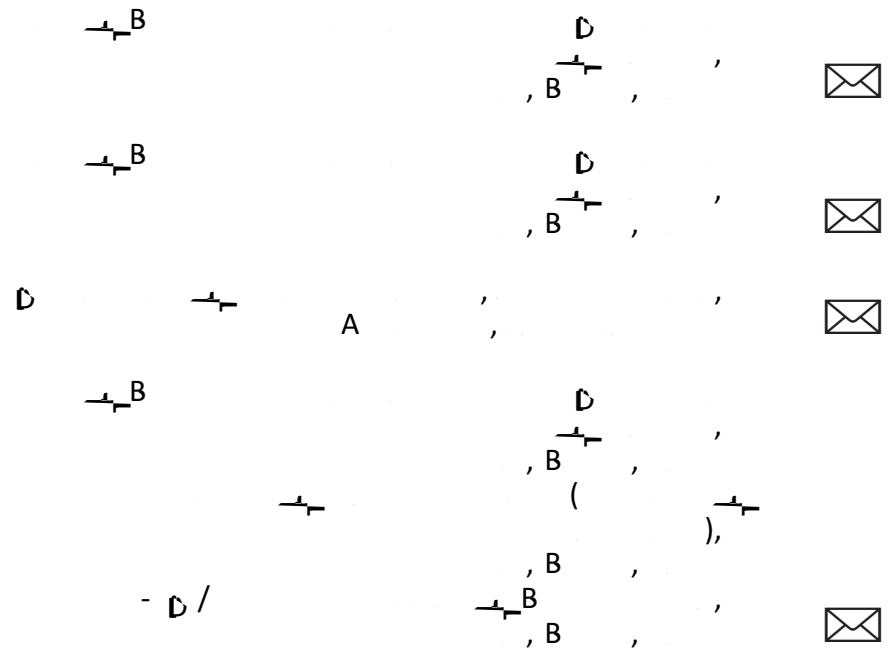# Reward breaks through the inhibitory region around attentional focus

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It is well known that directing attention to a location in space enhances the processing efficiency of stimuli presented at that location. Research has also shown that around this area of enhanced processing, there is an inhibitory region within which processing of information is suppressed. In this study, we investigated whether a reward-associated stimulus can break through the inhibitory surround. A distractor that was previously associated with high or low reward was presented near the target with a variable distance between them. For low-reward distractors, only the distractor very close to the target caused interference to target processing; for high-reward distractors, both near and relatively far distractors caused interference, demonstrating that task-irrelevant reward-associated stimuli can capture attention even when presented within the inhibitory surround.

Introduction

It is generally assumed that the role of selective attention is to prioritize some stimuli while rejecting others such that the selected stimuli are processed more efficiently. The ambiguity resolution theory of attention (Luck, Girelli, McDermott, & Ford, 1997) proposed that multiple objects located in the receptive field of the same populations of neurons interact with each other in competing for neural representation in the extrastriate cortex (see also Desimone & Duncan, 1995), causing ambiguity in coding individual objects. To resolve this ambiguity, an inhibition ring is formed surrounding the attended object to suppress distracting objects (Cutzu & Tsotsos, 2003; Hopf et al., 2006; Mounts, 2000b). Mounts (2000a) varied the spatial separation between a shape singleton target and a color singleton distractor in a visual search array and tested how the interference from the distractor was modulated by the distance. Reaction times (RTs) to the target were the slowest when the distractor was adjacent to the target and became faster as the distance between the distractor and the target increased (see also Wei, Lu, Muller, & Zhou, 2008). This effect was taken as evidence for an inhibitory region around the attended object, indicating that distractors located in this region fail to capture attention and cause any interference.

Attentional capture, i.e., a stimulus involuntarily distracting attention (Yantis & Jonides, 1984), may occur in different ways. A task-irrelevant stimulus could delay the processing of a target either when it is perceptually salient (Theeuwes, 1991, 1992; Wei & Zhou, 2006) or shares certain features with the target (Folk & Remington, 1998; Folk, Remington, & Johnston, 1992). Recent studies showed that a task-irrelevant nonsalient stimulus can also capture attention after it has been associated with reward (Anderson, Laurent, & Yantis, 2011; Hickey, Chelazzi, & Theeuwes, 2010; Theeuwes & Belopolsky, 2012; Wang, Yu, & Zhou, 2013). For example, in Anderson et al. (2011), through learning, a particular color was associated with either high or low reward. In the subsequent search task in which participants searched for a unique shape, a stimulus having one of these trained colors became a distractor, and it impaired task performance more severely when it was associated with high reward rather than low reward.

Despite the recent progress on reward-based attentional capture (Anderson, 2013; Awh, Belopolsky, & Theeuwes, 2012), an unsettled question is how reward-associated stimuli affect the sensory competition in visual space. Relative to a low-reward stimulus, a high-reward stimulus may break through the inhibition ring and increase the ambiguity in the receptive field if it is a distractor. In this study, we adopted the reward learning paradigm used by Anderson et al. (2011) and manipulated the spatial distance between the distractor and the target. We hypothesized that if, relative to a low-reward stimulus, the presence of high-reward stimulus increases spatial ambiguity and sensory competition it would still capture attention and cause interference even when it was presented in the inhibitory region around the target.

The attentional suppression depends on both sensory inputs of the competing objects and top-down control (Desimone & Duncan, 1995; Luck et al., 1997). Consistent with this hypothesis, Hopf and colleagues (2006) showed that the surround inhibition was observed only when top-down attention was focused on the peripheral target but not when it was engaged in a central demanding task. Similarly, Cutzu and Tsotsos (2003) found that the surround inhibition appeared only when a spatial cue was presented to indicate the location of the subsequent target. These results suggested that initial allocation of attention on the target is necessary for the formation of the inhibitory region around the target. In the present study, we always presented the target at the bottom of the lower visual field. This predictability of target location encouraged the endogenous allocation of attention on the target (Geng & Behrmann, 2002; Jiang, Swallow, & Rosenbaum, 2013) and allowed the surrounding inhibitory region to build up.

Method

Participants

Thirty-six right-handed university students were tested with 18 for Experiment 1 (10 females, mean age: 22.0 years) and the other 18 for Experiment 2 (eight females, mean age: 23.1 years). All the participants had normal or corrected-to-normal vision, and none of them reported a history of neurological or psychiatric disorders. Color blindness or weakness was assessed when they were recruited. They all gave informed consent prior to the experiments in a manner approved by the Ethics Committee of the Department of Psychology, Peking University.

Design and stimuli

The two experiments had essentially the same design with the crucial difference that Experiment 2 monitored participants' eye movements, and trials with obvious eye movements were removed from data analysis.

Each experiment consisted of a learning phase (Figure 1A) and a test phase (Figure 1B). In the two phases of Experiment 1, 20 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 in an imaginary circle (7° radius) around the central fixation (a black cross, 0.5° × 0.5°) with equal intervals (0.9°) between each two adjacent items. In the two phases of Experiment 2, the number of the items was reduced to 16, forming an imaginary circle with a 6° radius.

In the learning phase, the target was a red or blue (red or green in Experiment 2) circle among the other 19 (15 in Experiment 2) black circles. The target circle appeared randomly at the nine (seven in Experiment 2) locations in the lower visual field. A black line segment was presented in each of the circles, which was horizontal or vertical in the target circle and tilted 45° to the left or the right in the distractor circles (Figure 1A). Participants were asked to discriminate the orientation of the line segment in the target circle in each trial by pressing a response button with their index or middle fingers. One target color was associated with high reward and the other with low reward with the assignment counterbalanced over participants. The association of a target color with monetary reward was established by presenting a feedback frame indicating the points a participant earned in that trial and the total points accumulated thus far. For a high-reward target, a correct response

Figure 1. (A) ... (+10) ... (B) ...
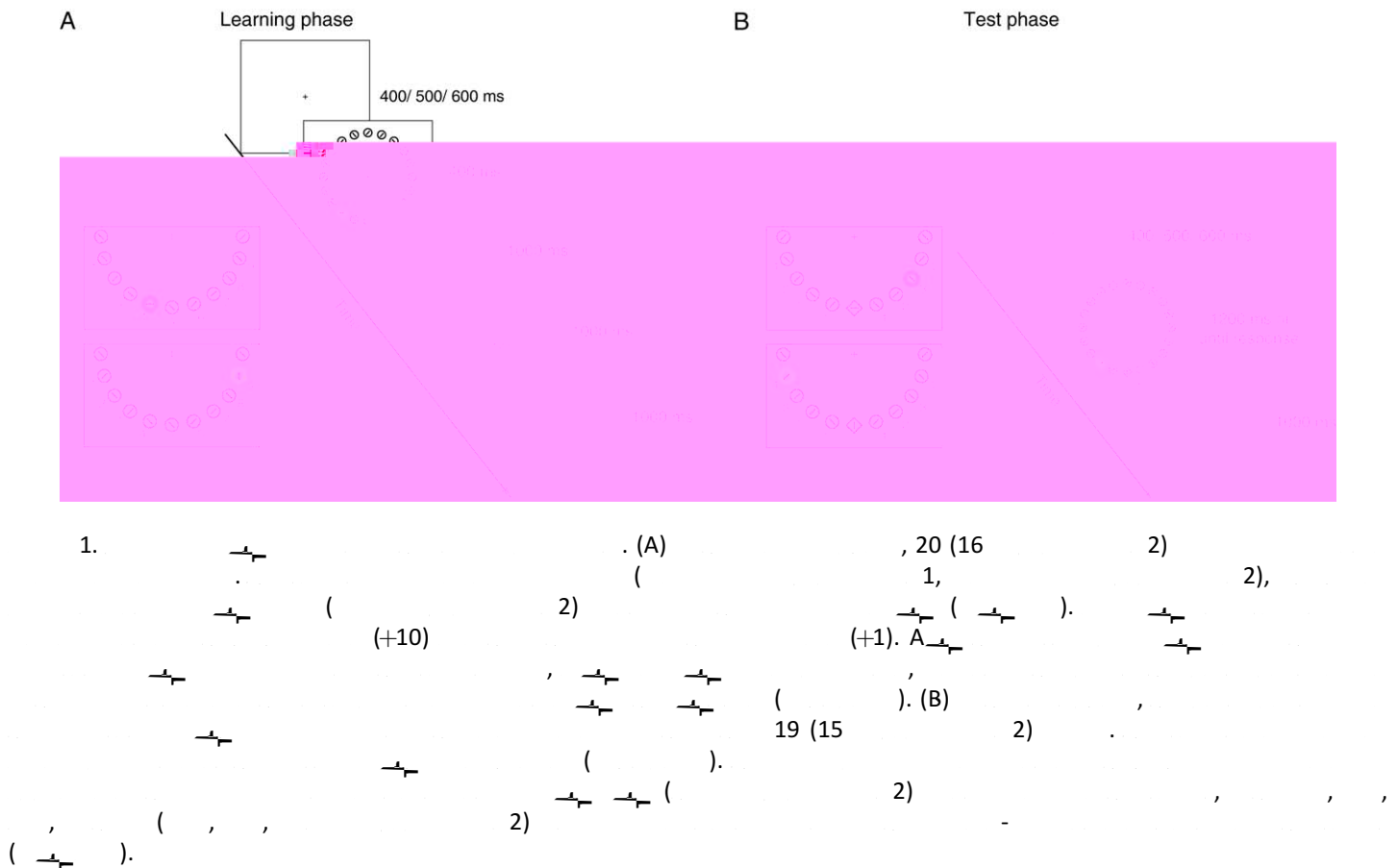
was followed by "+10" in the subsequent feedback frame in 80% of the trials, denoting the receipt of 10 points, and was followed by "+1" in the remaining 20% of the trials, denoting the receipt of one point. For a low-reward target, the percentages were reversed. Incorrect responses resulted in "0," and omissions were followed by a word "miss" in the feedback frame. Participants were informed of the conversion rate of the points (one point equaled to ¥0.01; ¥100 ≈ US$16) and were told that the points accumulated during the learning phase would be proportionally exchanged to the final monetary reward and added to their basic payment (¥30) for taking part in the experiment.

In the test phase, the target was a black diamond among the other 19 (15 in Experiment 2) distractor circles. The target diamond was always located at the bottom location of the imaginary circle. Each trial had a critical distractor whose color was either associated with high reward or low reward in the learning phase. This critical distractor was located at one of four (three in Experiment 2) possible locations, with zero, one, two, or three (zero, one, or two in Experiment 2) intervening distractors between it and the target (Figure 1B). Therefore, Experiment 1 had a 2 × 4 factorial design in the test phase:

distractor type (high vs. low reward) and colored distractor location (1 vs. 2 vs. 3 vs. 4); similarly, Experiment 2 had a 2 × 3 design, in which eye-tracking data in the test phase were recorded with an EyeLink 2000 system at a sampling rate of 500 Hz. Participants were told that there were no monetary rewards in the test phase.

Procedures

Participants were tested individually in a soundproof and dimly lighted room. They were seated in front of a CRT monitor screen with their head positioned on a chin rest and were required to fix at the central cross throughout each trial. The eye-to-monitor distance was fixed at 65 cm. Participants were also calibrated with a nine-point grid at the beginning of Experiment 2.

In both phases, each trial began with the presentation of the central fixation 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 was reached (400 ms in the learning phase and 1200 ms in the test phase). In the learning phase, the feedback frame was presented 1000 ms after button press and remained on the screen for

	1	2
1	4.3 (1.1)	2.0 (0.7)
2	5.4 (0.8)	3.0 (0.9)
3	3.5 (1.0)	3.6 (0.8)
4	4.9 (0.9)	
1	5.1 (0.8)	4.2 (0.8)
2	4.7 (1.0)	3.2 (0.8)
3	4.4 (0.7)	2.9 (0.8)
4	3.2 (0.6)	

1.   (%)   -
(   ) ⊥⊤
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1000 ms. No feedback was presented in the test phase. The intertrial interval in both phases was a blank screen of 1000 ms.

In Experiment 1, there were 252 trials for each of the two targets in the learning phase and 40 trials for each condition in the test phase. Experiment 2 had the same number of trials in the learning phase but had 48 trials for each condition in the test phase. Trials were divided into seven blocks in the learning phase and into five (for Experiment 1) or six (for Experiment 2) blocks in the test phase. Trials of different conditions were equally distributed in each block and were presented in a pseudorandomized order with the restriction that no more than three consecutive trials required the same responses. Participants were instructed to respond as quickly and accurately as possible to maximize their income. Twenty practice trials in which the monetary feedback was replaced by response feedback (correct vs. incorrect) were provided prior to each of the two phases.

Data analysis

For each experimental condition in the test phrase, omissions, incorrect responses, and trials with RTs ± 3 SDs beyond the mean RT for all the correct trials were first excluded. Mean RT of the remaining trials (94.0% of all the trials in Experiment 1) in each condition was then computed. The error rate in each condition was calculated as the proportion of the number of omissions and incorrect trials against the total number of trials in the condition (Table 1). For the eye-tracking data in Experiment 2, gaze positions from the onset of fixation to the execution of response were recorded and mean-corrected. For each participant, the mean position in each of the six conditions was first calculated. All of the mean positions along the vertical and horizontal axes were within 1.5° from the central fixation, ruling out the possibility that gazes were fixed on the target. For each participant, trials with gaze position ± 2 SDs beyond the mean position in each of the six conditions were further removed after the exclusion of behavioral outliers (including omissions, incorrect responses, and trials with RTs ± 3 SDs beyond the mean RT). The analyses of mean RTs and gaze positions were based on the remaining trials (88.5% of all the trials). Gaze positions along the vertical and the horizontal axes of the screen were plotted for the high- and low-reward conditions separately with a bin size of 0.4° of visual angle.

Results

Analysis of variance (ANOVA) on error rates in either the learning or the test phase did not show any main effects or interactions; RTs to the high- and low-reward targets in the learning phase did not differ from each other either. We, hence, focused on RTs in the test phase in the following report.

Experiment 1

ANOVA with distractor type (high vs. low reward) and distractor location (1, 2, 3, 4) as two within-participant factors showed a main effect of location, $F(3, 51) = 11.7$, < 0.001, and an interaction between distractor type and location, $F(3, 51) = 3.16$, < 0.05, but no main effect of distractor type, $F(1, 17) = 2.31$, > 0.1. Further analyses revealed different patterns of location effect for the two types of distractors. For the low-reward distractor (Figure 2A), RTs at L1 (582 ms) were longer than RTs at L2 (566 ms), L3 (561 ms), and L4 (562 ms) with no difference between the latter three conditions: L1 versus L2, $(17) = 3.15$, < 0.01; L1 versus L3, $(17) = 2.80$, < 0.05; L1 versus L4, $(17) = 3.13$, < 0.01. Thus, the low-reward distractor caused interference only when it was close to the target (location 1) but not when the distractor was further away from the target (locations 2, 3, and 4). For the high-reward distractor (Figure 2A), RTs at H1 (578 ms) and H2 (581 ms) were not different (< 1), and both were longer than RTs at H4 (558 ms): H1 versus H4, $(17) = 5.42$, < 0.001; H2 versus H4, $(17) = 4.19$, < 0.01. In addition, the mean RT at H3 (570 ms) was longer than that at H4, $(17) = 2.12$, $= 0.049$, but shorter than the RT at H2, $(17) = 2.34$, < 0.05. Similar patterns were observed when the target and distractor were in the upper visual field (see S- E $S1$). These results suggested that the high-reward distractor interfered with the processing of the target even when it was located relatively far from the target.

2. ... 1 (A) ... 2 (B). ... ( ) ... (, 2005).
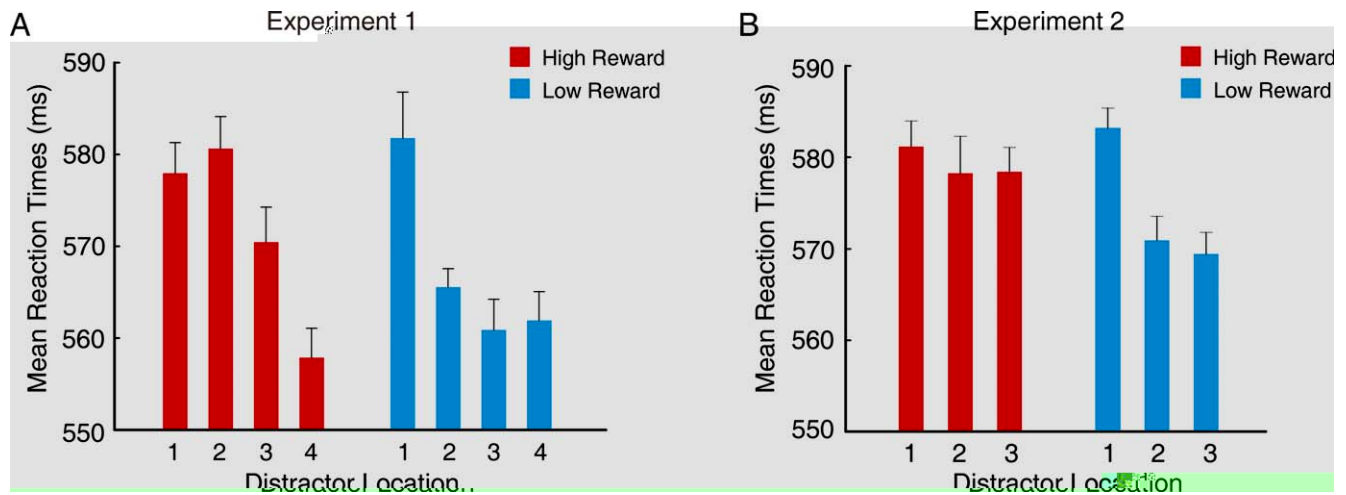
Experiment 2

Two-sample Kolmogorov-Simirnov tests comparing the distributions of gaze positions along the vertical and horizontal axes (Figure 3) revealed no difference between the high- and low-reward conditions, both $s > 0.5$. Analysis of RTs revealed no main effect of distractor type, $F(1, 17) = 2.93$, > 0.1, but a main effect of location, $F(2, 34) = 3.41$, < 0.05, and a marginally significant interaction between them, $F(2, 34) = 2.92$, $= 0.068$. For the low-reward distractor, the mean RT at L1 (583 ms) was longer than RTs at L2 (571 ms) and L3 (569 ms): L1 versus L2, $(17) = 3.12$, < 0.01; L1 versus L3, $(17) = 3.91$, < 0.01. However, RTs were comparable at the three locations for the high-reward distractor (581 ms, 578 ms, and 578 ms, respectively, at H1, H2, and H3), all $s < 1$. These results replicated the data in Experiment 1 except that

the interference effect was strengthened at H3, probably because the distractor was closer to the central fixation (6° in visual angle) than that in Experiment 1 (7°).

Discussion

Although previous studies have argued for an attentional priority for reward-associated stimuli (Anderson et al., 2011; Hickey et al., 2010), they are not able to answer to what extent reward-associated stimuli affect sensory competition because the distance between the target and the reward-associated distractor was not manipulated. Here we varied both the spatial separation and the reward magnitude of the distractor and found that, for the low-reward conditions, the

3. ... (A) ... (B) ... - ... - ... . (...) ... (A) ... (B) ... . -
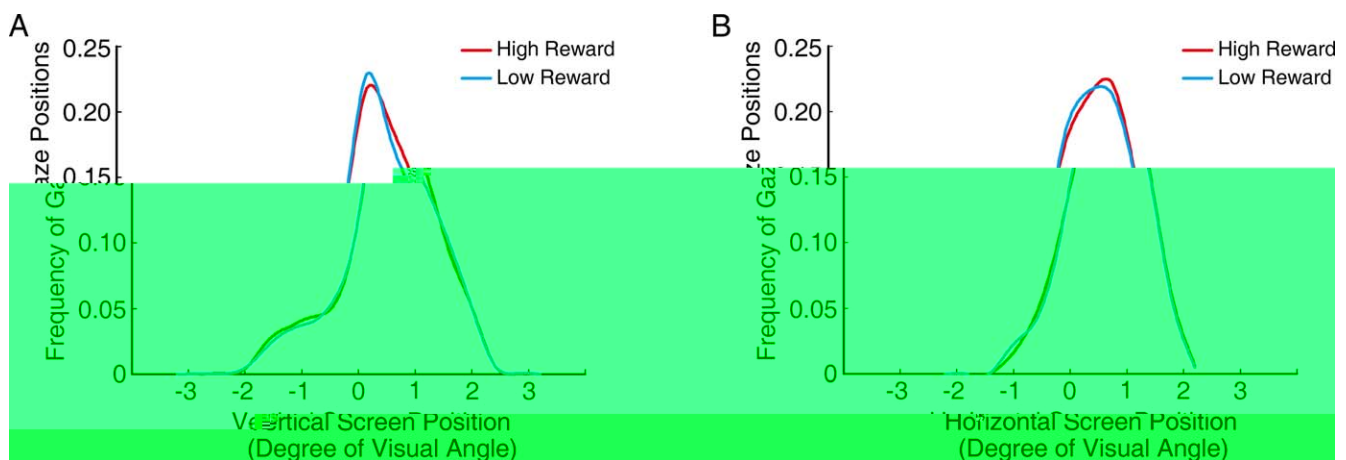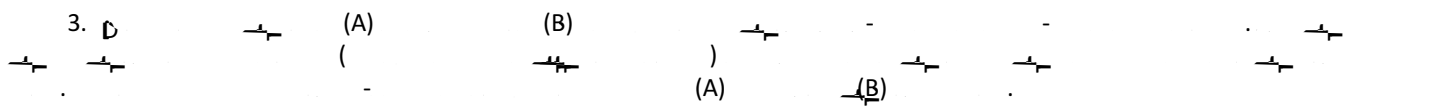
critical distractor interfered with target processing only when it was very close to the target, a pattern consistent with Mounts (2000b) and Cutzu and Tsotsos (2003); in contrast, the distractor associated with high reward interfered with task performance even when it was further away from the target (locations 2–3). This finding suggests that a reward-associated distractor can break through the inhibitory region surrounding the attentional focus and increase spatial ambiguity in the receptive field of the corresponding neurons.

According to the ambiguity resolution theory (Luck et al., 1997), the ambiguity for neural coding is modulated by the number of competitive items within the receptive field of the corresponding neurons with more items inducing stronger competition and interference. Consistent with this prediction, Wei et al. (2008) found that the interference between two neighboring targets in visual search was stronger when the set size was large (12 or 20 items) than when it was small (two or six items). The current results go further to demonstrate that the spatial ambiguity could also be affected by the value of objects located in the receptive field.

An alternative account for the current results could be that the increased interference induced by the high-reward distractor relative to the low-reward distractor may simply indicate an extended region of interference for the former rather than the "break through" of an inhibitory surround. Although these two accounts could not be distinguished in Experiments 1 and 2 in which the target location was fixed, they make distinct predictions when the target location is uncertain. Specifically, when the target location is uncertain, the lack of initial attention on the target will prevent the appearance of the inhibitory surround (Cutzu & Tsotsos, 2003; Hopf et al., 2006) and the appearance of the "break through" effect. In contrast, the alternative account would predict that the high-reward distractor still extends the interference to a larger region than the low-reward distractor. In a further experiment (Supplementary Experiment S2) in which the target could appear at the vertical meridian position in either the upper or lower visual field, we observed no "break through" for the high-reward distractor even though we observed an overall reward interference effect, inconsistent with the extended interference account. One possible explanation for this pattern is that when the target location is uncertain, attention is first attracted by the reward-associated, perceptually salient distractor and is then shifted to the target (Hickey, McDonald, & Theeuwes, 2006; Qi, Zeng, Ding, & Li, 2013), preventing the formation of the inhibitory region around the target.

Although the extended interference account could be ruled out for the current findings, the behavioral data alone are still not sufficient for us to be sure that the surround inhibition did appear. One potential problem is that placing the target on the vertical meridian of the left and right hemispheres may prevent the formation of surround inhibition. For example, Kastner et al. (2001) found that, when objects were placed on the opposite sides of the horizontal meridian, sensory suppression was observable only in brain areas that have a larger size of receptive field (e.g., V4), not in areas that have a smaller size (e.g., V2). This result suggests that surround inhibition near the meridian may emerge at later stages of visual processing. It is for future neural studies to determine at which processing stages the reward-associated stimulus overcomes surround inhibition in the visual cortex.

To conclude, by associating a distractor with reward and by placing the distractor at different distances from the target, we found that a low-reward distractor captured attention only when it was close to the target in visual search whereas the high-reward distractor captured attention at both the near and far locations, suggesting that reward-associated stimuli can break through the inhibitory region around attentional focus.

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