Vision Research 144 (2018) 20–28

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Stimuli that signal the availability of reward break into attentional focus

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A R T I C L E I N F O

No of reviewers - 2

Keywords:
Reward
Spatial attention
Reward availability
Attentional capture

A B S T R A C T

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

According to an incentive salience account, associating a stimulus with reward changes the representation of that stimulus such that it becomes more salient and attention-drawing (Berridge & Robinson, 1998; Hickey & Peelen, 2015; Hickey et al., 2010; Wang et al., 2015). From this perspective, the association of reward with a stimulus changes the attentional processing of this stimulus at an early processing stage (Hickey et al., 2010; Wang, Yu, & Zhou, 2013). Consistent with this notion, we found in our previous studies (Wang, Duan, Theeuwes, & Zhou, 2014; Wang et al., 2015) that the center-surround inhibition, which originates from the sensory competition of stimulus 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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https://doi.org/10.1016/j.visres.2017.10.008
Received 24 March 2017; Received in revised form 28 September 2017; Accepted 11 October 2017
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