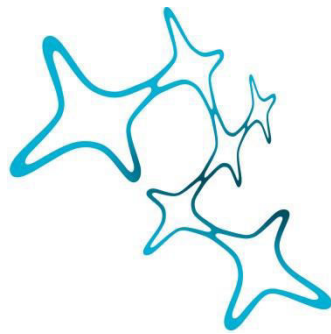

REWARD-BASED DISTRACTOR INTERFERENCE: ASSOCIATIVE LEARNING AND INTERFERENCE STAGE

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Summary

This thesis consists of five main chapters including three independent studies, focusing on reward-based distractor interference and reward-association. In particular, the thesis addresses at which attentional processing stages the reward-based distractor interference takes place, as well as whether and how the reward association is learned on different levels.

In the first chapter, I introduced a general background of attention, associative learning, and relations between reward associative learning and attention. In the end, I highlighted the open issues that this thesis aimed to address.

Chapter II (Study 1) aimed to answer the question at which processing stage the reward-based distractor interferes with the ongoing task. The study adopted the visual additional singleton search task but extended it to visual-tactile search. A classical finding of the reward-based distractor interference is that a reward-associated color feature (red or green), which appears as a task-irrelevant distractor, albeit it is not salient, captures attention and impedes task-relevant response (Anderson et al., 2011a). However, it is unclear at which attentional processing stage the reward-driven capture effects occur. To identify the distractor interference at the pre-attentional searching stage or post/focal- attentional decision-making stage, three experiments were conducted. Instead of a circular search display used in a standard attentional capture paradigm, this study used a horizontal search display to maximize potential attentional capture and disengagement. The results revealed that the reward-based distractor interference was only observed when the target and reward-based distractor were on the same side, indicating the interference likely occurred at the post/focal-attentional decision-making stage. To confirm this, Experiments 2 and 3 adopted the crossmodal search paradigm, in which the search stage and post-selective identification stage took place in different modalities. Such design enabled us to distinguish whether the interference effect occurs at the searching stage or the post/focal-attentional decision-making stage. The results further corroborated that the reward-driven capture effects occur at the post/focal-attention stage.

Chapter III (Study 2) focused on the question related to the level of reward associative learning. Most previous studies on reward-based attentional capture implicitly used feature-based reward association, particularly on the feature level, e.g., color-reward association. This leaves the question open regarding whether the associative reward could be established at the level of response mapping or task-set mapping. Two experiments were

designed to address this question. In Experiment 1, high/low rewards were associated with both the two colors (pink/green) and the left/right response in the training phase, and the reward-associated color became one of the task-irrelevant distractors in the test phase. We failed to find any evidence on the reward-response association. However, the results showed the distractor with previously reward-associated features facilitated search, indicating a better distractor handling in the test phase. In Experiment 2, the reward was associated with task-sets (present/absent) in the training phase and the task-sets kept the same in the test phase, while the search task was changed. The results suggested that reward-associated learning facilitated distractor handling and task-set learning.

Chapter IV (Study 3) tackled the open research question - whether reward associative learning could take place at the multi-conjunction level. The question is important, given that previous studies on reward-based attentional capture only investigated associative learning of a single feature. As reward association in daily life is usually complex, Study 3 aims to explore whether reward learning can be established through reward assignments with conjunction features (color & shape) and whether the interference of distractors with previously reward-associated features can be observed in a similar way as previous studies shown on single-feature-based reward-driven capture effects. Reward learning was found locally trial-by-trial throughout the whole learning process, however, it was hard to establish a reliable conjunction reward association. Furthermore, there was no reward-based distractor interference in the test phase. The findings suggest that conjunction reward-association is difficult, though a short-lived trial-to-trial conjunction reward learning can be established.

The final Chapter V discussed the findings of these three studies and their inter-relations. And I summarized how these findings could contribute to the debate of reward-based distractor interference. In summary, this thesis helps to improve our knowledge about reward-based distractor interference, particularly on the identification of the processing stage of distractor interference and what can be associated with reward in reward associative learning.

1 General Introduction

Rewards allure men to brave danger. - Huang Shigong (Qin Dynasty)

As humans, reward is vital in guiding our attention and actions. Rewarding goal-relevant tasks often boosts our performance. By contrast, an irrelevant stimulus or event that is previously associated with reward often distracts our attention away from ongoing tasks, impeding performance. There is a surge of interest in the latter, namely reward-based attention capture, in recent literature (for reviews, see Anderson, 2013, 2016b). One common paradigm that has been adopted for studying reward-based attention capture is the modified additional singleton paradigm (Anderson et al., 2011a). The paradigm consists of the training phase and the test phase. In the training phase, a certain target feature, such as color (red or green), is associated with a monetary reward. In the test phase, however, the previously reward-associated feature becomes task-irrelevant (e.g., a color distractor in detecting shape singleton tasks). Nevertheless, the presence of this distractor with the reward-associated feature causes a distractor interference, manifested by the longer response time when a distractor with a high-reward relative to the low-reward feature is present (Anderson et al., 2011a).

Although the reward-feature association has been shown to capture attention in multiple recent studies, open questions, such as at which stage (e.g., preattentive or post-selective stage) of the attentional process, remain unanswered. For example, does the reward-associated feature capture attention at the preattentive search stage or the late focal selective stage? Would the reward-associated distractor interference go beyond the low-level feature-reward association to the high abstract level association, such as task-set? Would conjunction features be associated with high/low rewards in reward learning? Would reward be learned in ambiguous conditions? These unsolved questions are the focus of this thesis. In particular, the present thesis aims to uncover the interplay between reward associative learning and attentional guidance to answer the above questions.

Before addressing those questions in detail, in this chapter, I will first review the background of our studies, related concepts and the state-of-art research findings related to attention (in Section 1.1), associative learning (in Section 1.2), and interaction between reward and attention (in Section 1.3). Further, Section 1.4 introduces the aims and purposes

of our studies, including reward-driven capture effect and reward association, Section 1.5 gives an overview of the thesis, and Section 1.6 presents a brief conclusion of the study.

1.1 Attention

Attention plays an important role in almost every perceptual and cognitive process. Without top-down control of attention, we cannot focus on writing, studying, or driving a car. Without letting attention flexibly monitor abruptly urgent signals, such as an explosion near you, we cannot survive as well. Studies have shown three key components of human attention: processing capacity, alertness, and selectivity (Posner & Boies, 1971). Due to the limited amount of overall energy available to the brain and the high-energy expense of cortical neuronal activity involved in computation, attentional resources are limited by those biological constraints (Carrasco, 2011). The consequence of the limited capacity of information processing is that it is necessary to select task-relevant information while ignoring or inhibiting task-irrelevant distractors. Thus, selection is necessary for the attentional process (Lennie, 2003). It is also important to prioritize certain objects or events for further cognitive analysis or reactions, such that the limited attentional resource can be fully efficiently utilized.

Knudsen (2007) suggested that four component processes are fundamental to attention: (1) working memory, (b) competitive selection, (c) top-down sensitivity control, and (d) filtering for stimuli that are likely to be behaviorally important (salience filters) (Knudsen, 2007, p.58). The first component - working memory - is the place where an attended object enters for further processes, such as storage, manipulation, and comparison. Working memory also generates signals (e.g., orienting movements toward targets) that improve the quality of the information that it processes (Miller & Cohen, 2001). Thus, working memory largely determines the capacity of the attention. Both top-down sensitivity control and bottom-up salience filter compete for representation in working memory. The competition occurs at many levels in the functional architecture of attention and in the hierarchies of the nerve system (for a review, see Knudsen, 2007).

Given the large topic of attention, in the following, I will selectively review three aspects of attention: visual attention, attention allocation across modalities, and attentional selection in perceptual processing, which is closely related to the theme of this thesis.

1.1.1 Visual attention

Owing to the important role of vision in the primate brain, the majority of studies on attention are conducted on visual attention (Kanwisher & Wojciulik, 2000). Roughly speaking, there are three types of visual attention: (a) spatial attention, (b) feature-based attention, and (c) object-based attention (Carrasco, 2011).

Spatial attention generally refers to the attention directed to selected locations in the visual field, either overtly or covertly (Treue & Katzner, 2009). The overt attention comes with eye movements hence the shift of attention is outwardly visible (Lindsay, 2020), while the covert attention can be deployed to certain locations without an overt shift in fovea location (e.g., observers fixate on a central point throughout the task, but shift their attention to peripheral locations where the tasks-related stimuli appear) (Anton-Erxleben & Carrasco, 2013).

Feature-based attention is another important construct in visual attention. Attention can be selectively deployed to visual features, such as particular orientation, or can be captured by a salient feature, such as a red item among green items, without knowing the location of the object. Due to the limited attentional resources (Knudsen, 2007), not all features are selected at the same time. Often, certain features are prioritized at the expense of other features within and across dimensions (for a review, see Carrasco, 2011). Feature-based attention is often directed covertly independent of their locations (Carrasco, 2011). But feature-based attention can also be overt. For example, a red item immediately captures attention and eyes saccade to the red item. Given that in most cases the feature-based attention is coupled with the overt eye movements, it is not surprising that interaction between feature-based attention and overt attention (Zhou & Desimone, 2011) has been found in the same brain areas of frontal eye fields, an area closely related to eye movements.

Depending on whether a particular feature is task-relevant and/or salient, feature-based attention can be deployed either by top-down process (Müller et al., 1995) or by bottom-up priming (Theeuwes, 2013; Theeuwes & Van der Burg, 2011). Both top-down and bottom-up processes may work together over time. For example, a salient distractor singleton (e.g., a red color distractor) may initially capture attention based on its saliency. When this salient distractor often occurs at a particular location, a top-down inhibition process may gradually be developed over time to inhibit that feature at that particular location (Awh et al., 2012; Theeuwes, 2013). However, it is still controversial whether such top-down processes can fully inhibit bottom-up feature-based attentional capture. Some argue that this

bottom-up feature-based attentional capture cannot be fully inhibited (e.g., Theeuwes, 2013), while others suggest single feature (e.g., red) is only a subset of a dimension (e.g., color), and this can be fully suppressed as long as its dimension is filtered out during the top-down process (Sauter et al., 2018; Zhang et al., 2019). For example, recent studies on probability cueing of singleton distractor (a color-defined singleton distractor occurs in a particular location with a high probability) have shown that if the distractor singleton comes from a different dimension as the target (e.g., a color distractor but a shape target), the top-down attentional process can successfully suppress the color distractor singleton (Sauter et al., 2018; Zhang et al., 2019). There is also a debate whether feature-based attentional guidance occurs at the early or late stage of the search process. In a ‘feature search’ mode (e.g., to detect a red tilted bar among vertical distractors), relevant features (e.g., red and tilted orientation) have been shown to grant priority in processing at an early stage process, such as subsetting of stimuli that contain at least one of the target’s features (e.g., Egeth et al., 1984; McElree & Carrasco, 1999; Wolfe & Horowitz, 2004).

The third type of attention - object-based attention - refers to attentional guidance by object structures. A large body of evidence in support of object-based attention comes from studies with a two-rectangle paradigm (Egley et al., 1994), in which observers are shown with two rectangles oriented either horizontally and vertically. A typical finding of those studies is that when one side of one rectangle is cued, searching/identifying the target at the opposite side of the cued rectangle is faster as compared to the target in the other rectangle. This facilitation cannot be explained by purely spatial attention, rather suggests that an attentional gradient pattern extends to the boundaries of the object (for a review, see Chen, 2012). There are two main accounts of object-based attention: spreading and prioritization. The ‘attentional spreading’ account suggests that attention is automatically spreading along object boundaries, while the ‘attentional prioritization’ account suggests that the enhancement comes from priority assignment to the attended object. It should be noted that the effects generated by object-based attention are relatively smaller than the effect of spatial attention, and the object-based effects are more variable in size (Nah, 2018; Olson, 2001; Pilz et al., 2012).

Although three types of visual attention are distinct from each other, they also interact and work together within the same task. For example, it has been shown that both object-based and feature-based attention work independently to enhance visual features, while the difference is that enhancement from object-based attention was constrained to the attended object (Xiao et al., 2014). Spatial attention and object-based attention can be

integrated to deal with dynamic visual search tasks by using grouping-based salience (Sun & Fisher, 2003), but spatial attention and object-based attention differ in the factors such as high spatial and high object validity of cues (Jordan & Fallah, 2004). It is also worth noting that spatial and object-based attention differs in dealing with external noise. Spatial attention is independent of noise manipulation, while object-based attention could be enhanced in high-noise conditions (Chou et al., 2014). Consistent with the spatial attention being found in brain areas such as dorsal frontal and parietal cortex (Beauchamp et al., 2001; Corbetta et al., 2000; Hopfinger et al., 2000; Mangun et al., 2000; Vandenberghe et al., 2001; Yantis et al., 2002), the nonspatial shifts of object-based attention has also been mediated by these areas (Serences et al., 2004).

1.1.2 Attention allocation across modalities

We live in a multisensory world, attention is not limited to vision alone. Thus, the same constraint of limited attentional resources is applied to multisensory attentional guidance, we have to select useful and relevant stimulus/modality from vast sensory inputs while inhibiting irrelevant distractors/modalities. However, attentional capacity for multisensory processing, as compared to unisensory processing, has been shown to be different. Studies have shown attentional capacity is larger in multisensory than unisensory tasks. For example, an EEG study (Talsma et al., 2006) using steady-state evoked potentials (SSVEPs), with which the amplitude of SSVEP could serve as a biomarker of attention, has shown the SSVEP amplitudes were larger in audiovisual relative to the unimodal letter stream tasks. This has been confirmed by a recent visual-auditory study (Mishra & Gazzaley, 2012), which showed that multisensory processing can be benefited when attention is distributed across the sensory modalities. Similarly, distributing attention across visual-tactile sensory modalities has been found to enhance a weak a priori association between the visual and tactile spatial signals (Badde et al., 2020).

The large attentional capacity in multisensory tasks is likely due to the independent resources among different modalities. A study examining the thresholds of auditory pitch and visual contrast discrimination in conjunction with crossmodal secondary tasks found no interference of auditory task on visual performance occurs, which suggested that the sensory modalities are under separate control instead of being constrained by a supramodal attentional resource for low-level tasks (Alais et al., 2006). Similarly, a study on attentional resources within and across visual/tactile modalities using a visual search & localization dual-task paradigm showed that RTs are shorter when the visual search and localization tasks were in

separate visual/tactile modalities, as compared to that within the same visual modality, which indicated that attentional resources are partly independent in visual and tactile modalities (Wahn & König, 2016). In their review paper, Wahn and König (2017) surveyed studies on multisensory attention and concluded that attentional resources are allocated flexibly depending on the task demands. For example, for object-based attention tasks, attentional resources are allocated distinctly in visual-auditory sensory modalities, but shared resources are found in visual-tactile tasks. Shared resources were also found across the modalities when time-critical object-based attention tasks were performed. When spatial attention tasks were combined with object-based attention tasks, partly shared resources were found, but when spatial attention tasks were performed alone, shared attentional resources were consistently found across sensory modalities (Wahn & König, 2017).

It should be noted that tasks switching within a sensory modality and across sensory modalities lead to an unwanted cost, measured by the performance of the tasks (Pashler & Harris, 2000), though training can reduce the switching cost (Gopher, 1996). Interestingly, it has been shown that tasks switching across sensory modalities had smaller costs relative to the switching within a sensory modality (Murray et al., 2009). The neural support for this is that tasks switching within a modality need the same neural circuits to reconfigure, but switching across modality uses a different sensory neural circuit, which is much easier.

1.1.3 Priority map and attentive processing stage

Information needs to be selected before being processed. Generally, there are two types of attentive processing stages, one is ‘early selection’ and the other is ‘late selection’. Similarly, Treisman’s feature integration theory (FIT) divides the attentive processing into a preattentive stage and an attentive stage (A. M. Treisman & Gelade, 1980).

In the pre-attentive processing stage, general features of an item are detected and separated unconsciously (Han et al., 2000; Mouchetant-Rostaing et al., 2000; Taylor, 2002). During this stage, the information from the environment is filtered and the important information is selected for further processing. Pre-attentive processing is supposed to be unlimited, as they do not cost attentional capacity (Reimer et al., 2015). Early Broadbent’s filter theory (1958) proposes that unattended stimuli have been completely filtered out. However, some later studies have shown that sometimes the unattended stimuli could also be processed and even more deeply. Later on, Treisman proposed an ‘attenuation theory’ based on Broadbent’s filter theory, and she argued that the information from the unattended stimuli is attenuated instead of completely filtered out. Signals of unattended stimuli are too weak to

be sufficient for further identification, but in some exceptional cases they could (A. M. Treisman, 1969; M. Treisman, 1960). One typical example of the latter is that one's own name can grab one's attention from the unattended stream.

It should be noted that the pre-selective processing stage can be influenced by bottom-up and top-down factors (Müller et al., 2003). Pre-capture (bottom-up) and contingent-capture (top-down) are the two accounts of pre-attentive processing (Folk & Remington, 2006). The pre-capture account suggests that stimulus salience affects pre-attentive processing while the contingent-capture account emphasizes the role of the top-down attentional set. Both accounts are based on the functional architecture of selective attention, which consists of 'disengage', 'move' and 'engage' operations accomplished by different regions on neural level (Posner & Petersen, 1990). 'Disengage' is to give up priorities for some input signals in order to shift attention to another signal/location. This operation is either top-down (goal-directed) or bottom-up (stimulus-driven) (Folk et al., 1994; Remington et al., 1992; Schreij et al., 2008; Yantis, 1995). After this operation, attention is moved to the next target, then engages with the new signals and gives priority to the input signals (Posner & Petersen, 1990). To summarize selective attentional mechanisms and to visualize what stimulus being selected and what being inhibited, Koch and Ullman (1984) proposed a location-based saliency concept, and it has been later implemented by Niebur and Koch (1995), now known as the saliency map. The key idea is that the most salient location, in terms of basic feature contrasts, would be a good candidate for attentional selection. However, the original saliency map lacks integration from the top-down selection. To incorporate top-down selection and selection history, a general priority map has been proposed to substitute the saliency map (Fecteau & Munoz, 2006).

There are some controversies on the processing stage of the inter-trial effect, whether it is a pre-attentive or post-attentive effect. Here the inter-trial effect refers to the target repetition benefits and switching cost in visual search. It has been shown (Found & Müller, 1996; Müller et al., 1995) that repeating the same dimension (e.g., color) would facilitate target response even if the target feature is changed (e.g., from a red to a green pop-out target). Using the EEG method, Töllner et al. (Töllner et al., 2008, 2011) such repetition effect has been linked to an early component - Posterior contralateral negativity (PCN), a biomarker supporting the preattentive stage of processing. Several late studies (e.g., Rangelov et al., 2012; Zehetleitner et al., 2011) also demonstrated that these effects exert in the pre-attentive processing stage (Zehetleitner et al., 2011). On the contrary, some researchers argued that inter-trial effects can arise from the post-selective processing stage. The main

evidence comes from a non-search task (Mortier et al., 2005), in which participants were asked to identify if a single presented item is a target or non-target. Prior to the experiment, participants were told a set of targets. A similar dimension-repetition benefit has been observed in the non-search task. Given that the single stimulus has the same pre-selective processing, the repetition effect must come from the late post-selective processing stage (Theeuwes et al., 2006). Krummenacher et al. (2010) argued that both inter-trial effects are possible and governed by two separated pre- and post-processes, and they are not mutually exclusive.

1.2 Associative learning

From the aspect of attention, associative learning appears to change the way in which humans and other animals attend to their environment (Le Pelley et al., 2016). Associative learning is a form of conditioning. Through conditioning, two unrelated elements or events became related in the brains of living organisms. Associative learning is the learning ability to perceive some regular patterns from contingency phenomena. There are two types of associative learning: classical conditioning and operant/instrumental conditioning. Classical condition is based on the involuntary pairing of stimuli with biologically significant events, such as the sight of meat causing salivation of an animal. By contrast, operant/instrumental conditioning, a behavior to a stimulus is associated with reward or punishment. For example, touching a hot stove would burn the touched hand, and kids learn this causal association by avoiding touching a hot stove. The operant behavior is voluntary. Conditioning can be predictive or non-predictive. Predictiveness and learned value captures more attention and leads to valuable outcomes (Le Pelley et al., 2016).

In this section, we selectively review associative learning studies related to predictiveness principle, uncertainty principle, and learned value (learning of reward-association), which is related to the search topics in the following chapters.

1.2.1 Predictiveness and uncertainty principle

One important issue in associative learning concerning attention is to which item should be attended more than the rest. There are two distinct accounts on this: the predictiveness and uncertainty accounts. The predictiveness account supports the notion that predictive cues capture more attention than non-predictive cues (House & Zeaman, 1963; Kruschke, 1992, 2001, 2006; Mackintosh, 1975; Schmajuk & Moore, 1985). That is, associative learning

increases the allocation of attentional resources to predictive cues/events, evident by the fact that previously predictive cues are learned more quickly than previous non-predictive cues. A typical example in visual search is the contextual cueing effect (Chun & Jiang, 1998), a predictive display (repeatedly presented) facilitates visual search over the course of training. By contrast, the uncertainty account argues it makes little sense to devote much attention to already learned predictable cues/events. Rather, the most efficient way is to allocate attention to those ‘surprised’ cues/events that failed by the prediction (Dickinson, 1980; Pearce & Hall, 1980). The uncertainty account is in line with the predictive coding theory, only prediction errors are feedback to higher levels of neuronal hierarchy (Feldman & Friston, 2010; Friston, 2010). There is also ample evidence to support the uncertainty account. For example, stimulus uncertainty induces a cognitive state that motivates ‘curiosity’ to attract more attention than predictable stimuli (Frings et al., 2019). Autism adults relative to developed adults pay more attention to those surprising events (Allenmark et al., 2020). Reviewing both accounts, Le Pelley et al. (2016) suggest that both predictiveness and uncertainty principles contribute to associative learning (Beesley et al., 2015; George & Pearce, 2012; Le Pelley, 2004; Le Pelley et al., 2010; Pearce et al., 1998).

1.2.2 Learned value and attention

In a predictive operant condition, attention can be heavily influenced by the reward value that is associated with the stimulus. Findings from studies with the task-relevant learned value suggest that stimuli associated with high-value relative to low-value attract more attention. For example, Della-Libera and Chelazzi (2009) showed that selection or ignoring specific visual objects appears to be strongly biased by the past rewarding consequence of that object. According to the predictiveness account (Mackintosh, 1975), these results could also be due to the predictiveness of the reward.

When a high-value-associated feature turns out to be a feature of a task-irrelevant distractor, attention can still be captured by this learned association. One classic study is conducted by Anderson et al. (2011), in which the high/low reward values were first associated with the target-relevant features (e.g., color) in the training session. In the test session, the previously associated features became task-irrelevant distractors (Anderson et al., 2011b). A general finding of this paradigm is that the high-value, relative to the low-value, associated distractor captured more attention, hindered the performance, indicating attention remains to the reward feature, even though it is task-irrelevant. One potential alternative explanation for this finding is that the distractor feature in the test session

was task-relevant in the training session, such that participants paid more attention to the high-value-associated feature level than to the low-value-associated feature level just because attention is affected by the past experiences (Sha & Jiang, 2016). To rule out this alternative explanation, Anderson did another control experiment in which there was a control group with no reward association in either the training session or the test session, in which they showed that the results were not caused by the past experiences in this paradigm but only due to the learned value (Anderson et al., 2011a). Note though, in this control experiment, the number of participants was way lower than the formal experiment (only 10 participants as compared to the formal experiment of 26).

Le Pelley et al. suggested that learned predictiveness and learned value might be interactive rather than be completely separate. He argued that in some studies of learned value, the resulting attentional bias themselves can sometimes modulate the following learning. Therefore, more studies are needed to disentangle the factors of predictiveness and learned value that influence attention (Le Pelley et al., 2016).

1.3 Reward and attention

External reward elicits strong motivation, capturing attention towards the rewarded item. Through associative learning, attention can be biased to the feature or dimension that is associated with the rewarded item (e.g., Della Libera & Chelazzi, 2009). Reward influences selective attention and decision making (usually leads to better performances), mediating through rewarded feature association to improve the performance of the task related to the reward-associated feature. However, the reward-based association may also produce adverse interference effects if the reward-associated feature occurs to be a distractor feature (Anderson et al., 2011a), which has been termed as value-driven attentional capture. Given that the thesis focuses on reward-based interference, in this section, we review recent studies related to this topic.

1.3.1 Reward Association

Very often, reward is associated with a certain location for humans and other animals. For example, a certain place has a bunch of flowers that attract bees to visit that place. For humans, it has been shown that reward not only explicitly, but also implicitly enhances perceptual and attentional processing of objects in the reward location. For example, using a simple search task with location-contingent reward manipulation, Chelazzi et al. (2014),

found that search performance was higher at the high-reward location relative to the low-reward location, and argued that reward learning altered the global spatial priority map. Similar effects have also been found with probability manipulation. Probability-based associative learning could be treated as a special type of reward association - intrinsic reward association, given that effective inhibition to boost performance is intrinsic rewarding. For example, a high probability of distractor occurrence at a particular location or region would trigger associative learning of inhibition (Goschy et al., 2014; Sauter et al., 2018; Wang & Theeuwes, 2018). The region where a salient distractor was frequently present is likely to be inhibited after the learning of probability-distractor association, which leads to a worse performance when the target is presented there even without the distractor (Sauter et al., 2018; Zhang et al., 2019).

In addition to reward-position association, reward-feature association has also been shown frequently in the literature. For example, Yantis et al. (2012) showed that color-reward association learned from a visual search task with circle items could be transferred to color letters in a flank task. A flanking letter with formerly high-reward relative to low-reward color caused more compatibility effect (measured by the RT difference between the flank-central response compatible vs. incompatible conditions), which suggests that the feature-based reward association can be generalized and extended to different objects as far as the reward-associated feature remained. Such reward-feature association could also be used for top-down guidance search. For example, Lee and Shomstein (2014) investigated if reward-feature association learned from a bottom-up pop-out search task could be transferred to a top-down oriented compound search task. In their study, they used the orientation pop-out search task (horizontal vs. vertical line) for the reward-association training phase, in which one of the targets (either horizontal or vertical) was associated with the high reward. In the test phase, they tested with a color-orientation compound search task, in which the target was defined as 'red horizontal' or 'red vertical'. And they found high-reward orientation indeed facilitated the compound search, suggesting the bottom-up reward-association can be transferred to top-down attentional guidance.

1.3.2 Value-based reward-driven attentional capture effects

In recent years, there is a trend in the research community of reward learning. Instead of focusing on how reward association could help boost performance, researchers focused on how reward association could be detrimental (Anderson, 2013). It should be noted that the detrimental effect we discuss here is not the performance difference between the reward vs.

non-reward (i.e., a general motivational effect), rather a differential attentional capture effect between the high-value and low-value associated features (i.e., a value-based association). A typical paradigm is the attentional capture paradigm we have mentioned earlier (Anderson, 2015, 2016b; Anderson et al., 2011a; Yantis et al., 2012). In this paradigm, high/low-value-based features are first learned through training as target features and then associated with a distractor (singleton distractor). A typical finding is that the presence of the high-value distractor relative to the low-value distractor slowed down response speed and lowered the accuracy in general. Based on such findings, Anderson and colleagues termed this kind of detrimental cost as value-based attentional capture. Strictly speaking, this cost could be caused by the attentional capture of the value-based distractor or by the ineffective distractor filtering. Using the eye-tracking technique, Anderson and Yantis (2012) showed that the presence of a reward-associated stimulus came to evoke pupil dilation over the course of training, indicating some evidence of attentional capture. However, it remains likely ineffective distractor filtering could partially contribute to this value-induced cost.

It should be noted that the effect of the value-based attentional capture sometimes is weak. It is not uncommon that some studies didn't find any difference between the high- and low-reward association, but a significant difference between the reward and non-reward conditions (e.g., Sali et al., 2014). The weak attentional capture is more marked with social reward association (e.g., Anderson, 2016a, 2017; A. J. Kim & Anderson, 2020). Sali et al. (2014) argued that the degree of reward-based attentional capture depends on the predictive information about reward outcomes. By systematically varying the monetary reward and predictiveness of reward outcomes, Sali et al. (2014) found it is not high/low reward per se, rather the unique mapping (prediction) of high/low reward to the feature matters. When detecting two color-targets (e.g., red and green) always got the same reward (say 6 cents) in the training, those colors shown in a distractor did not induce any attentional capture in the test. But when two target colors had differential rewards (say red got 1 cent and green 6 cents), classical reward-based attentional capture emerged. It is important to note that predictive reward mapping is necessary, but not sufficient to induce differential learning. Studies with social reward association, as mentioned above (e.g., Anderson, 2016a, 2017; A. J. Kim & Anderson, 2020), did not manifest significant differences between the high and low reward learning. Nevertheless, some attentional captures were still observed.

Although most studies showed the reward-based distractor captures attention and subsequently hinders performance, there are at least some situations in which the same conditions could facilitate performance (Della Libera & Chelazzi, 2006, 2009; Lee &

Shomstein, 2014) - an opposite of the distractor interference. For example, in Lee and Shomstein's study (2014), the reward-associated orientation was shared across the target and the distractor in a conjunction search. The presence of reward-associated distractors enhances better distractor rejection (i.e., facilitated ignoring). Anderson (2016b) admitted that such an opposite effect is hard to incorporate with his attentional capture framework. He also speculated one possibility is that "stimuli that predict reward as distractors come to automatically capture attention, but can be more quickly rejected when rejection is associated with reward outcome" (p. 33, Anderson, 2016). In other words, whether it causes a cost or benefit depends on whether the association is attending or rejecting.

It should be noted that the studies showing costs or benefits of the presence of the reward-associated distractor used the rewarded feature for the distractor. Lee and Shomstein's study (2014), which showed a facilitation effect of the distractor, additionally kept the task-set reward association the same for the training and test sessions (i.e., both for the orientation task). Thus, the facilitation might come from the same task-set association, which has not been fully dissociated in their study. Importantly, the task-based association has been neglected in most of the aforementioned studies. In real environments, reward associations may not always be unique. A good performance receives not only applause but also flowers. Multiple reward remapping coexists and may as well compete with each other. Up to date, it remains an open question regarding what other reward associations could be established and what consequences of those reward associations in visual search. For example, could multiple conjunction feature association be learned? Could the reward association occur at the task-set level or even higher abstract categorical levels? Those unanswered questions will be addressed in this thesis.

In addition to different types of reward association, it remains unknown at which processing stage the reward-associated distractor captures attention. This question is mainly neglected in the literature. Some studies implicitly argue the reward association at the early stage (e.g., Anderson et al., 2011a; Chelazzi et al., 2014), while others are not fully sure at which stage it might occur (e.g., Anderson, 2015). For example, Anderson (2015) reported evidence that distractor interference is bound to the feature-location conjunction if the reward feature (e.g., red color) is contingent on its location in the training phase. In particular, search performance was only impaired when the distractor singleton with the reward-associated feature (e.g., red) at the previously rewarded location; but search performance was unaffected when the distractor with the reward-associated feature occurred elsewhere. Based on this, Anderson proposed that the reward association at the early feature level is modulated by the

global (spatial) priority map. But he conceded there may be two different interpretations of the mechanism underlying this location \times feature interaction in value-driven attentional capture (see similar arguments in Yantis et al., 2012): One is that reward learning is tied to the reward-associated location, involving the global priority map. Alternatively, the reward-associated feature may generate an attentional priority signal regardless of the location where it occurs (e.g., prioritizing the processing of the reward-associated, such as red, color), but that signal is suppressed when the location of that feature has been learned to be associated with a low value (Anderson, 2015). The dissociation of two mechanisms hasn't been rigorously investigated.

1.4 Aims and Objectives

The literature reviewed above has shown ample evidence of the influences of reward on attentional selection and guidance. High relative to low reward-associated features captures more attention, as shown in value-driven reward search paradigms. However, up to date, there is still a lack of understanding concerning at which functional level of the selective attentional process that reward-driven attentional capture occurs. Concerning the functional architecture of attention, studies on reward-driven capture mostly suggested that reward association occurred at the feature level (e.g., Anderson et al., 2011a), whereas studies on reward to target found the reward alters the prior map (e.g., Chelazzi et al., 2014). Would the reward-driven attentional capture occur at the intermediate levels, such as dimension, modality? This is one of the focuses of this thesis. In addition, we hypothesized that the reward-based attentional capture has differential impacts on search performance. If the target and the distractor are both selected at the late selection processing, the reward-driven attentional bias could only be observed when the previously reward-associated distractor appears near the target location or being selected during the search. By contrast, if the reward-driven attentional capture occurs at the early selection stage, the effect should be relatively independent of the distractor location. On this ground, we adopted the left-right horizontal search arrays, such that the target and distractor can be on the same side (near) or opposite side (far) in Study 1 (see Chapter 2).

Second, reward association can be learned through a training process, but the way how reward is associated might be varied. Studies with reward-feature association used a simple feature-reward probability mapping, such as a red target for a high reward with a high probability (e.g., 80%) and a green target for low reward with a high probability (Anderson et

al., 2011a, 2011b). Similarly, in the position-reward association, reward is bound to a specific location with a high probability (Chelazzi et al., 2014). Even in a recent contingent reward association (Anderson, 2015), the spatial-feature contingency has unique feature-location mapping. It remains open if reward association can go beyond feature and spatial locations. In the real environment, a single reward is often ambiguous. For example, animals get food after a bell rings, as well as the light turns on and an experimenter enters the room. Reward association requires participants to find out the probability contingency among many possible associations. In those typical reward studies, participants receive rewards after their responses. One interesting question related to this is whether reward can be associated with the response mapping itself. When the response mapping and feature mapping are ambiguous, which would be learned during the association phase? To answer this question, we carried two experiments in Study 2. In Experiment 1, we examined whether reward was associated with response or the color by using the reward-mapping to both the left/right response and pink/orange color. In Experiment 2, a prior mapping cue was added to further explore the question (Chapter 3).

Moreover, it remains an open question whether reward association could be based on conjunction features or dimensions. To address this question, Study 3 was designed with a 2 × 2 conjunction reward mapping scheme (Chapter 4).

1.5 Thesis overview

The present thesis focuses on the following three aspects: 1) we aimed to identify the processing stage of reward-driven attentional capture; 2) we intended to uncover the rewards association beyond the level of feature level; 3) we aimed to test if reward could be associated with complex conjunction features.

Study 1 (Chapter 2) adopted the value-driven additional singleton task in three experiments, each consisting of a training session in which reward was associated with certain colors and a test session in which the previously reward-associated color became a task-irrelevant distractor feature. In order to pin down whether the reward-driven capture occurs at the pre-attentive or post-selective process stage, we applied a visual search display with horizontal arrangement of the items, equally divided into the left and the right in Experiment 1. We reasoned that attentional capture by the distractor has differential disengage time if the distractor and target were on the same vs. different size. If the reward-driven capture occurs at the pre-attentive processing stage, the distance of the target

and the distractor should have no impact on the reward-driven capture effects. On the contrary, if the reward-driven capture occurs at the post-attentive processing, the distance between the target and the distractor would affect the search performance. In order to distinguish the search stage and selection stage, we further applied cross-modal search in Experiments 2 and 3. In Experiment 2, search was constrained to the visual modality while the target discrimination on the tactile modality, and vice versa in Experiment 3.

In Study 2 (Chapter 3), we extended previous research questions on reward-feature association to reward response/category association. Experiment 1 aimed to examine whether reward is associated with the response or feature when both mappings were possible. Experiment 2 further explored if the reward association was at the feature level or the task level. Same as in Study 1, Experiments 1 and 2 consisted of a training phase and a test phase. In order to rule out potential confoundings caused by the difference of target-presence and target-absence, non-reward tasks in Session 1 and the reward-associated tasks in Session 2 were carried out in a separation of one week. The mapping between cue and target presence which determined the expected response was considered in the way of task-set reward association, instead of the simple reward association with a single feature.

In Study 3 (Chapter 4), we designed a 2×2 conjunction feature-reward association experiment. In each trial of the training phase, high/low value was associated with two conjunction features (color and shape), each with two levels (color: pink and green, shape: i-shape and l-shape), of a target stimulus. In the test phase, stimuli with the previous reward-associated features became the task-irrelevant distractors, and a neutral color was added for both shapes as the distractor feature which was taken as a baseline. Here we carried out the reward-learning in the way of compound-feature association (color & shape) instead of unique-feature association.

1.6 Conclusions

Here I outline the main findings. For more detailed findings and conclusions, please see Chapter 5.

The results from Study 1 showed that the reward-driven capture occurs at the post-attentive processing stage of the late target selection and identification, where focal attention is required. Experiment 1 (visual search tasks) indicated the reward-driven capture effects when the visual target and the visual distractor were on the same side, while no capture costs were observed when the visual target and the visual distractor were on the

opposite side, and the results also indicated that reward-driven attentional capture occurs at the post-selective stage. Experiment 2 (visual search-tactile detection tasks) separated the pre-attentional search and post-attentional decision stages by implementing a crossmodal compound-search task. The results failed to show any reward-driven capture effects even when the visual target and the visual distractor were on the same side. By contrast, Experiment 3 (tactile search-visual detection tasks) showed the reward-driven capture effects and high-reward distractors generated greater interference than low-reward distractors, which is consistent with the literature of value-driven ‘attentional capture’ (Anderson et al., 2011a; H. Kim & Anderson, 2019).

The findings from Study 2 suggested that reward can be associated with the task-set category, instead of the feature. Experiment 1 showed that reward was associated with the task-set and indicated a post-attentional attentional processing reward-capture. In the training phase of Experiment 2, we observed the expected reward-based facilitation. High reward not only reduced response time but also increased accuracy. In the test phase, however, no capture effect has been found in the presence of a reward-based distractor. An interaction between reward assignment and target presence in the test phase was found.

Study 3 showed that conjunction multiple-feature-reward association might be too complex to be learned. In the training phase, cross-dimension conjunction reward-association failed to show direct benefits on the pop-out target discrimination. This might be due to the reward learning effect in our paradigm being counteracted to some extent by the pop-out search, which was already an efficient visual search. Interestingly, we found intertrial effects on reward manipulation in the training phase, suggesting there was continuous reward-association learning. In the test phase, however, no reward capture effect for the conjunction features (shape and color). There was a slight reward capture effect shown in color (high/low reward color, reward-irrelevant color) for l-shape distractor. This indicated that the reward capture effect was only shown on the simple shape (l-shape). For compound features, conjunction reward-association failed to produce any reward capture effects. We concluded that conjunction cross-dimension reward-association can generate local trial-to-trial reward learning benefits, but failed to produce any reward capture effects. Although it is unlikely, limited training intensity might contribute to the null finding. To make the conclusion more robust, future studies with extensive training should be conducted.

In summary, reward-driven capture effects occur at the post (focal) -attentive processing stage of target selection and identification, and the effects are only manifested within the same sensory modality. Reward association in the attentional capture paradigm can

go beyond the feature association, up to the level of task-set association. Moreover, association of reward to complex conjunction features was relatively difficult, although local learning of trial-to-trial reward association was observed.

2 On the processing stage of the reward-based distractor interference

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2.1 Abstract

A reward-associated but task-irrelevant distractor can capture attention in visual search. However, it is unclear at which stage in a functional architecture of attention selection the reward-based interference occurs. To investigate this, we designed three experiments using the visual and visual-tactile search paradigm. We applied color-reward association in the training session and used the reward-associated color as a distractor in the test phase. The reward-driven distractor interference only occurred when the target and distractor were on the same side, but not on the opposite side (Experiment 1). When the search was in visual modality but the target identification was in the tactile modality, we found no reward-based distractor interference (Experiment 2). Interestingly, the interference reemerged when the search was in the tactile modality, but the target identification was in the visual modality as the reward-based distractor (Experiment 3). Our findings suggest that the reward-based distractor interference likely occurs at the stage of the late target selection and identification, at which focal attention is required. The reward-based distractor interference only occurs within the same target modality.

keywords: reward-driven, attentional capture, crossmodal search, pre-attention, focal-attention

2.2 Introduction

Reward exerts a profound influence on selective attention and decision making (for a review, see Botvinick & Braver, 2015). Studies have shown that attention can be automatically drawn to features previously associated with reward (Anderson et al., 2011a; Hickey et al., 2010a; Hickey & Peelen, 2015, 2017), even when the reward-associated feature belongs to a task-irrelevant distractor. As for the latter, the reward association does the opposite: hampering the task-relevant response (e.g., Anderson, 2015; Anderson et al., 2011a). This interference effect has been interpreted in terms of reward-based attentional capture, although technically *distractor interference* would be more appropriate, given that the interference could occur as a result of more frequent ‘capture of attention by the former distractor or some other effects, such as an increased ‘filtering cost’ (Ferrante et al., 2018).

A typical experimental paradigm to probe for reward-based attentional capture is a revised additional-singleton search paradigm (Anderson et al., 2011a). The paradigm comprises training and a test session. In the training session, high and low monetary rewards are associated with two target colors (e.g., red and green). Participants have to find a target-colored circle (presented in a circular array of heterogeneously colored circles) and discriminate the orientation of a line segment inside it. A correct response results in either a high or low monetary reward, depending on the color-reward association. In the subsequent test phase, the previous reward-associated color (red or green) belongs to a task-irrelevant distractor in a visual search task. The task now is to search for a singleton shape target (presented amongst shape-homogeneous non-targets that are heterogeneous in color, where one of the non-targets may appear in a previously rewarded color: this item is referred to as singleton distractor) and to identify the orientation of the line segment within it (see Figure 1A). A typical finding from this paradigm is that a task-irrelevant distractor with the color previously associated with a high-value reward, compared to a low-value reward distractor, slows the response time (RT) in the test phase (Anderson, 2015; Anderson et al., 2011a; L. Wang et al., 2013).

Although many studies have shown that reward-associated distractor interference in visual search can be established through learning (Anderson et al., 2011a), it remains controversial concerning underlying interfering mechanisms. Does it occur at the preattentive search guidance stage or the late post-selective decision-making stage? When the distractor

interferes at the search guidance stage, there are several possible levels within the functional architecture of search guidance at which the reward-based interference may occur: distractor interference at the specific feature level, or the dimension/modality level, or the global master saliency level. For instance, manipulating the reward association to color features (red and green), Anderson et al. (2011) found distractor interference was bound to the reward-associated color, suggesting the interference likely took place at the early feature level. In contrast, using a probability-contingent spatial map to manipulate reward, Chelazzi et al. (2014) found reward to prompt the acquisition of attentional biases for locations associated with high-probability reward. In other words, probability-contingent reward learning occurred at the level of the search-guiding attentional-priority map, which is thought to represent the selection priority associated with particular locations, but not the features of objects at these locations (feature information is lost in the computation of overall-saliency). Recent studies have similarly shown that manipulating the probabilities with which distractors occur at certain display locations gives rise to related processes of distractor-location learning (Goschy et al., 2014; Sauter et al., 2018; B. Wang & Theeuwes, 2018). For instance, when a salient distractor occurs very frequently in one display region, that region becomes inhibited as a result of associative learning, resulting in reduced interference (‘attentional capture’) by distractors occurring in the suppressed region, but also slowed responding to targets appearing there. Of note, though, the level at which the learned inhibition is implemented appears to depend on the relation of the distractor to the target dimension (Sauter et al., 2018; Zhang et al., 2019): target detection is strongly impacted when the distractor is defined in the same dimension as the target (e.g., orientation distractor, orientation target), but not when it is defined in a different dimension (e.g., color distractor, orientation target) – indicative of learned priority-map-based inhibition with same-dimension distractors and dimension-based inhibition with different-dimension distractors (Liesefeld & Müller, 2020). Investigating the interplay between space- and feature-based associations in value-driven attentional capture, Anderson (2015) also reported evidence that distractor interference is bound to the feature-location conjunction if the reward feature (e.g., red color) is contingent on its location in the training phase. In particular, search performance was only impaired when the distractor singleton with the reward-associated feature (e.g., red) at the previously rewarded location; but search performance was unaffected when the distractor with the reward-associated feature occurred elsewhere. Based on this, Anderson proposed that the reward association at the feature level is modulated by the global (spatial) priority map. But he conceded there may be two different interpretations of the mechanism

underlying this location \times feature interaction in value-driven attentional capture (see similar arguments in Yantis et al., 2012): One is that reward learning is tied to the reward-associated location, involving the global priority map. Alternatively, the reward-associated feature may generate an attentional priority signal regardless of the location where it occurs (e.g., prioritizing the processing of the reward-associated, such as red, color), but that signal is suppressed when the location of that feature has been learned to be associated with a low value (Anderson, 2015).

In light of the dichotomy between early pre-attentive and subsequent post-selective processing (Light et al., 2007; Nikjeh et al., 2009; Töllner et al., 2011; Zehetleitner et al., 2011), reward-based attentional capture could also occur at the post-selective decision-making stage, at which the target identification is interfered by the concurrently selected distractor. For example, in a typical non-search Eriksen flanker task (Eriksen & Eriksen, 1974), a conflict distractor within the attentional spot captures some attentional resource away from the target, causing an interference-effect. The interference is more marked when the flank distractor is closer to the target. If the reward-feature-based distractor interference occurs similarly at the post-selective stage, we should observe the target-distractor positional effect. That is, the magnitude of the inference is closely linked to the target-distractor locations according to the attentional gradient. Up to date, however, none of the above-mentioned studies have identified the processing stage at which the reward-associated distractor interferes. given that early feature selection does not involve any spatial information. Attention is likely broadened by the distractor when the target and the distractor are both being selected at the late selection processing stage.

On these grounds, we hypothesized that if the reward-associated distractor interferes with the search at an early search stage, a distractor on the opposite side of the target would divert attention away from the target and thus produce greater costs in search time (e.g., requiring disengagement of attention from the wrong side and re-orientation to the correct side) relative to a distractor located on the target side. By contrast, if the distractor *only* interferes at the post-selective, focal-attentional stage, interference would be more marked when the target and distractor are positioned on the same side, rather than on opposite sides. It should be noted, distractor interference at the early and late stages is not mutually exclusive. They could take place at both stages. To examine both possibilities, we introduced a baseline condition where the reward-feature-based distractor was absent, such as the search performance (response times RTs and accuracies) can be compared.

Specifically, we conducted three experiments implementing a reward-associated visual search in the training session and a compound search (either within- or across modalities) in the test phase, to identify the processing stage of reward-associated distractor interference. We introduced a visual search paradigm with a more ‘horizontal’ display arrangement (as compared to the circular arrangement of Andersen et al., 2011) in Experiment 1 to examine whether reward-based attentional interference or ‘capture’, occurs at the pre-attentive, search-guidance stage or the post-selective, decision-making stage (see Figure 1B). If the reward-based distractor interferes at the early search-guidance stage (e.g., magnified feature saliency at the preattentive stage (Anderson et al., 2011b)), the effect should be observable when the distractor and target are on opposite sides. By contrast, if reward-based attentional interference occurs at the late focal-attentional decision selection stage, the proximity of the distractor to the target will greatly impact search performance. Experiments 2 and 3 were designed to further dissociate the pre-attentive search-guidance and focal-attentional decision stages implementing a novel crossmodal compound-search task. In Experiment 2, the task was to detect the target in the visual modality and discriminate it based on a tactile feature. This was reversed in Experiment 3, in which the target was singled out among the non-targets in the tactile dimensions and participants had to respond to it based on a visual feature. The combination of Experiments 2 and 3 was meant to provide corroborative evidence as to the stage(s) at which reward-based attentional capture occurs.

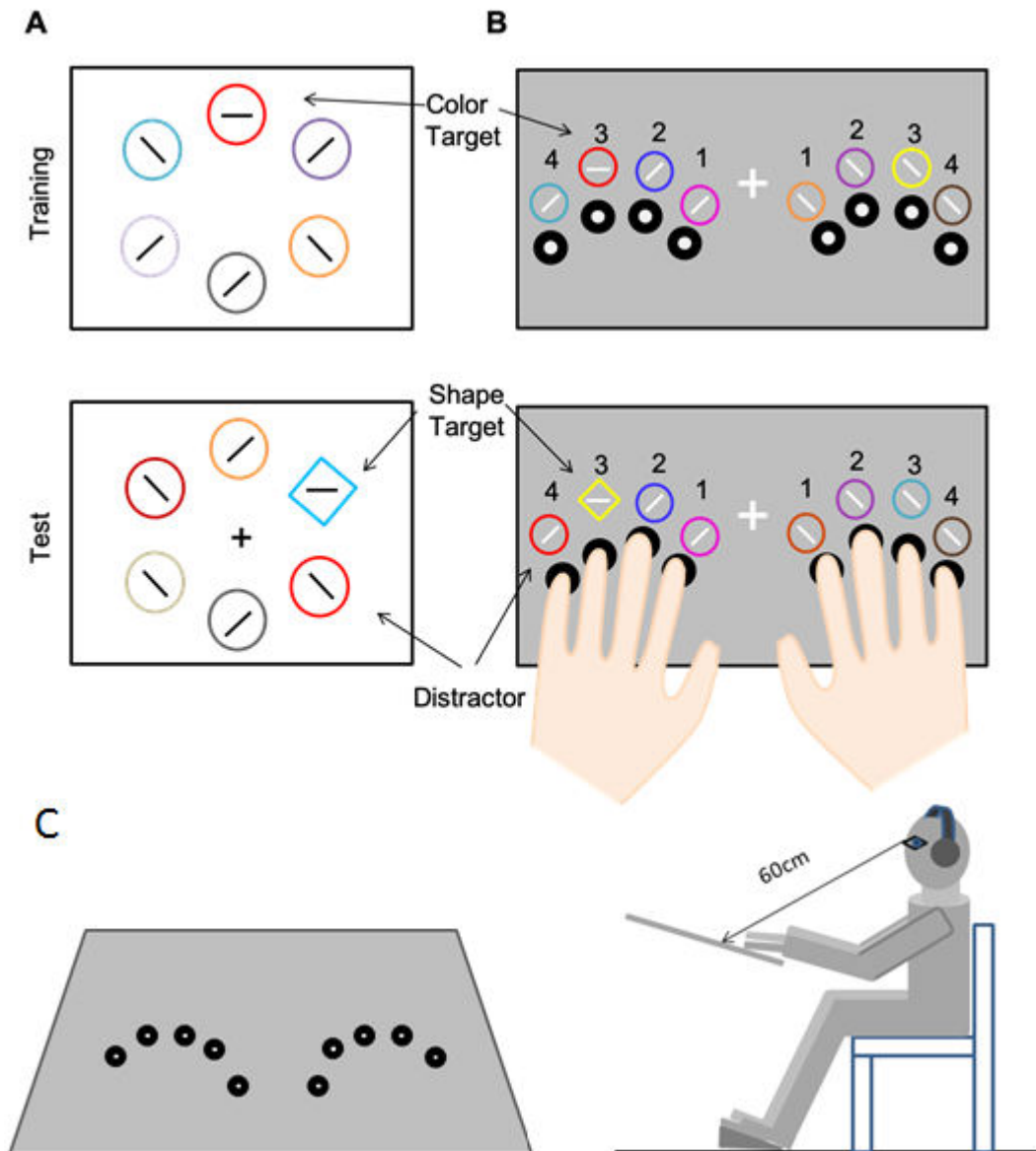


Figure 1. Illustration of the search paradigm, which was adapted from the circular display arrangements used by Anderson et al. (2011) (illustrated in **A**) to our ‘horizontal’ crossmodal display arrangements (**B**), and the experimental set-up (**C**) Viewing distance from participants’ eyes to the panel is 60 cm. Participants respond by stepping on the pedals under the panel on the ground. In (**A**) and (**B**) the upper panel depicts the training phase, in which the visual search array consisted of a color-defined target (here the red circle) among heterogeneously colored nontarget circles. The task is to discern and respond to the orientation of the bar inside the target (horizontal vs. vertical). Critically, there are two target colors (e.g., red and green), one of which is associated with high reward and the other with low reward with a high probability (80%). The lower panel depicts the test phase, in which the task is to find the singleton-shape target, here the diamond, amongst

shape-homogeneous (but color- heterogeneous) non-target circles and discriminate the orientation inside the target using foot stepping on the left or right pedal. Crucially, one of the non-target circles is a ‘distractor’ item of a color previously associated with either high or low reward. In Experiment 1, we only used visual (but not tactile) stimulus presentation, though participants were asked to rest their fingers on the eight tactile actuators; in Experiments 2 and 3, we introduced crossmodal search tasks which are detailed in Figures 4 and 8, respectively. The numbers above the search items denote their eccentricity (they serve here only for purposes of illustration, i.e., they were not shown in the actual search displays).

2.3 Experiment 1

Experiment 1 aimed to examine whether reward-driven attentional interference depends on the target-distractor spatial configuration, to establish at which processing stage(s) the interference arises. To this end, we used a ‘horizontal’ search array in both the training and test phases of the experiment (Figure 1). The search array was arranged along with the fingertips (excepting the thumbs) of the two hands, essentially ensuring the same arrangement as in the crossmodal (visual-tactile) searches implemented in Experiments 2 and 3. Given that the horizontal item arrangement inevitably introduced a variation of stimulus eccentricity (in contrast to the usual, circular arrangement), we treated eccentricity as one factor in our analysis.

2.3.1 Method

Participants

21 volunteers, all with normal or corrected-to-normal visual acuity and normal (self-reported) color vision and tactile sensation, participated in the Experiment (13 females; mean age 26.4 years). The sample size was determined based on previous studies, using 18 to 26 participants (Anderson et al., 2011a, 2019; Yantis et al., 2012). All participants provided written informed consent before the experiment and were paid at a rate of 9 Euro/hour, plus an extra reward bonus (maximum of 3 Euros) earned during the experiment. The study was approved by the Ethics Board of the LMU Munich Faculty of Pedagogics and Psychology.

Stimuli and apparatus

The experiment was carried out in a moderately lit experimental room. Stimuli were generated by Psychtoolbox-3 (Kleiner et al., 2007) with customized Matlab code. The visual stimuli were delivered via a rear projector (Optoma GT760, resolution of 1024 × 768 pixels)

onto a semi-transparent grey screen (subtending $53.8 \text{ cm} \times 40.8 \text{ cm}$) tilted at an angle of 30 degrees relative to the horizontal (see Figure 1C). Participants were seated comfortably in a chair in front of the screen surface, at a viewing distance of 65 cm to the fixation cross on the screen. Two pedals were positioned near participants' feet, which served as response devices in the experiment.

The visual search display (see Figure 1B) consisted of eight items, either circle-shaped (2° of visual angle in diameter) or diamond-shaped ($2^\circ \times 2^\circ$), each containing a white line segment ($1^\circ \times 0.1^\circ$). These items were presented at eight locations positioned along two invisible 'curves' along the horizontal display axis, four locations per curve; the distance between adjacent items was set on average at 1.91° . The colors of the eight items were selected from the following set of ten colors: {red (CIE [Yxy]: 3.56, 0.421, 0.359), green (CIE: 3.50, 0.326, 0.412), orange (CIE: 3.59, 0.328, 0.383), dark blue (CIE: 3.54, 0.364, 0.322), pink (CIE: 3.52, 0.329, 0.411), grey (CIE: 3.55, 0.372, 0.379), brown (CIE: 3.57, 0.387, 0.366), purple (CIE: 3.55, 0.306, 0.380), cyan (CIE: 3.50, 0.327, 0.433), light blue (CIE: 3.55, 0.324, 0.399)}.

Design and Procedure

The experiment consisted of the training and test phase, both closely modeled after the general task design of Anderson (Anderson et al., 2011a). The training phase consisted of 16 blocks of 80 trials each, yielding 1280 trials in total. Each trial started with the presentation of a central, white fixation cross (on a black background) for 500 ms, followed by the search array for 500 ms. Search arrays were composed of 8 colored circles, each containing an oriented line segment (Figure 1B). The circles were color-heterogeneous (no two items were of the same color), but always included one red or, respectively, one green item: the search target. That is, the target on a given trial was defined by being the only item in either red or green color, which appeared at a randomly selected location (i.e., the target appeared equally frequently at all possible display locations). The line segment within the target item was oriented either vertically or horizontally (in all other, non-target items, the lines were tilted 45° randomly to the left or the right), and participants' task was to respond to the orientation of the target line segment (by foot-pedal response) as fast and as accurately as possible. The red and green targets were randomly assigned to be high- and, respectively, low-reward colors across participants (i.e., for 10 participants, red was associated with high reward and green with low reward, and vice versa for the other 11 participants). For each participant, high- and low-reward color targets occurred equally frequently (in randomized order) across trials. On trials with the high-reward color target, there was an 80% probability that

participants would gain (upon a correct response) a reward of ‘+50’ points, and a 20% probability that they would gain a reward of ‘+10 points’. Conversely, on trials with the low-reward color target, participants would gain a reward of ‘+10 points’ with 80% probability, and one of ‘+50 points’ with 20% probability. The search display disappeared after 500 ms, but participants had an additional 1000 ms to issue their response by stepping on one of the foot pedals. The mapping of the horizontal/vertical target orientation to the left/right response pedal was fixed for each participant but counterbalanced across participants. A feedback display was shown for 800 ms after participants gave a response. On trials with a correct response, the feedback display showed the points earned by the participant on the current trial, along with the total earned thus far. Following an incorrect response or a miss (failure to respond within 1500 ms of search-display onset), the message ‘Error!’ was shown in the center of the display. The next trial started after an inter-trial interval of 1000 ms. At the end of the experiment, the points that participants obtained were converted to real money earnings (ranging from 0 to 3 Euros according to the total points they got).

The subsequent test phase consisted of seven blocks, each of 64 trials, yielding 448 trials in total. Each trial started with a fixation cross for 500 ms, immediately followed by a search display that consisted of eight heterogeneously colored shapes: seven circles and one diamond, each containing an oriented white line segment inside. Now, the target item was the diamond shape (i.e., that it was singled out by a shape difference relative to the seven, shape-homogenous non-targets). Again, participants were required to step on the left/right foot pedal according to the orientation (horizontal/vertical) of the line segment inside the target shape, as quickly and accurately as possible (the non-target items contained obliquely oriented line segments). Importantly, in half of the trials (i.e., 224 trials), one of the non-target circles was of a color that had previously (in the training session) been associated with a (high or a low) reward, that is: on a given trial, one of the circles was either red or it was green (equally likely). This reward-associated item served as a ‘distractor’ stimulus; the remaining seven items were randomly assigned one of the non-rewarded colors. Note that the color of the diamond-shaped target was never reward-associated (i.e., red or green), that is, the target and distractor positions never coincided. In the other half of the trials, the search displays contained no distractor (i.e., all circles had a non-rewarded color).

The search display disappeared after 1500 ms, or once a response was made within 1500 ms. Participants received a response to feedback: either the message “Correct!” or

“Error!”, displayed for 800 ms in the center of the display. There was no reward associated with responses in the test phase. The next trial started after an inter-trial interval of 1000 ms.

The whole experiment lasted about 2 hours. Participants were allowed to take a break after each block. Between the training and test phases, there was a mandatory break of at least five minutes. At the beginning of the experiment, participants were informed that they could gain some extra monetary reward (over and above their basic remuneration) according to the total points they would earn in the training phase.

Statistical and Bayes-factor analysis

Given that reward is known to influence both response speed and accuracy (Drugowitsch et al., 2015; Simen et al., 2009), we evaluate both reaction times (RTs) and accuracies (see Appendix), as well as their combination score - inverse-efficiency scores (IES, Bruyer & Brysbaert, 2011; Townsend & Ashby, 1983), which is the most common method for correcting speed-accuracy trade-off. The IES is calculated as the quotient of the mean reaction time (RT) divided by the correct responses (PC) rate,

$$IES = RT/PC.$$

Accordingly, IES scores keep the same unit as the RTs (ms). Given that the separate analysis of RTs and accuracies were in agreement with the analysis of IES, we reported the IES results in the main text and the separate analysis in Appendix.

Repeated-measures ANOVAs and Bayesian analyses of variance (ANOVAs) were performed using JASP 0.10 (<http://www.jasp-stats.org>) with default settings (i.e., r-scale fixed effects = 0.5, r-scale random effects = 1, r-scale covariates = 0.354). Inclusion Bayes factors compare models with a particular predictor to models that exclude that predictor, providing a measure of the extent to which the data support inclusion of a factor in the model. Bayesian t-tests were performed using the `ttestBF` function of the R package “BayesFactor” with the default setting (i.e., `rscale = “medium”`).

2.3.2 Results

Trials with extreme RTs that exceeded the three standard deviations of individual means were excluded for further analyses. Due to a large variation in RTs in the first trial of each block, they were also excluded. In total, 1.92% and 0.87% of the trials were removed for further analysis for the training and the test phases, respectively.

Training Phase

Figure 2 presents the mean IES as a function of target eccentricity, separately for the high- and low-reward targets. By visual inspection, the RTs adjusted by response accuracy was relatively stable for target eccentricities 1 and 2 (i.e., target locations adjacent to fixation or with one intervening location between the target position and fixation), but then increased markedly with increasing target eccentricity. This suggests that search with heterogeneous color items, which receives little bottom-up saliency-based guidance, favors the more central target locations. However, inside this favored central region, there appears to be a reward-driven effect: RTs are faster to targets associated with high reward, as compared to targets associated with low reward; that is, there is an influence of reward-based (top-down) guidance. This influence appears to diminish with increasing target eccentricity outside this central area.

A two-way repeated-measures ANOVA of the mean IES with the factors Target Eccentricity (1, 2, 3, 4) and Reward (high vs. low), revealed only a significant Eccentricity main effect, $F(3, 60) = 84.61, p < .001, \eta_p^2 = .81$, and a marginally significant Reward effect, $F(1, 20) = 3.81, p = .07, BF_{incl} = 2.26$, but the interaction was non-significant, $F(3, 60) = 0.42, p = .74, BF_{incl} = 0.08$. The resulting pattern was similar when examining the unadjusted mean RTs (see Appendix, Supplementary 1, Table S1): Both main effects of Reward and Eccentricity were significant ($p < .001$), but not the interaction ($p = .35$). Thus, while we cannot conclude that the reward-driven RT component decreased with larger target eccentricities, the finding of facilitated overall RTs to high-reward-associated color targets is consistent with previous studies (Anderson et al., 2011a). The fact that this effect was statistically less robust in the IES (than in the RT analysis) suggests that, in addition to speeding responses, high-reward targets are also associated with somewhat increased response errors. The high-reward item has likely been detected, but the decision of the line orientation inside was hurried by the high-reward association.

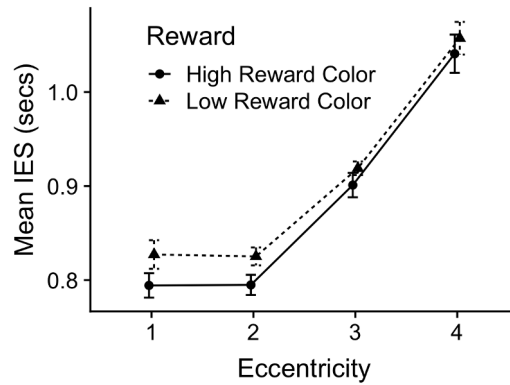


Figure 2. Mean IES as a function of target eccentricity, separately for the high- and low-reward-associated color targets, in the training phase of Experiment 1. The order of the target eccentricity is illustrated in Figure 1. Error bars depict the within-subject standard error.

Test Phase

To examine for interactions between target-distractor positioning (lateralization to the same vs. opposite sides) and the reward-based attentional interference in the test phase, we split the data into three distractor conditions: distractor-*absent* trials (50% of the total trials), distractor on the same side as the target (*ipsilateral* trials, 25% of the total trials), and distractor on the opposite side (*contralateral* trials, 25% of the total trials). The mean RTs (See Appendix, Supplementary 1, Table S2, Figure S1) show a similar eccentricity pattern as in the training session. Given that we were interested in the distractor interference caused by the presence of the reward-associated distractor, we used the distractor-*absent* condition as the baseline and subtracted the baseline IE scores from the respective reward-association condition, separated for the ipsi- and contra-lateral target-distractor locations. Figure 3a shows the distractor interference as a function of the target eccentricity, dependent on the distractor and the lateralization. By visual inspection, the distractor interference was more marked for the Ipsilateral relative to the Contralateral conditions. This pattern is clearer when the distractor interference collapses across the eccentricity, as shown in Figure 3b.

A further repeated-measures ANOVA with Eccentricity, Lateralization, and Distractor Association revealed that only the main effect of Lateralization was significant, $F(1, 20)=10.93$, $p=.004$, the other two factors, and all interactions were not significant (all $ps>.15$). Of particular interest, the reward-association of the distractor (high vs. low reward) did not show any evidence of difference, $F(1, 20)=2.18$, $p=.15$, $BF_{incl} = 0.12$. The same results were confirmed by an ANOVA pooling across target eccentricity (Figure 3b), which

revealed only the main effect of the Distractor-to-Target Lateralization to be significant, $F(1, 20) = 10.93, p = .004, \eta_p^2 = .35$. Neither the main effect of (high/low) Reward Association, $F(1, 20) = 2.17, p = .16, BF_{incl} = 0.51$, nor the interact with Distractor Lateralization, $F(1, 20) = 0.31, p = .58, BF_{incl} = 0.35$. The test confirmed that the cost was higher for the ipsilateral, as compared to the contralateral condition, while the reward value associated with the distractors (high/ vs. low) had little influence on the interference effect (Figure 3b).

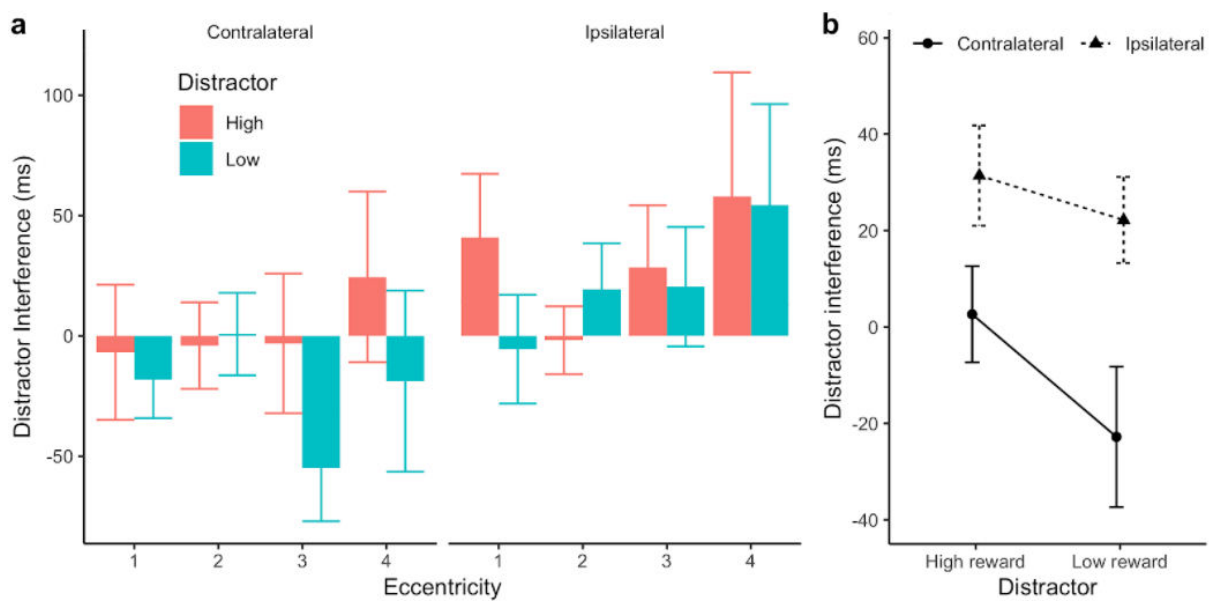


Figure 3. (a) Mean distractor interference in the test phase of Experiment 1, plotted as a function of target eccentricity, separately for reward-associated distractors – dependent on whether the target and distractor were positioned on the opposite sides (contralateral) or the same side (ipsilateral). (b) Mean interference caused by the distractor (relative to the distractor-absent baseline) is a function of its lateralization relative to the target (contralateral, ipsilateral) and its reward association (high, low).

Unlike the previous study (Anderson et al., 2011a), we failed to find any strong value-driven attentional capture with the ipsilateral/contralateral search display, but rather a general reward-associated attentional capture manifested by the positive costs both in the high and low reward conditions (Figure 3B). The results further confirmed that the attentional

capture effect induced by the reward-associated distractor is contingent on the target-distractor lateralization.

2.3.3 Discussion

In Experiment 1, using a left-right horizontally organized search array, we examined whether reward-driven attentional interference or ‘capture’, depends on the distractor-to-target lateralization. Unlike previous studies reporting interference to scale with the reward value associated with the color distractor (e.g., Anderson et al., 2011a; Anderson & Kim, 2019), we only found a general reward-based interference effect that did not differ significantly between high- and low-reward-associated distractors). Interestingly, though, the magnitude of this reward-based attentional interference effect depended on the distractor-to-target lateralization: there was a marked cost in search performance, relative to the distractor-absent baseline, when the reward-associated distractor appeared on the same side as the target, but not when it appeared on the opposite side (in which there was no discernible cost). This distractor-lateralization effect was not significantly modulated by the (high/low) reward value associated with the distractor. This suggests that the precise reward-value association (high/low) is of lesser importance in accounting for distractor interference than the positioning of the distractor relative to the target.

Our finding of an interaction between the distractor relative to target lateralization and reward-based interference suggests that interference occurs within the (larger) target region, during the stage of late, focal-attentional processing. Likely, the reward-associated distractor has been selected together with the target, causing broadening the focus of attention. As a result, we observed the interference cost. However, owing to the design of the present experiment, we couldn’t fully distinguish if the interference comes from the final search and selection stage (e.g., dwelling time before the selection) or the post-selective decision-making stage. To further investigate this, we distinguished the early search stage from the late stage of the target selection stage using a crossmodal design in Experiment 2. The crossmodal search task requires participants first to localize the visual shape-defined target and then discriminate the tactile target. Given that the search performance was greatly impacted by target eccentricity in Experiment 1 (see Figures 2 and 3), with RTs being particularly increased for ‘far’ eccentricities (3 and 4), we limited the search display to the ‘near’ eccentricities (1 and 2) in Experiment 2, introducing only four (rather than eight) cross-modal search items).

2.3 Experiment 2

The training session was the same as in Experiment 1, except that we used search displays consisting of only four, instead of eight, items. In the test phase, the task required participants first to detect and localize the singleton visual shape target (e.g., a diamond) and then discriminate and respond based on the vibration pattern at the target location (i.e., a crossmodal compound task). In other words, the search process was manipulated in the visual modality, and processing of the target for the response-critical information was manipulated in the tactile modality. We hypothesized that if reward-based interference occurs exclusively at the late, target identification stage, we should not observe any interference effect given that the response-critical target feature is defined in the tactile modality. By contrast, if reward-based interference arises at the search stage, we should observe a similar effect pattern as in Experiment 1. Experiment 2 consisted of two experiments: the target and distractor were assigned to different sides in one session (2A) and to the same side in the other session (2B).

2.3.1 Method

Participants

19 valid participants (21 recruited, but two failed to complete) took part in Experiment 2A (12 females; mean age 26.5 years). A different group of 19 participants took part in Experiment 2B (9 females; mean age 23.5 years). All participants had normal or corrected-to-normal visual acuity and normal color vision and tactile sensation. All provided written informed consent before the experiment and were paid at a rate of 9 Euro/hour for their participation, plus an extra reward bonus (of maximally 3 Euros) they could earn during the training.

Apparatus and stimuli

The stimuli used in the training phase was the same as in Experiment 1, except the search items were reduced from eight to four, positioned only at locations 1 and 2 (i.e., locations near the index and middle fingers, the eccentricity of 1.91° and 3.82° respectively, see Figure 1B). In the test phase, the visual item was either a circle or a diamond shape with a white cross inside (see Figure 4A). The color of the shapes was selected from the same color sets as used in Experiment 1. Besides, there were four vibrotactile stimuli with sinusoidal modulation of the amplitude: two high frequency (69 Hz) vibrations and two low frequency (1 Hz) vibrations delivered to four fingers. On each hand, there were one high and one low vibrotactile stimuli randomly assigned to the index and middle fingers. Tactile stimuli were

generated by solenoid actuators (a diameter of 1.8 cm, Dancer Design). The actuators activated lodged metal tips vibrating a pin 2-3 mm following the magnetization of the solenoid coils, controlled by an amplifier connected to the computer with a MOTU analog output device.

Design and Procedure

The procedure of the training phase was the same as in Experiment 1, except that it consisted of 8 blocks of 80 trials, that is, 640 trials in total, and the search items were reduced from eight to four, presented at the two positions near central fixation (eccentricities 1 and 2) bilaterally.

In the test phase, participants were asked to place their left- and right-hand index and middle fingers on the top of the actuators positioned at locations 1 and 2 on each side (Figure 4). A trial started with the presentation of a white fixation cross in the center of the search array for 500 ms. This was followed by the search display, which was presented for two seconds or until the participant responded. The search display consisted of four visual items (one diamond shape and three circles) and four vibrotactile stimuli delivered via the actuators underneath participants' fingers, two of low and two of high frequency (no vibrotactile stimulation was presented during the preceding training phase). The locations of the target were randomly selected from the four possible locations, while the previously reward-associated color distractors were positioned randomly at two positions on the other side of the target (Experiment 2A), or the other position on the same side of the target (Experiment 2B). In half of the trials, the display contained a distractor whose color was reward-associated (either green or red, equally likely); the other half were distractor-absent trials. For the trials with a reward-associated distractor, the target and distractor appeared on different sides in Experiment 2A, and on the same side in Experiment 2B. Participants were required to locate the shape-defined (e.g., diamond) position and report whether the vibration at its location was a low- or high-frequency pattern, by pushing the associated (left or right) foot pedal, as quickly and accurately as possible. The response mapping of the vibrotactile stimuli (low/high frequency) to the foot pedals (left/right) was counterbalanced across participants. Participants wore sound-insulation headphones to reduce the (vibration) noise generated by the tactile actuators, to help them focus attention on the tactile modality. After the response, a feedback message, either "Correct!" or "Error!", was presented for 800 ms. The next trial began after an inter-trial interval of 1000 ms. The test phase consisted of eight blocks of 32 trials each, 256 trials in total. Before the formal test session, participants

received a short training block to get familiar with the vibration targets, and those participants who reached the discrimination, accuracy above 75% could continue the formal experiments.

Participants completed the total experiment in around 70 minutes. They took a 5–10-minute break between the training and test phases. Before the experiment, participants were informed that they could earn extra money (up to 3 euros) according to the points they would gain in the training phase.

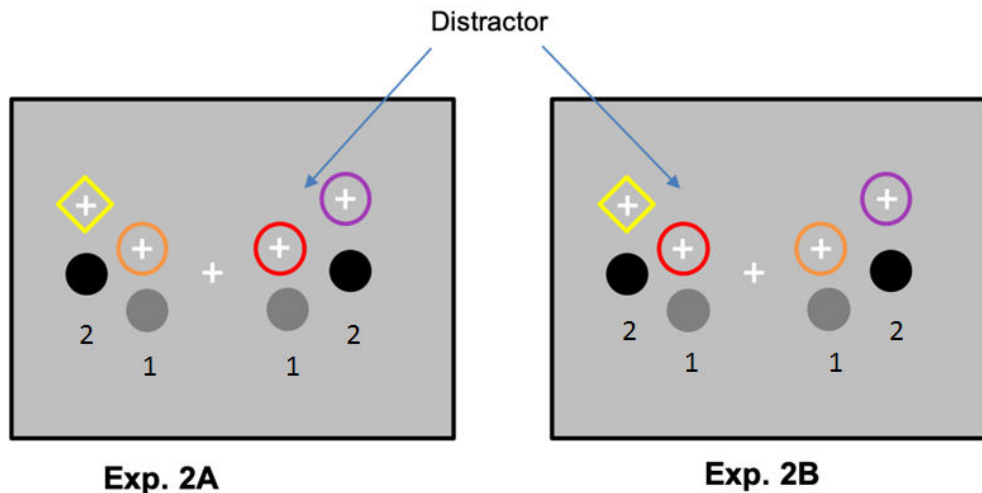


Figure 4. An example trial in the test phase of Experiments 2A and 2B. The search displays consisted of four heterogeneously colored shape items, one of which was the odd-one-out shape: a diamond target among circle non-targets. Participants reported the vibration frequency on the tactile stimulator delivered to the finger at the target location (while ignoring the vibrations at the non-target locations). Here, black denotes low frequency and gray high frequency. In half of the trials, a color distractor (i.e., a non-target circle in a color previously associated with high or low reward in the training session) was present in the search display. In the example, the reward-associated color is red. The target and the distractor were located on different sides in Experiment 2A, and on the same side in Experiment 2B.

2.3.2 Results

The same exclusion criteria as in Experiment 1 were used in Experiment 2. In total, 2.5% and 3.5% of the trials in the training and the test phases were removed respectively from Experiment 2A, and 2.5% and 3.7% from Experiment 2B. Mean RTs, accuracies, and their

statistical analyses were shown in Appendix. Here we only reported the IES results, given that both analyses had the same conclusion.

Training Phase

The mean RTs and accuracies were listed in Appendix (see Supplementary 2, Table S3). As can be seen from the mean IE scores (depicted as a function of target eccentricity and separately for the high- and low-reward-associated color targets) in Figure 5, there was clear facilitation of search performance for the high-reward target. Repeated-measures ANOVAs with the factors Target Eccentricity and Reward Association revealed the main effect of Reward Association to be significant for both Experiment 2A, $F(1, 18) = 32.26, p < .001, \eta_p^2 = .64$, and Experiment 2B, $F(1, 18) = 17.35, p < .001, \eta_p^2 = .49$. The Target-Eccentricity main effects were also significant, Experiment 2A, $F(1, 18) = 146.0, p < .001, \eta_p^2 = .89$, and Exp. 2B, $F(1, 18) = 59.08, p < .001, \eta_p^2 = .77$. However, the interaction effects were non-significant (all $ps > .1$). Thus, the reward manipulation appeared effective in the training sessions of both experiments.

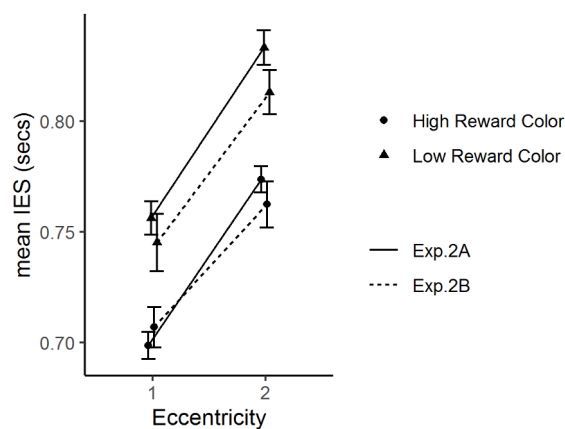


Figure 5. Mean IES as a function of target eccentricity, separately for the high- and low-reward-associated color targets in the training phases of Experiments 2A and 2B. Error bars depict the mean within-subject standard errors.

Test Phase

The mean RTs, accuracies, and IE scores were listed in Appendix (see Supplementary 2, Table S4) and shown in Figure S2. Here we focus on the effects of distractor interference, calculated from the difference between the distractor-present conditions to the distractor-absent baseline. Figure 6a presents the mean IE scores as a function of the target

eccentricity, for the three distractor conditions (absent, high-, low-reward-associated), separately for Experiment 2A (left; distractors located contralaterally to the target) and Experiment 2B (right; ipsilateral distractors). Target-Eccentricity \times Distractor-Condition ANOVAs revealed no significant effects for the contralateral distractors in Experiment 2A (all $ps > .14$, $BF_{incl} < .21$). For the ipsilateral distractors in Experiment 2B, both the main effects were not significant: Target-Eccentricity, $F(1,18) = .54$, $p = .47$, $BF_{incl} = 0.205$; Distractor-Condition, $F(1,18) = .049$, $p = .82$, $BF_{incl} = 0.188$, but the Target-Eccentricity \times Distractor-Condition interaction was significant, $F(1,18) = 5.29$, $p = .03$, $BF_{incl} = 0.074$. However, the Bayes factor indicates the interaction was rather weak, and not worth interpreting it.

Figure 6b reports the mean distractor-interference effects for Experiment 2A and Experiment 2B. By visual inspection, the effect pattern is similar to Experiment 1: (numerical) interference is observable only with ipsilateral distractors, and (numerical) interference appears greater with high- versus low-reward-associated distractors. However, as with the overall ANOVAs, one-way ANOVAs of the interference effects failed to reveal the Reward Association effect to be significant, both for Experiment 2A, $F(1, 18) = 0.43$, $p = .52$, $BF_{incl} = 0.22$, and Experiment 2B, $F(1, 18) = 0.05$, $p = .83$, $BF_{incl} = 0.24$. A further t -test comparing the highest-cost condition (Experiment 2B: Ipsilateral/High-reward color) against a zero effect also failed to reveal significant above-zero interference, $t(18) = 1.3$, $p = .21$. In other words, when post-selective processing of the target for response-critical information took place within the tactile modality whereas the reward-associated distractor was defined in the visual modality, reward-associated attentional interference was relatively weak.

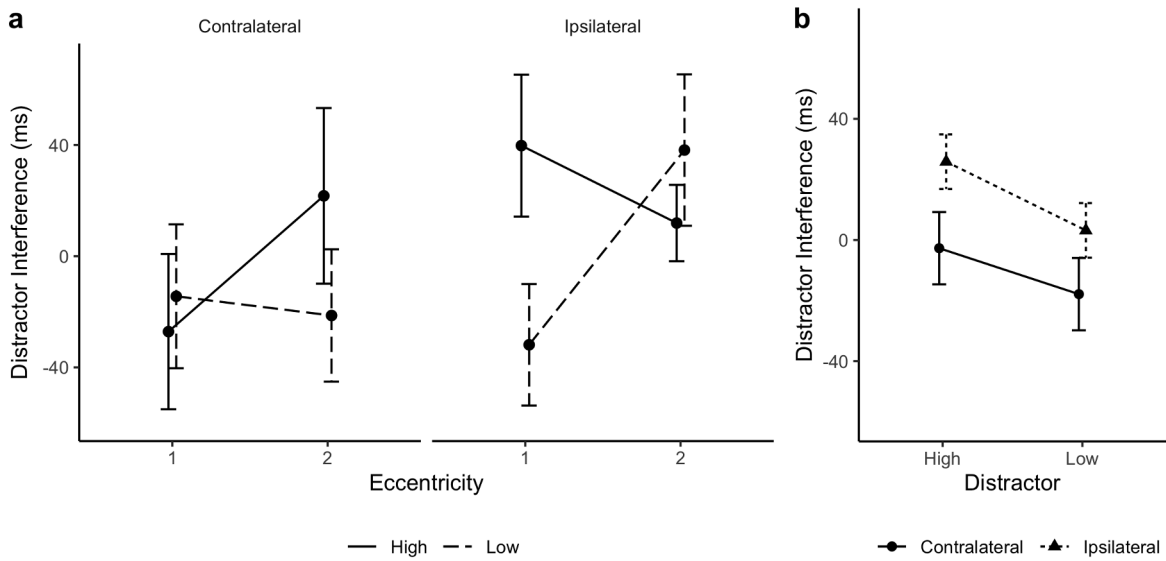


Figure 6. Results from the test phase of Experiment 2. (a) Mean distractor interference (relative to the distractor baseline) as a function of target eccentricity, for the high-, low-reward-associated distractor separately for the contralateral (Experiment 2A) and ipsilateral (Experiment 2B) placement of the target and distractor. (b) Distractor interference (relative to the distractor baseline) as a function of reward associated with the distractor, separately for the contra- and ipsilateral conditions. Error bars depict the mean within-subject standard errors.

2.3.3 Discussion

In the training phase, we established a significant target-color to reward association: high-reward-associated targets were detected faster than low-reward targets. In contrast to the pure visual search in Experiment 1, we introduced a crossmodal compound-search task in the test phase: participants had to localize the diamond shape and identify the vibrotactile stimulus at its location. Reward-associated attentional interference, which was robust in Experiment 1 (for ipsilateral targets and distractors), was greatly diminished in Experiment 2 (and non-significant even with high-reward distractors presented on the same side as the target). Recall that the significant interference effect in the ipsilateral target and distractor condition of Experiment 1 suggested that reward-associated distractor interference arises at the late, focal-attentional processing stage at which the task-relevant *visual* information (i.e., information within the reward-associated modality) is extracted to decide upon the response. Here in Experiment 2, when the response-critical information was contained in the tactile (rather than the visual) modality, the reward-associated interference effect almost vanished

(even within the ipsilateral target-&-distractor condition, which showed some numerical interference relative to the contralateral condition). Thus, the results suggest that the test phase of the target for response-critical information within the same modality as the reward-associated distractor plays a critical role in the reward-based attentional interference effect. To further corroborate the role of the late processing stage in reward-driven interference, we conducted another experiment (Experiment 3) in which, in the test phase, the target was singled out from the non-targets in the tactile modality (by a unique vibration pattern) whereas the response-critical information remained in the visual modality (i.e., the same modality in which the distractor is defined).

2.4 Experiment 3

2.4.1 Method

Participants

20 participants were enrolled in Experiment 3 (13 females; mean age 26.5 years), all with normal or corrected-to-normal visual acuity and normal color vision and tactile sensation. All participants gave written informed consent before the experiment and were paid at a rate of 9 Euro/hour for their participation, plus an extra reward bonus (of up to 3 Euros) they could earn during the training phase.

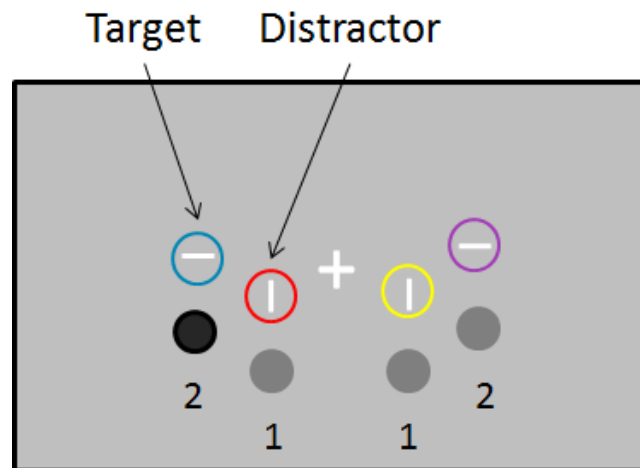


Figure 7. An example trial in the test phase of Experiment 3. Search displays consisted of 4 different colored circles, each circle with a horizontal or vertical line segment inside. Participants searched for an odd-one-out vibrotactile target and reported the orientation of the line segment inside the (target) circle at that location. In the example, a distractor, whose color (red) had been associated with reward in the preceding training session, appeared on

the same side as the target. The numbers “1” and “2” indicated the eccentricities of the stimuli (see Figure 1). They were not shown on the screen.

Stimuli and procedure

The stimulus settings and procedure were the same as in Experiment 2, except for the following differences in the test phase (the training phase was identical to Experiment 2): test-phase displays consisted of four visual circles with either a horizontal or a vertical bar inside, and four tactile vibrations (see Figure 7). Only one location vibrated at a high (69-Hz) frequency, whereas the three others vibrated at a low (1-Hz) frequency. Thus, participants had to locate the singleton target item by its odd-one-out vibration frequency, but then report whether the line segment inside the target circle was horizontal or vertical as quickly and accurately as possible. The color of the target circle was never reward-associated. On distractor-present trials (50% of the trials), one of the four circles appeared in a color that was previously reward-associated (25% high-reward-associated and 25% low-reward-associated distractors). As established in Experiments 1 and 2, reward-based attentional interference was evident only when the target and distractor appeared on the same side. Thus, Experiment 3 only tested the ipsilateral target-and-distractor condition.

2.4.2 Results

The same exclusion criteria were used to exclude extreme RTs and the first trial of each block. In total, 2.33% and 4.18% of trials were excluded in the training and, respectively, the test phase of Experiment 3.

Training Phase

The mean RTs and accuracies were listed in Appendix (see Supplementary 3, Table S5). Figure 8a presents the IE scores as a function of target eccentricity, separately for the high- and low-reward-associated color targets. A two-way repeated-measures ANOVA revealed both main effects to be significant: Target Eccentricity, $F(1, 19) = 59.75, p < .001, \eta_p^2 = .76$, and Reward Association, $F(1, 19) = 13.41, p < .01, \eta_p^2 = .41$. The interaction was non-significant, $F(1, 19) = 2.61, p = .12, BF_{incl} = 0.38$. Thus, again, participants learned the differential rewards associated with the two target colors to adapt their search performance accordingly.

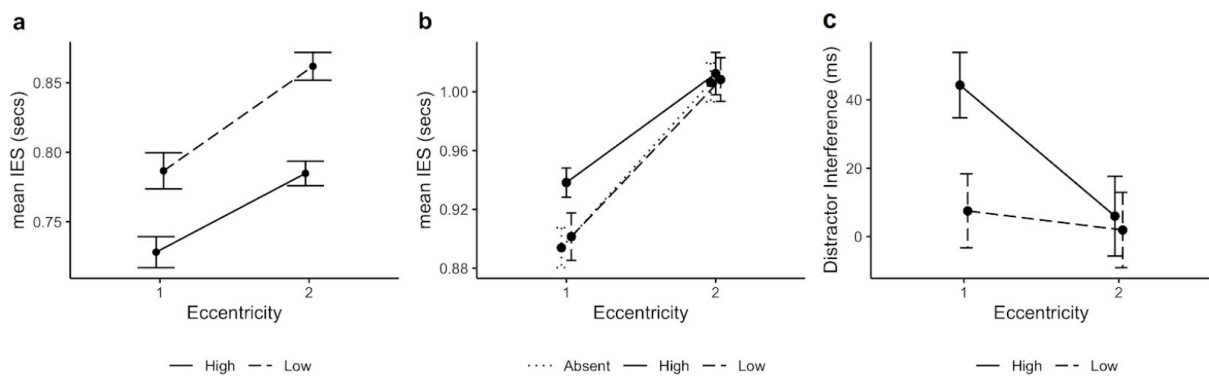


Figure 8. Results from Experiment 3. (a) Mean IES as a function of target eccentricity in the training phase, separated for the high- and low-reward-associated color targets. (b) Mean IES as a function of target eccentricity in the test phase, separately for the different distractor conditions (distractor absent, high-, low-reward-associated distractor). (c) Mean distractor interference as a function of target eccentricity in the test phase, separately for the high- and low-reward-associated distractor conditions. Error bars depict the mean within-subject standard errors. See the numbers 1 and 2 in Figure 1 for the two possible target eccentricities.

Test Phase

Again, here we focused on the distractor interference (mean RTs, accuracies, and mean IE scores were included in Appendix, see Supplementary 3, Table S6, Figure S3, which revealed the same results). Figure 8b shows the mean IE scores as a function of target eccentricity, separately for the distractor conditions. A two-way ANOVA with both main then main effect of Reward Association, $F(2, 38) = 4.74, p = .015, \eta_p^2 = .20$, and Target Eccentricity, $F(1, 19) = 19.29, p < .001, \eta_p^2 = .50$, to be significant. The presence of the high-reward-associated distractor slowed down the response, and the target located at the inner position (Eccentricity of 1) had better performance than the outer position (Eccentricity of 2). The eccentricity effect was similar as shown in the training session. The interaction between Target-Eccentricity and Distractor was non-significant, $F(2, 38) = 2.19, p = .13, BF_{incl} = 0.31$. Figure 8c depicts the mean distractor interference, which also confirmed more marked distractor interference for the presence of the high-reward-associated distractor relative to the low-reward-associated distractor. Thus, unlike the findings in Experiments 1 and 2, we found a significant value-based attentional capture. A post hoc comparison

revealed the high-reward distractor interfered more than the low-reward distractor ($p < .01$), while there was no significant difference between the low-reward and the baseline conditions ($p > .1$).

2.4.3 Discussion

In Experiment 3, the compound-search task required participants to find an odd-one-out vibrotactile target and discriminate the orientation of the bar within the (target) circle at the same location. That is, while the visuo-tactile target had to be selected based on information in the tactile modality, it had to be processed for response based on information in the visual modality. Implementing this scenario, we found not only significant interference by reward-associated distractors (as in Experiment 1, but not in Experiment 2). Of note, in line with previous findings (Anderson et al., 2011a), high-reward-associated distractors produced greater interference than low-reward-associated distractors. It is important to note that the experimental settings in Experiment 3 analogous to those in Experiment 2, except that the search-critical target information was vibrotactile and the response-critical information visual in Experiment 3, instead of search-critical visual information and response-critical vibrotactile information in Experiment 2. Under the latter conditions (Experiment 2), we failed to find significant reward-based interference (even by high-reward-associated distractors on the same side as the target), whereas we found significant reward-based interference under the reverse conditions (Experiment 3). Thus, all three experiments taken together, our findings suggest that reward-associated distractors likely interfered at the stage of post-selective target processing, i.e., extracting and discriminating the response-critical information, rather than at the early stage of target selection.

2.5 General Discussion

The present study conducted three experiments to investigate at which stage in the functional architecture of search reward-based distractor interference may arise. We adopted Anderson's color-reward association paradigm (Anderson et al., 2011a), but rearranged the search items into a horizontal, left-right display and made the task visuo-tactile (in the tests session of Experiments 2 and 3). In Experiment 1, apart from the rearrangement of the display into a left-right region, the paradigm was the same as in Anderson et al. (2011): participants learned to associate *visual* (color) features with reward in the training phase; in the test phase, they searched for a singleton *visual* (shape) target and responded to a separate *visual*

(line-orientation) feature. The test-phase results revealed reward-associated interference to be manifested only when the target and the reward-associated distractor were presented on the side, though without a discernible difference in interference between high- and low-reward-associated distractors. Experiments 2 and 3 extended the task into a visuo-tactile compound search in the test phase, to separate the pre-attentive target selection and post-selective target processing stages into two different modalities. When the task was to localize the target based on visual information and to identify and respond to a tactile feature of the target (Experiment 2), reward-associated distractor interference diminished to an insignificant level (even when target and distractor were presented on the same side). In contrast, when the task was to localize the target based on tactile information and to identify and respond to a visual target feature, where the reward-associated distractor was also defined in the visual modality (Experiment 3), reward-associated distractor interference reemerged strongly (with target and distractor presented on the same side). Besides, high-reward-associated distractors generated greater interference than low-reward-associated distractors, consistent with the literature of ‘value-driven attentional capture (Anderson et al., 2011a; Kim & Anderson, 2019).

Several studies have argued that reward history enhances the saliency of reward-associated items (Hickey et al., 2010b). Reward-based reinforcement of a specific feature (e.g., color) alters the top-down attentional set (e.g., attending to the specific color features with priority), thus (top-down) boosting the entry-level encoding of reward-associated distractors, making them capture attention like physically salient distractors (Hickey et al., 2010b). Other researchers provided an alternative argument: reward history affects processing only after attention was captured by the distractor, namely by prolonging attentional disengagement from the reward-associated distractor (Anderson, 2015; Yantis et al., 2012). Thus, both accounts would predict interference at the search stage, whenever the reward-associated distractor engages attention, whether by enhanced saliency or random selection. However, both accounts fail to predict the findings of the present study. The results of Experiment 1 showed that distractors appearing contralateral to the target caused no interference (relative to the distractor-absent condition). By contrast, reward-associated distractors produced robust interference when they occurred on the same side as the target. The dissociative effect of ipsi- versus contralateral distractors suggests that the reward-associated distractor did not act as a salient stimulus with the potential to capture attention at the early, search stage (otherwise, there should also have been a cost for distractors positioned contralateral to the target). Instead, the interference likely arose after

the selection of the target, that is, when focusing attention on the target to extract and discriminate the response-relevant information: during this stage, a nearby (i.e., same-side) reward-associated distractor may divert (focal-attentional) processing resources, generating interference.

Recall that the reward-associated distractor produced a general cost, that is, the interference it produced was independent of whether it was associated with high or low reward. Reward has been suggested to induce a powerful bias in visual selection (Awh et al., 2012). Thus, if the bias is already strong in the low-value condition, this would make it hard to resolve differences in interference between high- and low-reward-associated distractors. On the other hand, (Sha & Jiang, 2016) have recently reported that interference by reward-associated color distractors was not increased for the stimulus that had been learned to be associated with high-, as compared to the low-, reward. This led them to argue that, rather than being strictly reward-driven, the interference effect may largely reflect capture by visual features that had previously (during the training phase) been learned to be target-defining – perhaps owing to the corresponding search (‘target’) templates being readily available in memory.

Although Experiment 1 indicated that reward-driven attentional capture occurs at the late stage, there would still be two possibilities concerning when attentional capture takes place. The interference may occur during the final phases of the search stage when attention is focused on the target to extract and analyze the response-relevant information: while attention zooms in on the target, a reward-associated distractor within the broader target zone may be registered and thus delay the full deployment of attention to the target. Even response-relevant information may be extracted from such a distractor, potentially causing interference with the response decision required by the target, like response-incompatible flanker stimuli in the classical Eriksen (Eriksen & Eriksen, 1974) flanker paradigm (see also e.g., Ivanov & Theeuwes, 2020 for evidence of such in-/compatibility effects). Another possibility is that the interference arises during the post-selection, focal-attentional target processing stage when the reward-associated color captures attention. Experiments 2 and 3 were designed to distinguish these two possibilities, by delivering the search-critical and the response-critical target information via separate, visual and tactile, modalities. In Experiment 2, participants had to search for the target via the visual modality (locating the singleton shape) and then discriminate its response-critical feature in the tactile modality (identifying its high/low vibration frequency). Under these conditions, the interference by reward-associated distractors (on the same side as the target) diminished to a non-significant

level. This abolishment of the interference effect suggests that the reward-based distractor interference observed in Experiment 1 arose at the late stage of target identification within the *visual* modality. To confirm this hypothesis, Experiment 3 reversed the search-critical and response-critical modalities relative to Experiment 2: the target was defined by a tactile feature and the response by a visual feature. Under these conditions, there was again strong interference by the reward-associated color distractor (on the same side as the target), and the magnitude scaled with the value previously associated with the distractor color: interference was greater for high vs. low-value color distractors. We take this to confirm that reward-based attentional interference arises at the stage of target identification, provided that the target and the reward-associated distractor share the same (visual) modality.

The occurrence of interference at the late stage also suggests that reward-based association does not alter the priority map, given that the priority map is the critical representation that guides search from one item location to another. An alteration of the priority map through reward association should be expressed in interference at the early stage. Previous studies using reward-location association paradigms (Anderson, 2015; Chelazzi et al., 2013, 2014) found reward-based interference to be bound to the rewarded-associated location. That is, in these paradigms, particular display locations were assigned a certain (high/low) probability of receiving the reward when a target appeared at the respective locations (in the training phase). This then influenced that magnitude of interference caused by distractors occurring at these locations, indicative of reward-dependent alterations of the search-guiding attentional priority map. By contrast, in the training session of the present study, the reward was associated with colors (either green or red), unbound to any specific locations. Unlike a physically salient color that can directly boost the attentional priority of the respective location on the search-guiding map (Chelazzi et al., 2014; Ferrante et al., 2018; Zhang et al., 2019), we found no evidence that reward-associated features directly impacted the priority map: distractor interference occurred only when the color-defined – that is, *visual* – distractor appeared on the same side as the target (regardless of whether the target was selected via the visual or the tactile modality) and when the response required discrimination of a *visual* target feature. This suggests that the interference most likely arose after target selection, that is, a stage at which the target was attentionally processed for the response-critical visual information. Interference within the focus of attention is consistent with (Lihui Wang et al., 2015), who found that low-reward distractors interfered only with the target processing when they were very near to the target, while high-reward distractors had a relatively large impact range. In

the present study, both high- and low-reward-associated distractors produced interference only when they were close to the target (i.e., in the ipsilateral condition), suggesting that reward history likely biases the competition of *visual* feature selection within the focus of attention, giving priority to the reward-associated distractor feature (color) rather than the response-critical target feature (line orientation) and thus extending the time required to make the response decision.

Interestingly, our findings also suggest that this competitive interaction within the visual modality can be effectively bypassed by defining the response-critical target feature in the tactile modality: making the tactile vibration frequency response-critical in Experiment 2 reduced reward-based interference by the visually defined distractor to a non-significant level. This suggests that when the task requires response-critical features to be extracted and discriminated in the tactile modality, processing of this information can be effectively shielded from inference by reward-associated, but response-irrelevant distractors in the visual modality. In other words, visual distractors interfere only when the task requires focal-attentional processing of visual information (Experiment 3). In contrast, when the response-critical information is provided by the tactile modality, post-selective processing is set to analyze tactile information, permitting effective filtering of irrelevant (and potentially interfering) information in the visual modality (Experiment 2). [The fact that irrelevant color information did penetrate this stage when target analysis was set to process orientation information –causing interference within the same (the visual) modality – may indicate that focal attention can only be coarsely allocated to the target modality, rather than selectively to the response-critical dimension within that modality.]

It has been argued that “the temporal profile of value-driven attentional capture is immediate and sustained over the period when bottom-up cues typically fade and top-down cues become more effective” (Stankevich & Geng, 2015, p. 226). This is consistent with the present findings. The reward-associated distractor did not interfere at the early search process, but at the post-selective stage when the target (its response-critical feature) and distractor shared the same modality. In this aspect, reward-driven attentional capture is different from capture by bottom-up salient distractors. The latter often captures attention immediately, guiding eyes involuntarily toward the distractor at the early search stage (e.g., Geyer et al., 2008; Sauter et al., 2021). By contrast, we observed reward-associated interference only when the reward-associated distractor appeared in the vicinity of the target (so that they could be selected together by focal attention) and when the reward-associated distractor and the response-critical target feature belonged to the same modality.

In the present study, differential interference between high- vs. low-reward-associated distractors was obtained only in Experiment 3, suggesting the value-dependent modulation of attentional interference is relatively weak. This is consistent with the view that reward-based interference is influenced by other factors, including the spatial contingencies (Anderson, 2015), perceptual distractor salience (L. Wang et al., 2013), and, in particular, the previous target association (Sha & Jiang, 2016). For example, Wang et al. (2013) observed value-based attentional capture with the color-reward association, but not with the shape-reward association (where shapes are assumed to be less salient than colors); there was evidence of value-based interference for shapes only when they were paired with strong punishment.

In conclusion, our findings provide new evidence that reward-based distractor interference is contingent on the distractor-to-target lateralization, and the interference arises at the late stage of focal-attentional target processing when the distractor is defined in the same (visual) modality as the response-critical target information.

2.6 Appendix

2.6.1 Supplementary 1: RT and Accuracy analyses for Experiment 1.

The mean RTs and correspondent accuracies for the training phase are listed in Table S1. A two-way repeated-measures ANOVA on the mean RTs with the factors of reward and eccentricity revealed RT was significantly faster in the high-reward relative to the low-reward condition, $F(1, 20) = 14.64, p < .01, \eta_p^2 = .42$. There was also a significant difference in eccentricity: $F(3, 60) = 4.74, p < .001, \eta_p^2 = .78$. The response was generally faster for the central items relative to the peripheral items. However, there was no interaction, $F(3, 60) = 1.11, p = .35, BF_{incl} = 0.32$. A second two-way repeated-measures ANOVA on Accuracy with the factors of reward and eccentricity revealed that the accuracy was higher in the high-reward as compared to the low-reward condition, $F(1, 20) = 0.44, p = .52, BF_{incl} =$. There was also a significant difference in eccentricity: $F(3, 60) = 27.89, p < .001, \eta_p^2 = .58$. No interaction was found, $F(3, 60) = 0.49, p = .69, BF_{incl} = 0.08$.

Table S1

Mean Correct Reaction Times (RTs) and mean Accuracies for the Target Conditions of Experiment 1 in the training phase

Eccentricity	RT(ms)		Accuracy(%)	
	High Reward	Low Reward	High Reward	Low Reward
1	725.0±88.9	745.3±92.0	91.9±7.3	91.0±7.3
2	732.9±76.9	756.1±77.2	92.7±7.0	92.2±7.9
3	798.8±72.7	819.9±79.2	89.5±9.8	89.8±9.0
4	880.6±93.7	890.3±86.1	86.0±11.2	85.5±10.7

The mean RTs and correspondent accuracies for the test phase are listed in Table S2. A type III ANOVA on the mean RTs with the factors of reward, eccentricity, target-distractor lateralization revealed a significant difference in eccentricity, $F(3, 102.95) = 13.10, p < .001$, and the response was significantly faster when the target was in the central areas than peripheral areas. Target-distractor lateralization showed a significant difference, $F(2, 116.63) = 6.75, p < .005$. There was no significant difference in the distractor condition (absent, high, low), or any interactions (all $ps > 0.1$). A second type III ANOVA on the mean accuracies with the factors of reward, eccentricity, target-distractor lateralization revealed a significant difference in eccentricity, $F(3, 104.17) = 14.64, p < .001$, and the accuracy was higher in central areas than

peripheral areas. There was no significant difference in the distractor condition (absent, high, low) or target-distractor lateralization, or any interactions (all $ps > 0.1$).

Table S2

Mean Correct Reaction Times (RTs) and Mean Accuracies for the Target and Distractor Conditions of Experiment 1 Test phase

Condition	RT(ms)		Accuracy(%)	
Distractor absent				
Target Eccentricity 1	793.3±121.9		94.1±5.2	
Target Eccentricity 2	803.0±98.7		96.4± 4.3	
Target Eccentricity 3	877.1±87.2		93.5±5.9	
Target Eccentricity 4	961.3±101.6		87.5± 9.1	
Target & Distractor Contralateral	High	Low	High	Low
Target Eccentricity 1	783.5 ±125.9	789.2±129.6	94.3±7.8	95.6±5.5
Target Eccentricity 2	809.9±112.2	802.1±112.2	97.8± 5.7	96.2± 6.1
Target Eccentricity 3	884.1±110.8	846.9±97.5	94.6±7.9	95.4±6.0
Target Eccentricity 4	970.0±111.5	957.0±106.1	87.3±11.4	88.7± 9.8
Target & Distractor Ipsilateral	High	Low	High	Low
Target Eccentricity 1	816.0±143.6	798.0±126.7	92.9±8.5	95.1±6.6
Target Eccentricity 2	804.6±104.4	813.3±122.8	96.9±5.5	95.3±6.9
Target Eccentricity 3	901.5±100.6	898.4±122.2	93.6 ±8.1	94.2±7.6
Target Eccentricity 4	986.2±123.9	1020.9±125.7	87.3 ±13.8	88.8±10.9

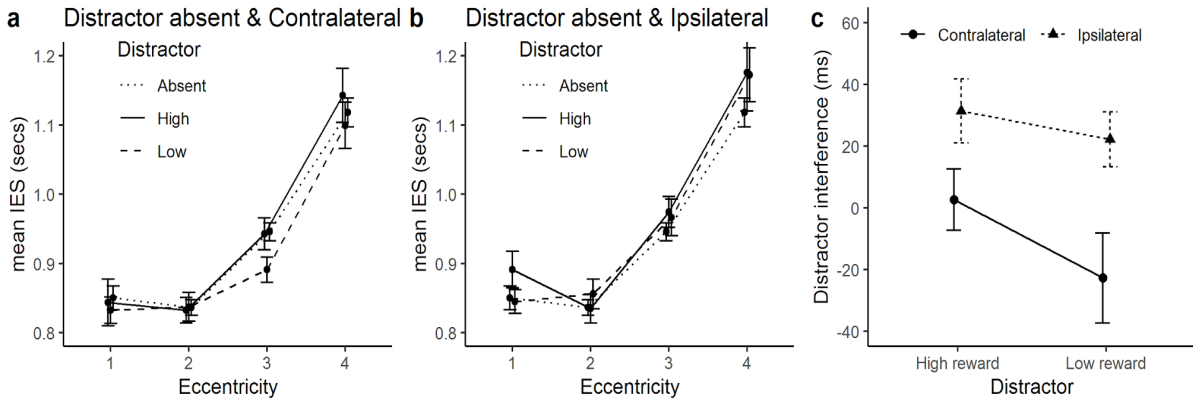


Figure S1. Mean IESs and distractor interference in the test phase of Experiment 1. Mean IES is plotted as a function of target eccentricity, separately for the three distractor conditions (Absent, High-, Low-reward associated) – dependent on whether the target and distractor were positioned on the opposite sides (contralateral) (a) or the same side (ipsilateral) (b). (c) Mean interference caused by the distractor (relative to the distractor-absent baseline) is a function of its lateralization relative to the target (contralateral, ipsilateral) and its reward association (high, low).

2.6.2 Supplementary 2: RT and Accuracy analyses for Experiment 2.

The mean RTs and correspondent accuracies for the training phase are listed in Table S3. A two-way repeated-measures ANOVA on the mean RTs with the factors of reward and eccentricity in Exp.2A revealed RT was significantly faster in the high-reward relative to the low-reward condition, $F(1, 18) = 21.45, p < .001, \eta_p^2 = .54$. There was also a significant difference in eccentricity: $F(1, 18) = 136.42, p < .001, \eta_p^2 = .88$. The response was generally faster for the central items relative to the peripheral items. However, there was no interaction, $F(1, 18) = 0.12, p = .74, BF_{incl} = 1.21$. A second two-way repeated-measures ANOVA on Accuracy with the factors of reward and eccentricity in Exp.2A revealed that the accuracy was higher in the high-reward as compared to the low-reward condition, $F(1, 18) = 5.75, p < .05, \eta_p^2 = .24$. There was also a significant difference in eccentricity: $F(1, 18) = 12.17, p < .005, \eta_p^2 = .40$. There was no interaction, $F(1, 18) = 0.05, p = .84, BF_{incl} = 1.02$.

A two-way repeated-measures ANOVA on the mean RTs with the factors of reward and eccentricity in Exp.2B revealed RT was significantly faster in the high-reward relative to the low-reward condition, $F(1, 16) = 11.60, p < .005, \eta_p^2 = .42$. There was also a significant difference in eccentricity: $F(1, 16) = 49.63, p < .001, \eta_p^2 = .76$. The response

was generally faster for the central items relative to the peripheral items. However, there was no interaction, $F(1, 16) = 2.54, p = .13, BF_{incl} = 1.78$. A second two-way repeated-measures ANOVA on Accuracy with the factors of reward and eccentricity in Exp.2B revealed that the accuracy was higher in the high-reward as compared to the low-reward condition, $F(1, 16) = 1.08, p = .31, \eta_p^2 = .06$. There was a significant difference in eccentricity: $F(1, 16) = 7.24, p < .05, \eta_p^2 = .31$. There was no interaction, $F(1, 16) = 0.04, p = .84, BF_{incl} = .30$.

Table S3

Mean Correct Reaction Times (RTs) and Mean Accuracies for the Target Conditions of Experiment 2 Training phase

Condition	Exp.2A		Exp.2B	
	RT(ms)	Accuracy(%)	RT(ms)	Accuracy(%)
High Reward Color				
Eccentricity 1	649.8± 111.2	93.0±4.9	659.3±113.2	93.49±3.3
Eccentricity 2	704.8±120.3	91.1±5.7	697.2±117.5	91.66±4.5
Low Reward Color				
Eccentricity 1	692.4± 122.2	91.7±6.2	688.2±94.2	92.36±4.0
Eccentricity 2	745.4±128.0	89.7±6.9	738.8±103.2	90.8±4.4

The mean RTs and correspondent accuracies for the test phase are listed in Table S4. A two-way repeated-measures ANOVA on the mean RTs with the factors of distractor color (high/low reward) and eccentricity in Exp.2A revealed RT was significantly faster when the target was in the central areas, $F(1, 18) = 11.65, p < .005, \eta_p^2 = .39$. There was no significant difference in the high/low-reward distractor color, $F(1, 18) = 0.06, p = .80, BF_{incl} = 0.22$, or the interaction, $F(1, 18) = 0.06, p = .80, BF_{incl} = 0.25$. A second two-way repeated-measures ANOVA on the mean RTs with the factors of distractor color (high/low reward) and eccentricity in Exp.2A revealed no significant differences in the main factors, distractor color $F(1, 18) = 0.19, p = .67, BF_{incl} = 0.24$, eccentricity $F(1, 18) = 2.48, p = .13, BF_{incl} = 0.66$, or the interaction, $F(1, 18) = 3.15, p = .09, BF_{incl} = 0.25$.

A two-way repeated-measures ANOVA on the mean RTs with the factors of distractor color (high/low reward) and eccentricity in Exp.2B revealed RT was significantly faster when the target was in the central areas, $F(1, 16) = 9.28, p < .01, \eta_p^2 = .37$. There was no significant difference in the high/low-reward distractor color, $F(1, 16) = 0.0005, p = .98,$

$BF_{incl} = 0.40$, or the interaction, $F(1, 16) = 7.66, p = .80, BF_{incl} = 1.01$. A second two-way repeated-measures ANOVA on the mean RTs with the factors of distractor color (high/low reward) and eccentricity in Exp.2B revealed a significant difference in distractor, $F(1, 16) = 5.37, p = .03, \eta_p^2 = 0.25$, but there was no significant difference in eccentricity $F(1, 16) = 0.02, p = .90, BF_{incl} = 0.19$, or the interaction, $F(1, 16) = 0.95, p = .34, BF_{incl} = 0.13$.

Table S4

Mean Correct Reaction Times (RTs) and Mean Accuracies for the Target and Distractor Conditions of Experiment 2 Test phase

Condition	Exp.2A		Exp.2B	
	RT(ms)	Accuracy(%)	RT(ms)	Accuracy(%)
Distractor absent				
Target Eccentricity 1	1191.8±101.8	87.7±11.3	1211.2±135.3	89.2±6.9
Target Eccentricity 2	1254.0± 114.9	91.7±5.8	1269.3±156.6	91.3±8.0
Distractor High Reward				
Target Eccentricity 1	1211.3±98.9	89.9±8.3	1230.6±140.4	88.2±6.7
Target Eccentricity 2	1254.1±123.1	90.5±7.4	1252.5±176.5	89.5±8.5
Distractor Low Reward				
Target Eccentricity 1	1212.5± 121.2	88.8±7.1	1204.7±155.3	90.8±6.1
Target Eccentricity 2	1249.5±113.9	92.9±6.3	1277.9±152.6	89.9±9.6

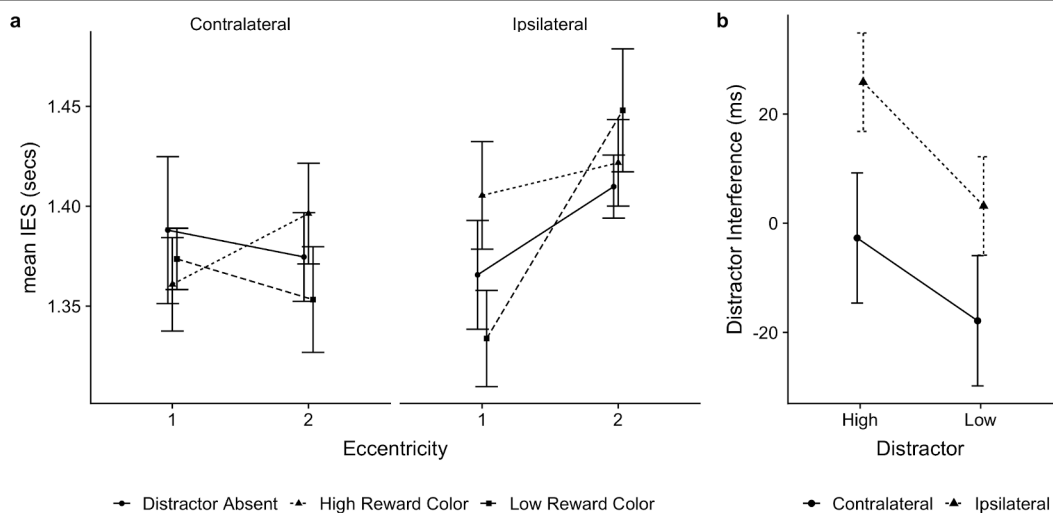


Figure S2. Results from the test phase of Experiment 2. (a) Mean IES as a function of target eccentricity, for the three distractor conditions (distractor absent, high-, low-reward-associated distractor) separately for the contralateral (Experiment 2A) and ipsilateral (Experiment 2B) placement of the target and distractor. (b) Distractor interference (relative to the distractor baseline) as a function of reward associated with the distractor, separately for the contra- and ipsilateral conditions. Error bars depict the mean within-subject standard errors.

2.6.3 Supplementary 3: RT and Accuracy analyses for Experiment 3.

The mean RTs and correspondent accuracies for the training phase are listed in Table S5. A two-way repeated-measures ANOVA on the mean RTs with the factors of reward and eccentricity revealed RT was significantly faster in the high-reward relative to the low-reward condition, $F(1, 19) = 27.33, p < .001, \eta_p^2 = .59$. There was also a significant difference in eccentricity: $F(1, 19) = 72.43, p < .001, \eta_p^2 = .79$. The response was generally faster for the central items relative to the peripheral items. However, there was no interaction, $F(1, 19) = 0.29, p = .60, BF_{incl} = 1.14$. A second two-way repeated-measures ANOVA on accuracy with the factors of reward and eccentricity revealed that the accuracy was higher in the high-reward compared to the low-reward condition though not significant, $F(1, 19) = 1.38, p = .26, BF_{incl} = 0.42$. There was no significant difference in eccentricity: $F(1, 19) = 3.7, p = .07, BF_{incl} = 0.63$, or interaction, $F(1, 19) = 1.21, p = .29, BF_{incl} = 0.26$.

Table S5

Mean Correct Reaction Times (RTs) and Mean Accuracies for the Target Conditions of Experiment 3 Training phase

Eccentricity	RT(ms)		Accuracy(%)	
	High Reward	Low Reward	High Reward	Low Reward
1	675.4±70.3	734.8±86.1	94.0±8.8	93.7±5.9
2	725.3± 77.4	787.0±94.4	93.5±9.3	92.0±8.1

The mean RTs and correspondent accuracies for the test phase are listed in Table S6. A two-way repeated-measures ANOVA on the mean RTs with the factors of reward and eccentricity revealed a significant difference in eccentricity, $F(1, 19) = 32.69, p < .001, \eta_p^2 = .63$. There was no significant difference in distractor condition (high, low),

$F(1, 19) = 0.21, p = .65, BF_{incl} = 0.28$, or the interaction, $F(1, 19) = 1.65, p = .22, BF_{incl} = 0.51$. A second two-way repeated-measures ANOVA on the mean accuracies with the factors of reward and eccentricity revealed accuracy was lower for high-reward distractor color, $F(1, 19) = 9.85, p < .01, \eta_p^2 = .34$. There was no significance in eccentricity, $F(1, 19) = 0.93, p = .35, BF_{incl} = 0.39$, or the interaction, $F(1, 19) = 0.57, p = .46, BF_{incl} = 0.31$.

Table S6

Mean Correct Reaction Times (RTs) and Mean Accuracies for the Target and Distractor Conditions of Experiment 3 Test phase

Eccentricity	RT(ms)			Accuracy(%)		
	Absent	High	Low	Absent	High	Low
1	875.2±150.9	903.4±165.4	885.6±157.6	98.1±2.6	96.6±3.6	98.5±3.0
2	953.0±150.5	966.1±164.3	976.2±169.1	95.6±6.1	96.1±5.3	97.3±4.0

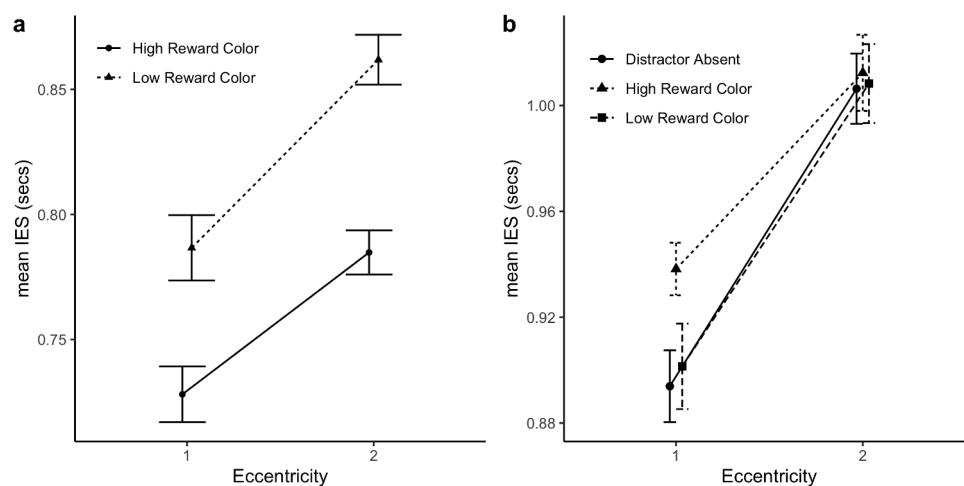


Figure S3. Results from Experiment 3. (a) Mean IES as a function of target eccentricity in the training phase, separated for the high- and low-reward-associated color targets. (b) Mean IES as a function of target eccentricity in the test phase, separately for the different distractor conditions (distractor absent, high-, low-reward-associated distractor). Error bars depict the

mean within-subject standard errors. See the numbers 1 and 2 in Figure 7 for the two possible target eccentricities.

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3 Reward-based task-association vs. feature-association in visual search

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3.1 Abstract

Our attention is strongly influenced by reward association. A reward-associated but task-irrelevant feature has been shown to interfere with ongoing visual search, and the interference could last for a relatively long period. However, previous studies on the reward association used mainly color features (e.g., red or green) for associative learning. It is unknown whether the reward association would be established not only at the feature, but also the task or response level if the reward mapping coexists at these levels. Here we conducted two experiments. In Experiment 1, we associated high/low rewards to two colors as well as to the left/right responses. We found the presence of previously high-reward associated distractors facilitated visual search, suggesting a better distractor handling with the high relative to low reward. In Experiment 2, we associated high/low rewards to two colors and task-sets (presence/absence) and used a pre-cue for response to avoid response mapping. And we found the reward was associated with the task-set, which facilitated search performance for the high-reward task relative to the low-reward task. Our findings suggest that reward-associated learning facilitated distractor handling and task-set learning.

keywords: reward association, reward mapping, feature-reward-association, task-set reward-association.

3.2 Introduction

External reward elicits strong motivation, capturing attention towards the rewarded item. Through associative learning, attention can be biased to the feature or dimension that is associated with the rewarded item. For example, Della-Libera and Chelazzi (2009) showed that selection or ignoring specific visual objects appears to be strongly biased by the past rewarding consequence of that object. Similarly, using the priming of the pop-out paradigm, Kristjánsson and colleagues (2010) found that reward schedules not only led to better performance overall for the more rewarding target color but also increased inter-trial priming for successive repetition. Using a modified additional singleton task, Anderson et al. (2011a) showed that after reward-feature association, distractors with the high-rewarded feature are more likely to capture attention than distractors with the low-rewarded feature. In Anderson's paradigm, participants first learned to associate two target colors to the high and low reward respectively using the standard compound search task - to search for a color-defined circle and to discriminate the orientation of the bar in it. In the test phase, the search task changed to a shape-defined compound search, while the previously reward-associated color feature became one of the task-irrelevant distractors. They showed that the presence of the reward-associated distractor hindered the performance, and the distractor interference was more marked with the presence of the high-value distractor relative to the low-value distractor. This has been termed as the value-driven attentional capture effect.

In most of the reward-related studies (Anderson et al., 2011a, 2011b; Bucker et al., 2015; MacLean et al., 2016; Roper et al., 2014), high/low reward is mapped to a feature of the target (e.g., color). For example, a particular color (e.g., red) is associated with high reward and another color (e.g., green) with low reward in high probability (usually 80%). With such reward-feature associative learning, it has been shown that the association is not bound to the rewarded object (Yantis et al., 2012). The color-reward association learned from a visual search task with circle items could be transferred to color letters in a flank task (Yantis et al., 2012). A flanking letter with formerly high-reward relative to low-reward color caused more compatibility effect (measured by the RT difference between the flank-central response compatible vs. incompatible conditions), which suggests that the feature-based reward association can be generalized and extended to different objects as far as the reward-associated feature remained. In another study, Lee and Shomstein (2014) further asked if feature-based reward association learned from a bottom-up pop-out search task could be transferred to a top-down oriented compound search task. If this is the case, it would

suggest that reward association occurs at the priority map. In their study, they used the orientation pop-out search task (horizontal vs. vertical line) for the reward-association training phase, in which one of the targets (either horizontal or vertical) was associated with the high reward. In the test phase, they tested with a color-orientation compound search task, in which the target was defined as ‘red horizontal’ or ‘red vertical’. And they found high-reward orientation indeed facilitated the compound search, suggesting the bottom-up reward-association can be transferred to top-down attentional guidance. Interestingly, though, when the high-reward associated orientation appeared in distractor items, the compound search remained facilitated, which is at odds with the value-driven attentional capture effect reported by other groups (Anderson et al., 2011b). Lee and Shomstein (2014) argued that the facilitation effect came from effective distractor filtering - high-reward distractors can be effectively filtered out.

However, two questions remain unsolved: firstly, in Lee and Shomstein’s (2014) study, the training and test phases shared the same feature-reward and task-set reward association (Horizontal vs. Vertical in the training, and red horizontal vs. red vertical training in the test). The transfer effect might also be benefited from the same task-set association, which has not been fully dissociated. Importantly, this task-based association has been neglected in most of the aforementioned studies. In real environments, reward associations may not always be unique. A good performance receives not only applause but also flowers. Multiple reward remapping coexists and may as well compete with each other. Thus, it is important to distinguish how feature-based and task-based reward-association are formed (and/or compete with each other) in such tasks. Secondly, the facilitation of the presence of high-reward distractors might also result from general arousing or motivational enhancement. The presence of the reward-associated feature, even in distractors, may motivate participants for fast responses. This alternative cannot be fully ruled out.

To address those questions, we designed a study that the reward association is mapped for the feature-based as well as the task-based association in the training phase. In the test phase, the formerly reward-associated colors became the feature of one distractor, but the task-set remained the same. Crucially, we included the absence of the reward-associated distractor, which allowed us to distinguish the influences of the two associations. If the feature-based reward association is dominant and captures attention according to Anderson et al. (2011a), the presence of a reward-associated distractor could impede the main search task. However, if a reward-based distractor enables effective distractor filtering according to Lee and Shomstein (2014), one may expect a facilitation effect. We hypothesize that if reward is

associated with the task-set, facilitation of reward-choice would remain in the distractor absence condition. By contrast, if the reward effect is merely a bottom-up feature-based, one would expect similar distractor interference as reported early (e.g., Anderson et al., 2011a). On this ground, we conducted two experiments. In both experiments, high and low rewards were mapped to two distinct colors respectively. In addition, the high/low reward was mapped to the left/right discrimination in Experiment 1, and the task-set (i.e., target presence/absence) in Experiment 2.

3.3 Experiment 1

3.3.1 Methods

Participants

24 participants (12 females, mean age 26.5, all 18-35 years old) took part in this experiment. All had a normal or corrected-to-normal vision and were naive to the purpose of the experiment. The sample size was determined based on previous reward-driven visual search studies (Asgeirsson & Kristjánsson, 2014; Lee & Shomstein, 2014), aiming for 80% power to detect a relatively large effect size ($f = 0.65$) in a repeated-measures analysis of variance with an alpha level of .05. Power estimates were computed using online WebPower (<http://webpower.psychstat.org>). All participants gave informed consent before the experiment, and they received 9 Euro/hour for their participation, plus an extra reward bonus (maximum of 3 Euros) earned during the experiment. The study was approved by the ethics board of LMU Department of Psychology.

Stimuli and apparatus

The experiment was carried out in a dim experimental room. Stimuli were generated by Psychophysics Toolbox (Kleiner et al., 2007) based upon customized code of Matlab (The MathWork Inc), and were presented on a CRT monitor (screen resolution of 1600 x 1200 pixels; refresh rate of 85 Hz). Participants were seated at a viewing distance of about 57 cm from the monitor.

The visual search display consisted of 27 bars, arranged around three invisible concentric circles. The search display subtended approximately $10^\circ \times 10^\circ$ of visual angle and each bar had a size of $0.9^\circ \times 0.2^\circ$. The turquoise-colored vertical bars were distractors. A pop-out target, defined by one feature (color in the training session, and orientation in the test session). The target in the training phase and a pop-out distractor (if present) in the test phase were always located in the middle invisible circle (see Figure 1).

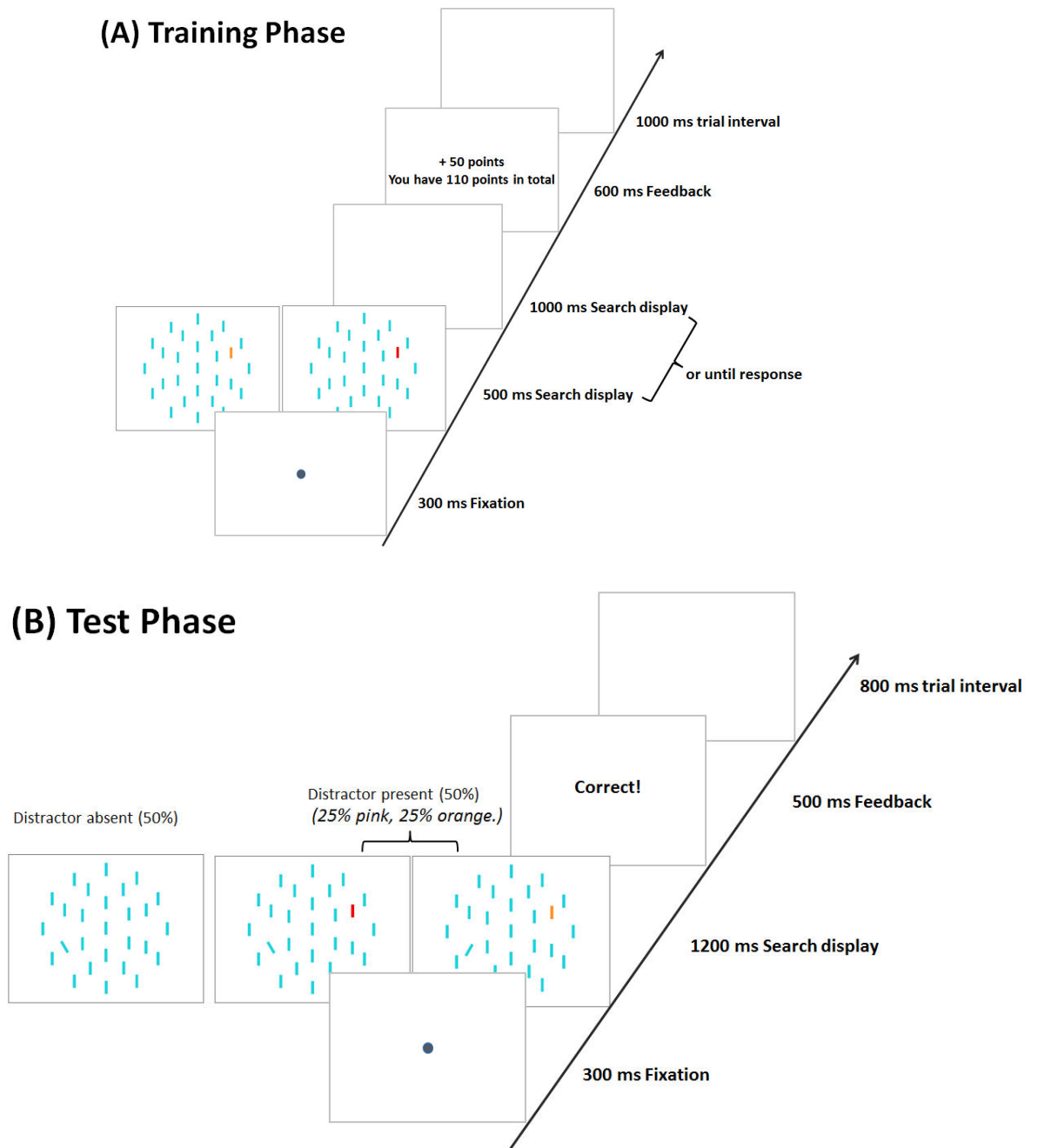


Figure 1. (A) A schematic illustration of the search paradigm used in the training phase. A trial started with a fixation point presented for 300 ms, followed by a search display for 500 ms or till a response (maximally 1500 ms). Immediately after the response, a feedback display with the bonus points was presented for 800 ms. After an inter-trial interval of 1000 ms, the next trial began. (B) A schematic illustration of search displays used in the test phase. A trial started with a fixation point presented for 300 ms, followed by a search display for 1500 ms or till a response. Then a feedback display with the response accuracy was presented for 500 ms. After an inter-trial interval of 800 ms, the next trial began.

Design and Procedure

The experiment consists of the training and test phases. The training phase was a pop-out search, in which the target was either pink or orange, among turquoise distractors. A training trial started with a fixation presented for 300 ms, followed by a search display for 500 ms. Participants were required to respond as quickly and accurately as possible if a target was pink or orange, using the left and right arrow keys. The target colors (pink, orange) were equally likely. And the color-response mapping was fixed for each participant, but randomized across participants. The search display disappeared and turned to blank after 500 ms, but participants had an additional 1000 ms period to give a response. Immediately after the response, a feedback display was presented for 600 ms. The feedback included the rewarded points the participant gained for the current trial and the total rewarded points that the participant had accumulated. The next trial began after an inter-trial interval (ITI) of 1000 ms (see Figure 1A).

The high/low reward assignments to the colors (either Pink or Orange) were randomized across participants but fixed within each participant. In the high-reward condition, 80% of the trials were associated with a 50-point high reward and 20% of the trials were associated with a 10-point low reward. In the low-reward condition, the probabilities of high and low reward were 20% and 80% respectively. Participants had a chance to earn their reward when they made a correct answer.

The test phase used the singleton distractor search task, in which the search display consisted of an orientation-defined target (oriented to left or right). In half of the trials, there was an additional color singleton distractor, whose color was previously associated with rewards (Figure 1B). The color of the singleton distractor was either pink or orange (equally likely) in the distractor presence trials. A trial in the test phase started with a 300 ms fixation display, then a search display was shown for a maximum of 1200 ms or until a response was made, followed by a 500 ms display with the feedback “correct!” or “Incorrect!”. There was a blank screen for 800 ms before the next trial started. The task was to identify if the titled bar was oriented to left or right while ignoring the color distractor singleton. Unlike the training phase, there was no reward associated with the correct responses.

We used the full-factorial within-subject design. That is, the color of the target (pink vs. orange) was all equally tested in the training phase, which consisted of 10 blocks with each block of 80 trials. The combinations of the target and the singleton distractor were also equally tested in the test phase with 8 blocks of each 32 trials. The total experiment lasted

about one hour. In the end, participants received a bonus (maximum three euros) according to the points they earned during the experiment.

Statistical and Bayes-factor analysis

Given that speed-accuracy trade-off (SAT) may vary unpredictably within or across participants (Liesefeld & Janczyk, 2019; Luce, 1986; Pachella, 1973; Townsend & Ashby, 1983), we evaluated speed and accuracy together using inverse efficiency score (IES, see Townsend & Ashby, 1983), which is the most common method for correcting speed-accuracy trade-off. The IES is calculated as the quotient of the mean reaction time (RT) divided by the percentage of correct responses (PC):

$$IES = RT/PC.$$

Accordingly, IES scores keep the same unit as the RTs (ms). Thus, IES scores can be thought of as error-adjusted RTs.

Repeated-measures ANOVAs and Bayesian analyses of variance (ANOVAs) were performed using JASP 0.10 (<http://www.jasp-stats.org>) with default settings (i.e. r-scale fixed effects = 0.5, r-scale random effects = 1, r-scale covariates = 0.354). Inclusion Bayes factors compare models with a particular predictor to models that exclude that predictor, providing a measure of the extent to which the data support inclusion of a factor in the model. Bayesian t-tests were performed using the `ttestBF` function of the R package “BayesFactor” with the default setting (i.e., `rscale = “medium”`). Mixed-model ANOVA was performed using the R package “lme4” in R studio.

3.3.2 Results

Trials with extreme RTs that exceeded the three standard deviations of individual means were excluded for further analyses. Due to the large variation in RTs in the first trial of each block, they were also excluded for further analyses. In total, for RT analysis, 4.3% of trials were removed in the training, and 3.3% of trials were removed in the test phase.

Training phase

Figure 2 depicts the mean IESs for the high and low rewards. A one-way repeated-measures ANOVA with the factor of Reward on the mean IESs failed to reveal any significances of reward assignment, $F(1, 26) = 1.65, p = .21, BF_{incl} = 0.54$. The non-significant speeded responses may suggest that the difference between the low and high reward manipulations may be relatively weak. However, this did not rule out the potential reward association. Similar non-significant associations have also been reported in previous studies (Anderson &

Yantis, 2013; e.g., Kim & Anderson, 2020; Sali et al., 2014). For example, Anderson et al. (2011a) found equally fast responses to the high and low reward targets during the training phase.

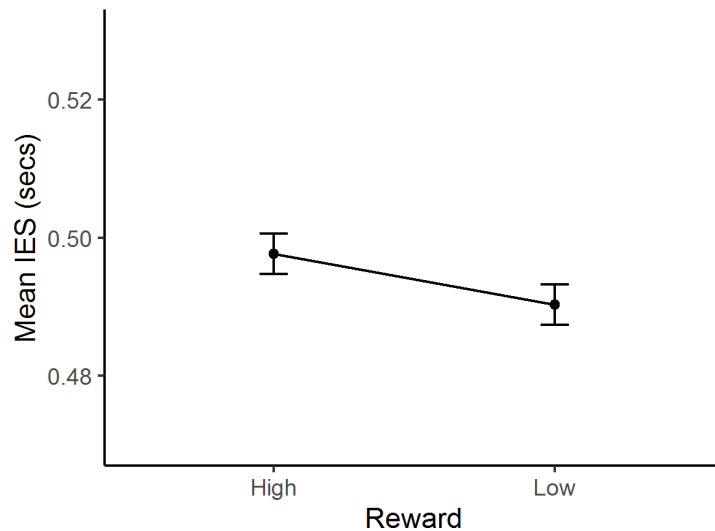


Figure 2. Mean IES as a function of the reward color in the training phase of Experiment 1. Error bars indicate within-subject one standard error.

Test phase

In the test phase, the task was changed to the orientation discrimination and the additional singleton distractor with the previously reward-associated color. Figure 3 depicts the mean IESs as a function of the type of distractor, separated for the reward-response mapping. A two-way repeated-measures ANOVA with Distractor and Response Mapping revealed a significant effect of Distractor, $F(2, 52) = 4.85$, $p = .01$, $\eta_p^2 = .16$, but neither for Response Mapping, $F(2, 26) = 0.02$, $p = .89$, $BF_{incl} = 0.14$, nor for the interaction between Distractor and Response Mapping, $F(2, 52) = 1.95$, $p = .15$, $BF_{incl} = 0.14$. Post-hoc analysis on Distractor Type revealed that the mean IES was faster in the high-reward relative to the low-reward conditions, $p = .0018$.

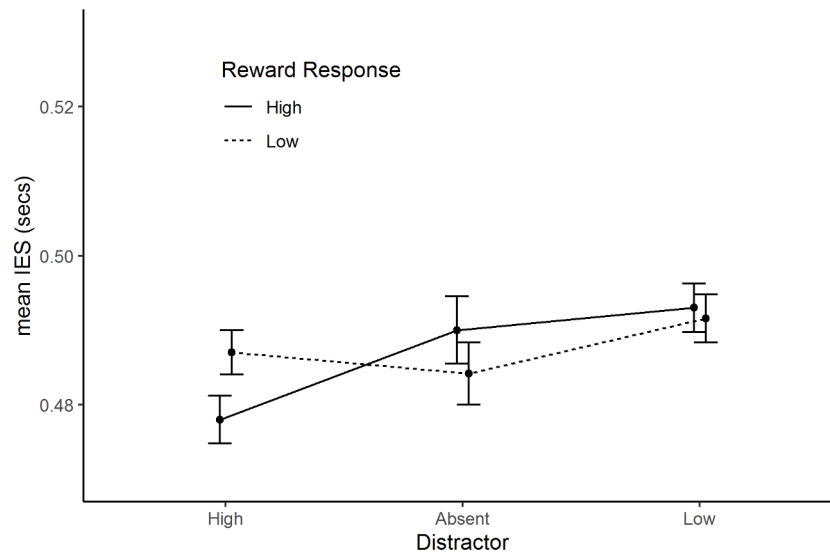


Figure 3. Mean IES as a function of the distractor reward color, separated for the rewarding response of the test phase. The error bar indicates one within-subject standard error.

3.3.3 Discussion

In Experiment 1, we trained participants to associate the target colors (pink and orange) to either high or low reward. The reward association was also fixed for the response mapping within each participant. To examine at which level that the reward association occurred, we changed the search task to the orientation task in the test phase, and the reward-associated color was assigned to the distractor singleton. We hypothesized that if the reward-association occurred at the feature level, we should observe similar distractor interference that was reported previously (Anderson et al., 2011a; Yantis et al., 2012). Alternatively, if the reward association took place at the task-set response level, we should observe facilitation at the rewarded response. However, our results neither support the distractor interference nor the response facilitation to the high-reward response. This, at the first glance, is rather puzzling. Yet, the facilitation of the presence of high-reward associated distractors is consistent with the previous finding (Lee & Shomstein, 2014). Lee and Shomstein (2014) argued that the reward association increased the efficiency of distractor rejection, rather than distractor inference. In addition to the efficient distractor handling, the reward-associated motivational effect may also play a role. The preattentive processing of the presence of high-reward features in the display may motivate participants to respond, thus facilitating the performance in general.

The absence of the reward association to the motor response suggests that the reward does not promote pure motor priming. This, however, does not rule out that the reward association could take place at the task level. In the present study, the task in the training session was the discrimination between two colors, while the task in the test session was the discrimination between two orientations. The change of the task set might impede the transfer of the task-level reward association. To investigate if the task-set association is possible, we conducted Experiment 2, in which the task set remained the same across the training and test sessions.

3.4 Experiment 2

3.4.1 Methods

Participants

24 participants (12 females, mean age 26.5, all 18-35 years old) took part in this experiment. All had a normal or corrected-to-normal vision and were naive to the purpose of the experiment. The sample size was determined based on previous reward-driven visual search studies (e.g., Lee & Shomstein, 2014), aiming for 80% power to detect a relatively large effect size ($f = 0.65$) in a repeated-measures analysis of variance with an alpha level of .05. All participants provided written informed consent before the experiment and were paid at a rate of 9 Euro/hour, plus an extra reward bonus (maximum of 3 Euros) earned during the experiment. The study was approved by the Ethics Board of the LMU Munich Faculty of Pedagogics and Psychology.

Stimuli and apparatus

The experiment was carried out in a dark experimental room. Stimuli were generated by Psychophysics Toolbox (Kleiner et al., 2007) based upon Matlab (The MathWork Inc), and were presented on a CRT monitor (screen resolution of 1600 x 1200 pixels; refresh rate of 85 Hz). Participants were seated at a viewing distance of 57 cm from the monitor.

The search display consisted of 27 bars, arranged around three invisible concentric circles. The search display subtended $10^\circ \times 10^\circ$ of visual angle and each bar had a size of $0.9^\circ \times 0.2^\circ$. The turquoise-colored vertical bars were distractors. A pop-out target, defined by one feature (color in the training session, and orientation in the test session). The target, if presented, was always located in the middle invisible circle (see Figure 4).

Design and Procedure

Although the reward-response mapping failed to show any significance in Experiment 1, we could not rule out the potential impact. Thus, we introduced a random swapping stimulus-response (S-R) mapping cue before the search display to effectively rule out any potential confounding from the reward-response mapping due to motor enhancement. In the cue display, two letters “A” (for the target absence) and “P” (for the target presence) were randomly presented one on the left and one on the right (Figure 4) to indicate which hand to respond to which choice. To obtain baseline responses without reward, the experiment consists of two sessions, with no reward manipulation in Session 1 (i.e., baseline) and with the reward manipulation in Session 2. Session 2 was tested one week after Session 1. Both sessions consisted of a training phase and a test phase.

The training phase was a pop-out search, in which the target was either green or pink, among turquoise distractors. A training trial started with a fixation presented for 300 ms, followed by an S-R mapping cue display (either ‘PA’ or ‘AP’) for 600 ms. Immediately after the cue display, the search display was shown for 800 ms. Participants were required to respond as quickly and accurately as possible if a target was presented, using the left and right arrow keys according to the S-R mapping. The target presence and absence were equally likely. Immediately after the response, a feedback display was presented for 600 ms. In Session 1, the feedback was only ‘correct’ or ‘incorrect’ information. In Session 2, in addition to the correct/incorrect information, the feedback included the reward the participant gained for the current trial and the total reward that the participant had accumulated. The reward was given in the form of points. After an inter-trial interval (ITI) of 800 ms, the next trial began (see Figure 4A).

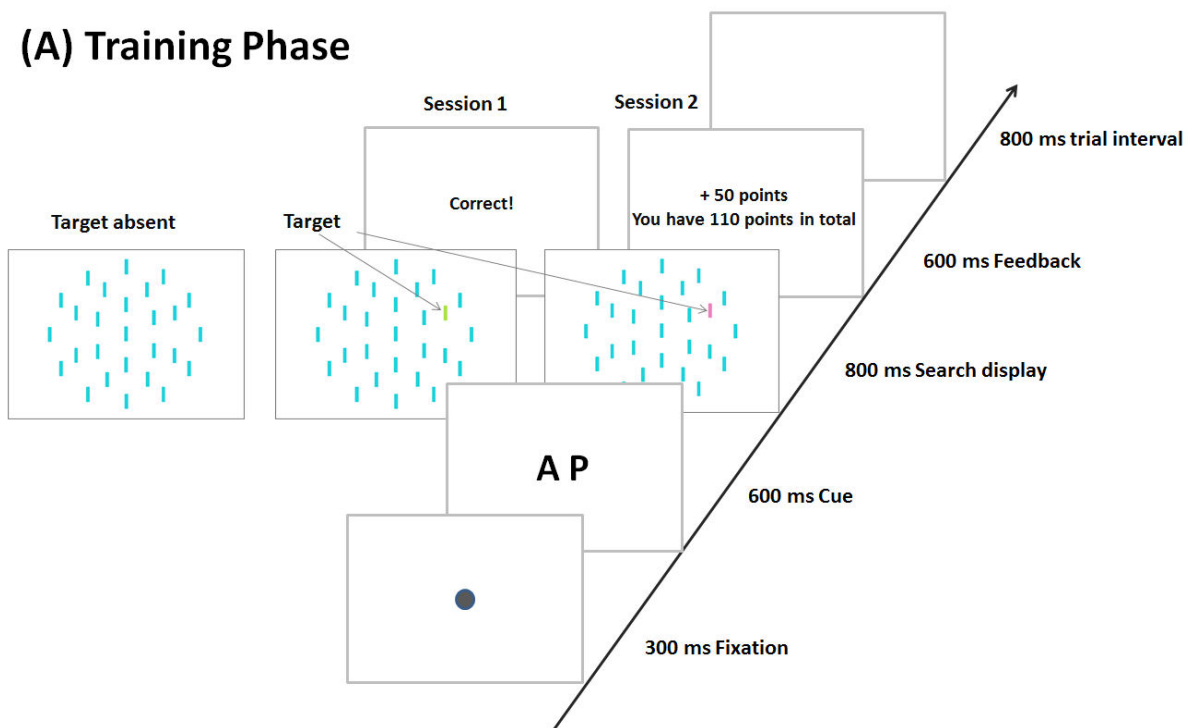
Participants were randomly assigned to one of the two groups in the training phase of Session 2: the high-reward-to-present group (High/Present) and the high-reward-to-absent group (High/Absent). For the High/Present group (14 participants), the high reward was associated with the target presence with a high probability of 80%. That is, when the target was present and correctly identified, participants had an 80% chance to get 50 points reward, while a 20% chance to earn 10 points. For the High/Absent group (10 participants), the target absence was associated with high reward (50%) with a probability of 80%, and 20% with low reward (10%).

The test phase used the singleton distractor search task, in which the search display consisted of an orientation-defined target, and a possible (50% of the test trials) color-defined

singleton distractor (Figure 4B). The color of the singleton distractor was previously associated with the target color in the training phase (i.e., pink or green, each of 50%). The trial procedure was the same as in the training phase, except that the search display was shown for a maximum of 1500 ms (The display was off immediately when participants made a response within 1500 ms). The task was to identify if there was a titled bar or not while ignoring the color distractor singleton. Unlike the training phase, there was no reward associated with the correct responses.

The combination of the S-R mapping ('AP' vs. 'PA'), the singleton distractor (presence vs. absence), and the target (presence vs. absence) were all equally tested in a randomized fashion. To make the inter-trial switch and repetition equally likely, we used the De Bruijn sequence generator (Brimijoin & O'Neill, 2010; de Bruijn, 1946) to generate trial sequences. The training phase consisted of 15 blocks, each block of 65 trials, and the test phase 6 blocks, with each of 65 trials. The training phase lasted about one hour and the test phase about 20 minutes. In the end, participants received a bonus of between 0 and 3 Euros according to the points they earned in the training phase.

(A) Training Phase



(B) Testing Phase

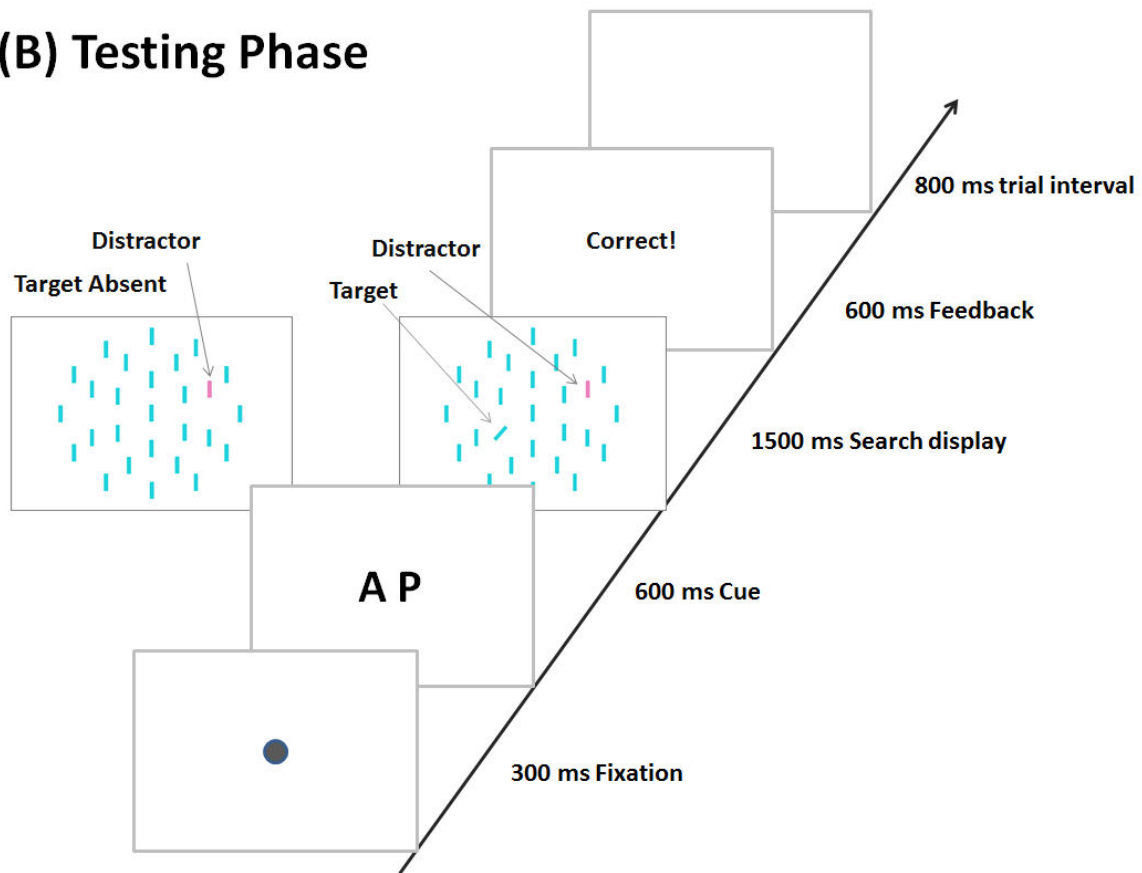


Figure 4. (A) A schematic illustration of the search paradigm used in the training phase. A trial started with a fixation point presented for 300 ms, followed by an S-R mapping cue for 600 ms. The search display was then shown for 800 ms or till a response was made. Immediately after the response, a feedback display was presented for 600 ms, indicating the response accuracy (Session 1) or rewarded points. The inter-trial interval (ISI) was 800. (B) A schematic illustration of search displays used in the test phase. A trial started with a fixation point presented for 300 ms, followed by an S-R mapping cue display for 600 ms. Immediately after the cue display, the search display was shown for 1500 ms or till a response was made. Then a feedback display of the response accuracy was shown for 600 ms. The next trial started after an ISI of 800 ms.

3.4.2 Results

Trials with extreme RTs (outside of 3 standard deviations of individual means) were excluded for further analysis. Also, the first trial of each block was excluded for further analysis due to a large variation in RTs. In total, 9.8% and 2.8% of the trials were removed in the training and the test phase in Session 1 respectively, and 9.1% and 2.9% in Session 2 respectively. The relatively higher exclusion for the training as compared to the test session was mainly due to the short exposure time of the search display in the training session (800 ms) relative to the test session (1500 ms).

Training phase

The mean IESs of the training sessions are shown in Figure 5. By visual inspection, mean IESs were slower for the None-reward assignment (Session 1) relative to the reward assignment (Session 2). This could be the result of reward assignment as well as the procedural learning effect. Interestingly, the reward association had differential impacts on the mean IESs (Session 2). A mixed-modals ANOVA with the between-subject factor of Reward and the within-subject factors of Target Presence and S-R mapping Cue on the mean IESs revealed a significant reward manipulation [$F(2, 49.58) = 30.36, p < .001$], and a significant cueing effect [$F(1, 24.17) = 6.79, p < .05$], but not for the target presence, [$F(1, 38.1) = 0.05, p = .81$]. The high reward-associated task (either Absence or Presence) was faster than the low reward-associated task. The S-R mapping of ‘AP’ was in general faster than the S-R mapping of ‘PA’. This could be due to the S-R mapping ‘AP’ relative to the ‘PA’ is semantically more compatible. There were no significant interactions, all $ps > .05$.

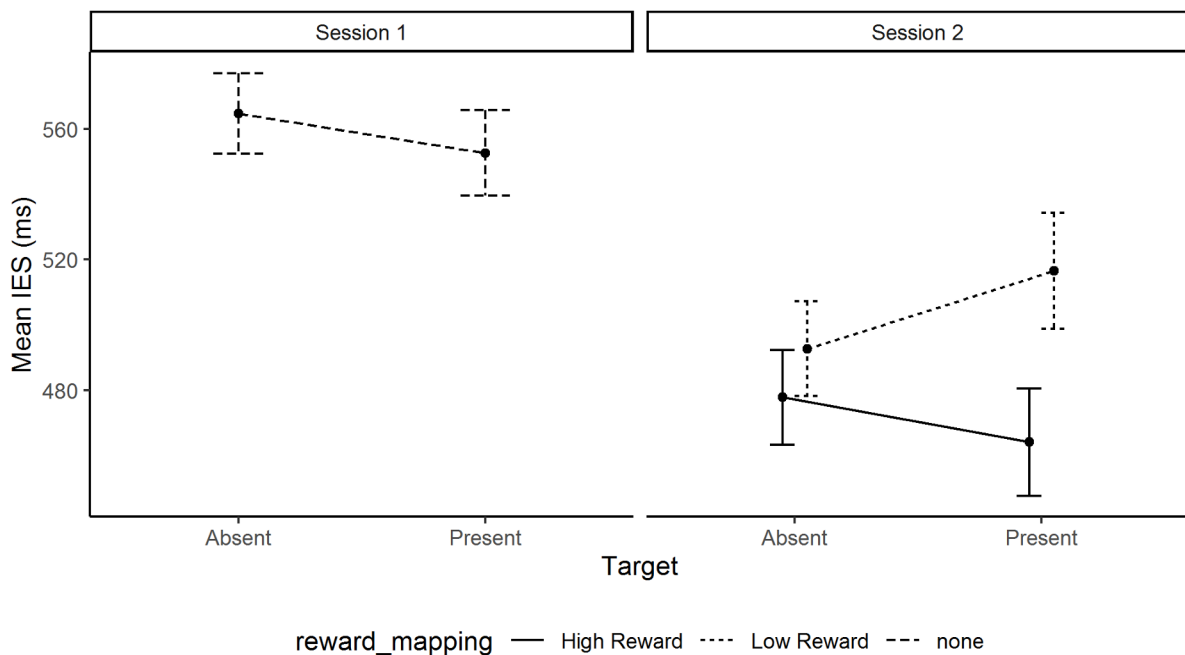


Figure 5. Mean IES as a function of the target present in the training phase, separate for reward mapping and two sessions of Experiment 2. The error bar indicates one within-subject standard error.

Given that we were interested in the reward-association, we further conducted a repeated-measures ANOVA for Session 2 with the main factor of reward and found it was

significant between the high-reward and low-reward mapping [$F(1,22) = 18.44$, $p < .001, \eta_p^2 = .446$], with larger IESs for the low-reward mapping, as compared to the high-reward mapping (see Figure 5). This suggests that reward association was more marked when the pop-out features were presented and likely being associated as well. There was no significant difference between the target presence and absence, and no interaction between reward assignment and target presence (all $ps > 0.1$). In short, the reward manipulation worked in the direction as we expected in the training session.

Test phase

In the test phase, the task was changed to detect the presence of the orientation target while ignoring the pop-out color singleton distractor. Here we were interested in how the reward association influenced the target detection. Thus, we averaged the mean IESs for each combination of the distractor presence and the target presence over three reward assignments (i.e., no reward in Session 1, the target-present/high-reward, and the target-absent/high-reward in Session 2). Figure 6 depicts the mean IESs as a function of the target presence, separated for the distractor presence and reward assignments.

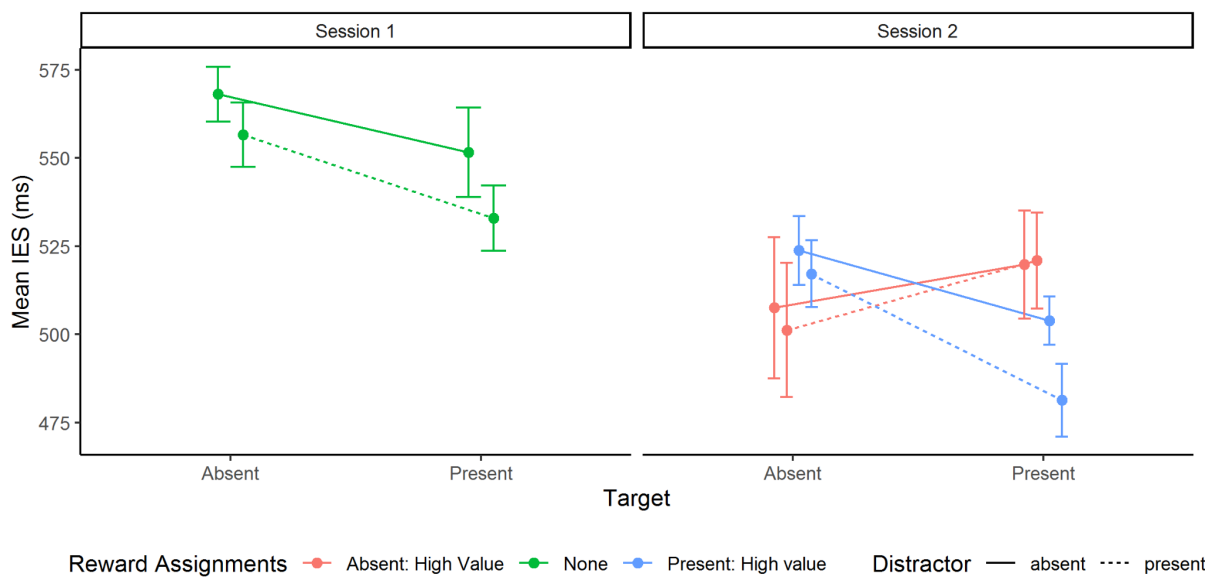


Figure 6. Mean IES as a function of the target presence, separated for the distractor presence and reward assignments in Sessions 1 and 2 of Experiment 2. The error bar indicates one within-subject standard error.

As the non-reward was first assigned in Session 1, while the reward was assigned in Session 2, we conducted repeated-measures ANOVAs separately to exclude the potential learning effect across the sessions. A two-way repeated-measures ANOVA with Target

(presence/absence) and Distractor (presence/absence) as the main factors for Session 1 revealed the main effect of Distractor (presence/absence) to be significant [$F(1, 23) = 4.29, p = .0498, \eta_p^2 = .16$], but neither the main effect of Target (presence/absence) nor the interaction between Distractor (presence/absence) and Target (presence/absence) was significant (Target: $F(1, 23) = 2.31, p = .14, BF_{incl} = 1.28$; interaction: $F(1, 23) = 0.63, p = .43, BF_{incl} = 0.34$). In contrast to the attentional capture in the additional singleton paradigm, the presence of the additional singleton distractor facilitated the target detection, a similar finding has been shown in a previous study (Lee & Shomstein, 2014). As the previous study showed that the target history may induce a similar effect as the reward manipulation (Sha & Jiang, 2016), the familiarity of the identity of the distractor, which was the target in the training phase, could potentially help a fast distractor rejection in the test phase (Lee & Shomstein, 2014).

We further examined the influence of reward-association in Session 2 with a three-way repeated-measures ANOVA with Target (presence/absence), Distractor (presence/absence), and Reward Assignment as the main factors, revealed an only significant interaction between Target (presence/absence) and Reward Assignment [$F(1, 22) = 5.12, p < .05$], but neither for the other main factors (all $ps > .1$) nor for the other two-way or three-way interactions (all $ps > .1$). The right panel of Figure 6 shows this significant interaction. Recall that the color target in the training session became the singleton distractor in the test session. When the high reward was assigned to the presence response in the training session, the response was facilitated for the Target presence in the test session, regardless of the distractor. Similarly, when the high reward was assigned to the absence response in the training session, the response was facilitated in the target absence trials.

3.4.3 Discussion

Different from Experiment 1, here we kept the task set the same across the training and test session - a detection task, while the target identity was different between the training and test session. In the training phase of Session 2, the high reward was assigned either to the target presence (color feature) or the target absence (only at the task level). The reward mapping was fixed at the task level and the feature level within each participant. We reasoned that if the reward was associated at the feature level (i.e., color), we should observe more marked distractor interference in the presence of the distractor (i.e., in the target high-reward group),

given that the distractor color was highly salient relative to the orientation target and the color was high-reward associated. However, we observed the presence of the color singleton distractor did not hinder the response time. More interestingly, in the high-reward-to-the-absent condition, facilitation was observed in the target absence condition ('Absence' was previously associated with the high reward), regardless of the presence of the singleton distractor. The non-significant effect of the distractor presence in both groups suggests that the reward association was unlikely established at the feature level. By contrast, the significant interaction between the target and reward assignment suggests that the reward was likely established at the level of task association. Here, the high-reward task response (both the target presence or absence) was facilitated, indicating the reward-association has been transferred from the pop-out color detection task to the orientation detection task when the task-set (i.e., detection task of the presence or absence) remained unchanged. Recall that in Experiment 1, the task set was changed from the training to the test session, while the response mapping remained unchanged, there was no significant reward effect at the response level. Here we kept the task set the same, and observed the facilitation effect of the reward, suggesting reward association at the task-set level is possible, but only observable when the task set remained the same.

3.5 General Discussion

The present study set out to disentangle at which level of reward association could occur. In previous studies of reward-based attentional capture (Anderson, 2013; Anderson et al., 2011a), the reward association was often unique at the feature level (e.g., the color-reward association). Here we tested in two studies, in which the reward could be mapped to the feature and the response or the task-set during the training session. In experiment 1 two colors (pink and orange) and correspondent responses were assigned to the high or low reward in the training session, while the color became the singleton distractor color in the test phase, in which the task was to discriminate the orientation bar. We hypothesized that if there was any response-based reward association, we should observe facilitation to the high-reward response relative to the low-reward response. However, we failed to find any benefits of the response-based reward association in the test phase. By contrast, we observed the presence of the high-reward distractor facilitated the search performance, which is inconsistent with previous studies of value-based attentional capture (Anderson et al., 2011a; Mine & Saiki, 2015), but consistent with the efficient distractor filtering account (Lee & Shomstein, 2014).

The facilitation effect in Experiment 1 also suggests that the reward was likely associated with the color feature. The reward association at the task-set level remained unsettled given that the task-set was changed from color discrimination to orientation discrimination. In Experiment 2, we then kept the task-set the same throughout the training and test sessions. We found that the presence of the singleton distractor with previously rewarded color did not impact the search performance in the test session, rather the reward-based task-set showed a strong difference. The task category that was previously associated with the high reward relative to the low reward was facilitated in the test session, regardless of the presence of the distractor. Importantly, we randomly assigned the response mapping using the S-R pre-cue in each trial, effectively ruling out any reward-based motor enhancement. Thus, the facilitation of the task-based reward association was manifested in Experiment 2. Interestingly, though, like Experiment 1, we found a facilitation effect even though the distractor was present, suggesting distractor handling in our study is quite different from those studies of value-based attention capture.

3.5.1 The level of reward association: Feature, Response, and task-set

The value-based distractor interference has been found in many studies using an additional singleton paradigm (Anderson et al., 2011a; Hickey et al., 2010; Hickey & Peelen, 2015, 2017). Most of the studies, however, only trained the color reward association with unambiguous mapping. That is, the reward is unique mapped to a specific color. It has been suggested that the reward-based association boosts the bottom-up saliency, capturing attention during the search task, thus subsequently impeding the search performance (Anderson, 2013; Anderson et al., 2011a). However, it remains a question regarding whether reward association may operate at the motor-level or top-down task-set level in the additional singleton search paradigm. Studies with simple response mapping tasks (such as mapping two responses to two keys or simple pointing) have shown that reward learning can be strongly associated with response (Hamel et al., 2019; Prasad & Mishra, 2020), as reward may potentially boost long-term retention. It is scarce if response association remains in a complex search task. Here we explicitly tested this in Experiment 1 by fixing the reward-response association unchanged between the training and test sessions. However, there was little evidence that the reward was associated at the response level when the task set was changed.

The issue of whether the reward association can be transferred across different stimuli or task sets has been investigated previously. For example, Yantis et al. (2012) tested if the

color-reward association can be transferred from the shape to the letter (i.e., across stimuli) and from the training of a search task to the test of a flank task. They found that the high-reward flank distractor slowed down the identification in the response incompatible condition (i.e., a conflict between the flank and the central target) relative to the response compatible condition. Their results demonstrate that feature-based reward association can be transferred across stimuli as well as across tasks. However, the premise of Yantis et al. (2012) is feature-based reward learning. In their paradigm, the feature reward association was unique in the training session, and the same feature (i.e., color) occurred in a different identity (letter) of a different task. By contrast, in the present study, the possibility of the reward association was not unique. Both the feature and the response (Experiment 1) or the task level (Experiment 2) are possible in the training phase. Thus, the question we asked here is different from what Yantis et al. (2012) investigated. Here we focused on the level of reward association. At the abstract task-set level, we found the transfer effect of reward association only when the task set remained the same (Experiment 2), not when the content of the task was changed (Experiment 1), suggesting at the high level of task-set reward association may be rather rigid and specific. This may well be true for the feature-based reward association, given that the ‘rewarded’ feature did not change in the test phase for the most of studies. It would be interesting in future studies to test if the reward-association could be generalized from one level to another, such as from the feature (e.g., specific color) to the dimension level (e.g., a general color).

3.5.2 Reward-based distractor interference and facilitation

Reward-based learning has a profound impact on search behavior. Both facilitation and interference have been found in the literature (e.g., Anderson, 2013; Anderson et al., 2011a; Della Libera & Chelazzi, 2006; Hickey et al., 2014; Itthipuripat et al., 2019). In studies using a typical additional singleton paradigm where the additional singleton distractor with the color previously associated with reward often found the presence of the reward-associated distractor is detrimental (Anderson et al., 2011a). The main argument is that the high value of reward could boost the saliency of the distractor with the reward-associated color, thus capturing attention during the search. The argument has been supported by studies with oculomotor measures (Hickey & van Zoest, 2012; Le Pelley et al., 2015), in which distractors signaling high reward relative low reward produced greater oculomotor capture. However, whether such attentional capture occurs at the early stage is rather controversial. The study we reported in Chapter 1 using the visual-tactile setup to disassociate the early search stage

and late identification stage suggested that the reward-based distractor interference is rather at the late stage. It is not the saliency of the color being boosted, rather the range of the focused selection being dispersed during the selection stage.

The present study, however, revealed that the value-associated distractor did not induce distractor interference, rather facilitation. At the face level, it seems to contradict the distractor interference reported in the literature. However, it is important to note that one important difference of the paradigm we used here as those studies reported the distractor interference effect (including our study, Chapter 1. Li et al, 2021). Those studies that found the distractor interference used a compound search task, to search a singleton shape and then to discriminate the bar orientation in that shape. Meanwhile, the color of the singleton distractor (either diamond or circle shape, not the bar inside the shape) is set to previously rewarded color. By contrast, in our study, the reward-associated color was assigned to the distractor bar, which shared the same identity (i.e., bar) with the target orientation bar, and the task was to discriminate (Experiment 1) or to detect (Experiment 2) the oriented bar. Thus, dimension-based filtering processing (Sauter et al., 2018; Zhang et al., 2019) may play a critical role in our paradigm. Interestingly, a previous study showing a similar facilitation effect with the presence of the reward-associated distractor also assigned the rewarded feature to the distractor identity (Lee & Shomstein, 2014). In Lee and Shomstein's study (2014), the reward-associated orientation was shared across the target and the distractor in a conjunction search. The opposite effects in those studies suggest that the handling of the reward-associated distractor is rather different between the compound search task and the pop-out (or compound) search task. In the pop-out search task, effective distractor filters may rather take place at a very early stage, likely through an effective dimension filtering (e.g., filtering out high-rewarded color). In this aspect, our finding is consistent with the efficient distractor filtering account (Lee & Shomstein, 2014).

3.5.3 The role of motivation and arousal in facilitation

It is known that reward and arousal are strongly coupled (Harris & Aston-Jones, 2006). For example, the lateral hypothalamus is involved in both arousal and reward (DiLeone et al., 2003). The impact of the motivation and arousal induced by reward can not be excluded in the present study. The motivation induced by the high-reward association might contribute to the facilitation effect we found in both experiments. The high-value reward, as compared to the low-value reward, may elevate the motivational level. The learned reward association

might become respondent conditioning. As a result, the presence of the distractor is likely a reward condition, rather than distracting. This might contribute to effective distractor filtering. However, the present study did not directly measure the arousal or motivational level. The role of motivation and arousal remains unclear and speculative. Future studies are warranted to disentangle this reward-arousal coupling effect and the opposite effects of distractor handling.

3.6 Conclusion

In the present study, feature-based, response-based, and task-based reward associations have been examined in two experiments. We failed to find the response-based reward association, but feature-based and task-based associations are possible. The task-based reward association requires the same task set. Importantly, we found the presence of the reward-associated feature facilitated responses in the pop-out search, for both discrimination and detection tasks. The findings suggest that reward-associated learning facilitated distractor handling. Both effective distractor filtering and motivational respondent conditioning may contribute to efficient distractor handling.

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4 Conjunction Reward-Association in visual search

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4.1 Abstract

Previous studies have shown that reward association could be detrimental when the reward-associated feature becomes task-irrelevant. However, the reward associative learning in those studies is unique and bound to a single feature, such as color. In daily life, reward association could be complex. Up to date, it is unknown whether associative reward learning could take place with conjunction features. To explore whether the reward can be learned through conjunction reward assignments (color & shape) and whether the distractor interference could be observed in a similar way as previously reported using single feature association, we conducted a study with high/low reward assignment only distinguishable with the combination of color and shape in the training phase, and in the test phase, the previously reward-associated item (both color and shape) became task-irrelevant distractor. We found trial-to-trial short-lived reward learning but failed to find any conjunction reward association and reward-based distractor interference. The results suggest that the conjunction associative reward training is difficult, albeit there is a short-lived reward learning effect.

keywords: reward capture effect, conjunction reward-association.

4.2 Introduction

Adaptive changes in behavior can be triggered by stimulus reward association, as demonstrated in Pavlovian classical condition (Stangor et al., 2014). Similarly, human attention can be prioritized in such a way that attentional selection is driven by reward-based stimuli. Reward can bias attention to the feature or dimension that is associated with reward (Della Libera & Chelazzi, 2009). Increasing evidence has been shown that a reward-associated distractor can capture attention away from the ongoing tasks even if the distractor is not salient (Anderson et al., 2011a).

A typical paradigm demonstrates such reward-based attentional capture is the reward-associated additional 'singleton' task, in which a reward associated distractor (non-salient) is presented together with the target and other distractors (Anderson et al., 2011a, 2011b; Bucker et al., 2015; Failing & Theeuwes, 2014). The reward-associated distractor is typically color defined. The color, such as red or green, in the target (i.e., task-relevant) is associated with high or low reward in the training phase. A correct response to the target leads to high or low reward with a certain high probability (usually 80% vs. 20%), such that the reward and color can be associated via learning. In the test phase, the previously reward-associated feature (e.g., the color red and green) is shown in a task-irrelevant distractor. For half of the trials, a distractor with this previously reward-associated feature appears in the search display. A typical finding is that even if in the test phase the previously reward-associated feature became task-irrelevant and non-salient (other distractors were colored too), it still interferes with the ongoing task. A distractor previously associated with high-value interferes more relative to the distractor associated with low-value to the ongoing task. This interference is termed the value-driven attentional capture effect (Anderson et al., 2011a).

However, there is an ongoing debate whether this value-based distractor interference is biased toward the influence of 'selection history'. In a review paper, Awh and colleagues argue that in addition to goal-driven and stimulus-driven, attentional selection can also be based on a past selection episode, referred to as selection history. In line with this notion, Shan and Jiang (2016) conducted a study to disentangle the influences of selection history and value-based reward association. In one of their experiments, the target color in the training session was not reward associated, but the color appeared as the distractor color in the test phase, and they found a similar effect as those value-based attentional capture effect, which led them to argue that attentional capture by the distractor color may not be fully

value-based, rather a selection-history effect. Le Pelley (2016) also made a similar notion that attentional capture may result from selection history owing to the intensive repetition of a stimulus feature that is task-relevant. In response to the aforementioned criticisms, Anderson and Halpern (2017) conducted a replication study in which the training phase without reward and did not replicate the history-driven attentional capture, showing that reward-driven capture effects are modulated by a distinct process different from the selection history. Similarly, Mine and Saiki also argued that task relevance is not necessary to observe reward-driven attentional capture effects (Mine & Saiki, 2015).

It is important to note that in most studies of value-driven attentional capture the reward is associated with a single feature, often two specific colors, one with a high reward and the other with a low reward (Anderson et al., 2011a, 2011b; Awh et al., 2012; Bucker et al., 2015; MacLean et al., 2016; Moher et al., 2015; Roper et al., 2014; Jan Theeuwes & Failing, 2014). Yantis argued that the reward-driven attentional capture depends on reward-associated features rather than reward-associated objects (Yantis et al., 2012). Notably, using the color feature as a distractor is inherited from the original additional singleton paradigm (J. Theeuwes, 1992), in which color as compared to orientation, captures attention more from a compound search task (to find an odd-one-out object and to discriminate the orientation of the line in it). Thus, it is not surprising that in studies on value-based attentional capture as well as studies with the selection-history (e.g., Sha & Jiang, 2015), color is the main manipulated dimension, given that distractor interference (either from value-based or history-selection-based) is stronger with the color dimension than other dimensions (such as orientation, shape). This leaves the question open whether reward associative learning could be based on the conjunction of multiple features, such as color and shape, with one feature from a less salient dimension. Learning multiple-feature conjunctions is important in our daily life. For example, we should be warned with a red light at a crossroad, but not with a red apple in a supermarket. Yet, learning multiple-feature association might be difficult and requires explicit instruction. In those reward associative learning tasks, learning is often implicitly driven by a single feature-reward association. Thus, whether reward-based implicit learning of multiple-feature is similar to the single feature-reward association remains unanswered.

On this ground, the present study designed a color-shape conjunction reward paradigm to investigate the following research questions: i) whether distractors with multiple-feature reward association is possible, ii) if so, whether the reward-associated distractor interference is based on selection history or reward association. Thus, instead of

associating a reward with a unique feature color, in the present study, we associated the high or low reward value with a target defined by two features (color and shape identity) in the training phase. Specifically, a high-reward value is associated with a target of pink “i” or green “I”, while a low-reward value is associated with a target of pink ‘I’ and green ‘i’. All targets are equally likely, such that if observers use a single feature, either color or shape, to learn reward association, they could not establish an effective reward association given that the marginal reward distribution is equal. The reward was given with a correct answer in the form of points, and those points were translated to monetary reward at the end of the experiment. In the test session, those reward-associated items became a singleton distractor in an orientation discrimination task. In addition to the reward-associated items, we also included non-reward color-shape singleton distractors. The inclusion of those ‘neutral’ singleton is two-fold: First, those ‘neutral’ distractors serve as baselines for classical singleton attentional capture effect; second, given that selection-history and reward-history are often confounded in the literature. Using those ‘neutral’ distractors could disassociate two effects. In the training session, only the target identity is task-relevant. Thus, if the attentional capture is based on selection history, the distractor interference should be observable for those target identity even when the distractor color hasn’t been shown in the training session. By contrast, if the distractor interference in the test session is mainly driven by the reward associative learning, distractor interference should only be observable in those search displays with a distractor defined by previous reward-associated color and shape. However, it is also possible that the implicit reward learning with multiple-feature conjunction is difficult, we may not be able to observe any differences among those manipulations.

4.3 Method

The experiment consisted of two phases: a training phase and a test phase. In the training phase, a high/low-value reward was associated with the color and shape identity of the target. When the target was “i”, the high-value reward was associated with pink color and the low-value reward with the green color. When the target was “I”, the high-value reward was associated with the green color and the low-value reward with the pink color. The reward was given in the form of points, and participants could obtain a reward bonus (maximums of 3 Euros) according to the points they could get in the training phase. In the test phase, the target

was a tilted bar, and no reward was provided. Besides, there was a color singleton distractor defined by the shape (i-shape, I-shape) and the color (pink, green, orange, turquoise).

Participants

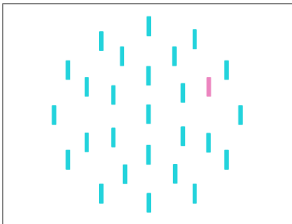
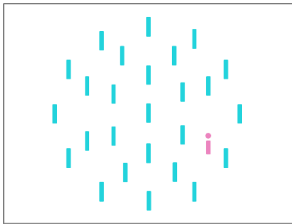
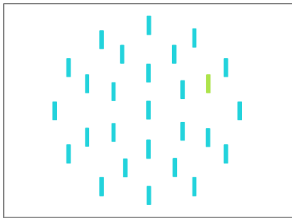
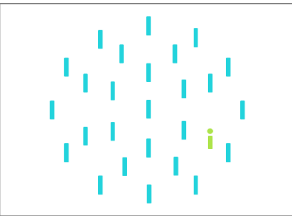
24 participants (13 females, ranging between 18 to 35 years old) took part in this experiment. All had a normal or corrected-to-normal vision and were naive to the purpose of the experiment. The sample size was set the same as the previous two studies, aiming for 80% power to detect a relatively large effect size ($f = 0.65$) in a repeated-measures analysis of variance with an alpha level of .05. Power estimates were computed using online WebPower (<http://webpower.psychstat.org>). Participants received 9 Euro/hour for their participation, plus an extra reward bonus (maximum of 3 Euros) earned during the training phase. All participants gave informed consent before the experiment. The study was approved by the ethics board of LMU Department of Psychology and conformed to the Helsinki Declaration and Guidelines.

Stimuli and design

The experiment was carried out in a dim-lit experimental cabin. Stimuli were generated by Psychophysics Toolbox (Kleiner et al., 2007) based upon Matlab (The MathWork Inc), and were presented on a CRT monitor (screen resolution of 1600 x 1200 pixels; refresh rate of 85 Hz; display area of 39x29 cm). Participants were seated at a viewing distance of 65 cm from the monitor.

The visual search display consisted of 27 bars, arranged around three invisible concentric circles. The search display subtended approximately $10^\circ \times 10^\circ$ of visual angle and each bar had a size of approximately $0.9^\circ \times 0.2^\circ$. The distractors were turquoise-colored vertical bars. Targets and Distractors always appeared in the second circle from outside.

Table 1. Four types of search displays used in the training session.

Target	Identity	
	l-shape	i-shape
Pink		
Green		

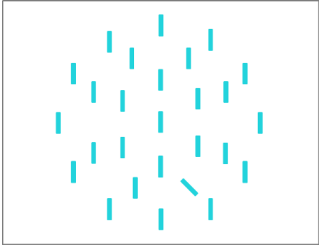
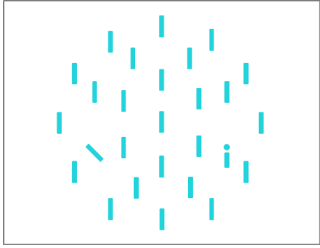
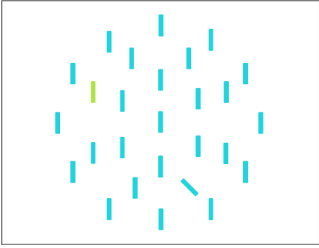
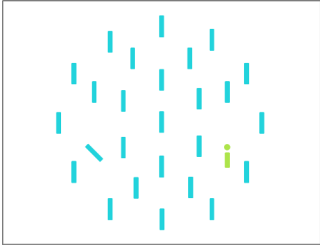
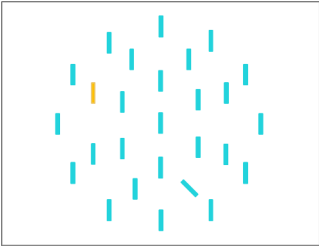
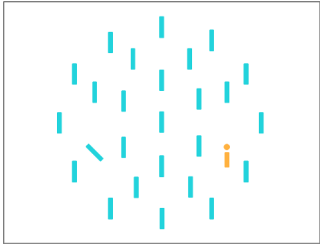
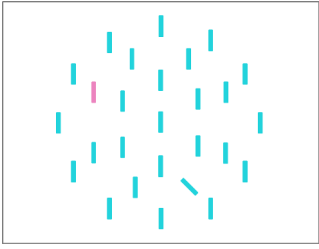
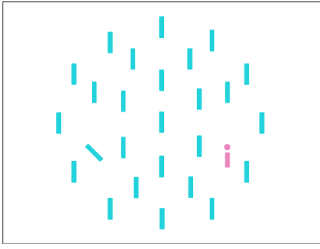
Note. The high reward was associated with the pink “i” and the green “l”, the low reward with the pink “l” and the green “i”. Thus, on average, on color dimension or identity dimension reward on two features are equally likely.

In the training phase, the target was a color-defined pop-out stimulus. For half of the trials, the target was i-shape. For the other half of the trials, the target was l-shape (a bar) (see Table 1). Participants were asked to respond with the left or right arrow key corresponding to the pop-out target “l” or “i” respectively. The reward was contingent on the color and target identity. When the target was a pink “i” or a green “l”, a correct response resulted in a high-value reward (50 points). By contrast, when the target was green “i” or a pink “l”, a correct response resulted in a low-value reward (10 points). A monetary reward was provided according to the total points participants earned in the training phase.

In the test phase, the target was orientation-defined, either left or right tilted bar, and turquoise-colored. In half of the trials, there was an additional “i” distractor, colored as turquoise, green, pink, or orange (equal probable). In the other half of the trials, there was a color singleton “l” distractor with colors of pink, green, orange, or turquoise (in this case the singleton was absent). Participants were asked to respond as quickly as possible with the left

or right arrow key whether the target was tilted to the left or right respectively while ignoring the distractor singleton. We used a full-factorial within-subject design (See Table 2). No reward was associated with the tasks in the test phase.

Table 2. Eight types of search displays used in the test phase.

Distractor	Identity	
	I	i
Turquoise		
Green		
Orange		
Pink		

Note: The target orientation was randomly tilted to the left or the right during the experiment. Four out of the eight types of distractors (Pink or Green) were previously

associated with a monetary reward, while the other four (Turquoise or Orange) were not. The condition with the turquoise vertical distractors is the additional singleton absence condition.

Procedure

The training phase consisted of 16 blocks, each block of 65 trials. A trial started with a fixation point for 300 ms, followed by a search display (see Table 1) for 1500 ms or till a response. Participants were required to respond as quickly and accurately as possible using either the left or right arrow key according to the presence of the target. If the target was I-shape, participants were required to press the left arrow key, and the right arrow key if the target was an i-shape. Immediately followed the response, a feedback display was shown for 600 ms. The feedback display included information about how many points the participant gained for the responded trial and the total points that the participant had accumulated so far. When the pop-out stimuli were the i-shape target, a correct response resulted in a high-value (50 points) / low-value (10 points) reward when the target was pink/green, and green /pink when the pop-out stimulus was the I-shape target. After an inter-trial interval (ITI) of 800 ms, the next trial began.

The test phase consisted of 8 blocks, each block of 64 trials. A trial started with a fixation point for 300 ms, followed by a search display (see Table 2) for 1500 ms or till a response. Participants were required to respond as quickly and accurately as possible using the left and right arrow buttons of the keyboard according to the orientation of the target. If the upper side of the target was tilted to the left, participants were required to press the left arrow key, and the right arrow key if the target was tilted right. Immediately after the response, a feedback display with “Correct!” or “Incorrect!” was presented for 600 ms. After an inter-trial interval (ITI) of 800 ms, the next trial began.

Each participant completed the training phase and the test phase on the same day. The training phase took about one hour and the test phase took about 30 minutes.

Statistical and Bayes-factor analysis

Given that speed-accuracy trade-off (SAT) may vary unpredictably within or across participants (Liesefeld & Janczyk, 2019; Luce, 1986; Pachella, 1973; Townsend & Ashby, 1983), we evaluated speed and accuracy together using inverse efficiency score (IES, see Townsend & Ashby, 1983), which is the most common method for correcting speed-accuracy

trade-off (SAT). The IES is calculated as the quotient of the mean reaction time (RT) divided by the percentage of correct responses (PC):

$$IES = RT/PC.$$

Accordingly, IES scores keep the same unit as the RTs (ms). Thus, IES scores can be thought of as error-adjusted RTs.

Repeated-measures ANOVAs and Bayesian analyses of variance (ANOVAs) were performed using JASP 0.10 (<http://www.jasp-stats.org>) with default settings (i.e. r-scale fixed effects = 0.5, r-scale random effects = 1, r-scale covariates = 0.354). Inclusion Bayes factors compare models with a particular predictor to models that exclude that predictor, providing a measure of the extent to which the data support inclusion of a factor in the model. Bayesian t-tests were performed using the `ttestBF` function of the R package “BayesFactor” with the default setting (i.e., `rscale = “medium”`).

4.4 Results

Trials with extreme RTs that exceeded the three standard deviations of individual means were excluded for further analysis. Also, the first trial of each block was excluded for further analysis due to large variation in RTs. In total, 9.1% and 3.1% of the total trials were removed for the training and the test phase respectively. Note, no single participant made the error trials exceeding 10%, which satisfies the criterion of application of IES. Thus, we applied the IES transformation for correcting SAT.

Training phase

Given that the reward association was contingent on the conjunction of color and shape identity, we first administered a two-way repeated-measures ANOVA with factors of target shape identity and color to the mean IESs. However, it failed to reveal any significant difference for target identity, $F(1, 23) = 0.06$, $p = .81$, $BF_{incl} = 0.18$, or target color, $F(1, 23) = 0.21$, $p = .37$, $BF_{incl} = 0.16$. The Bayes factors were all smaller than 0.33, favoring the null hypothesis. That is, there was no difference between two color-reward associations, or between two identity-reward associations. Importantly, there was no significant interaction between the target color and identity, $F(1, 23) = 0.82$, $p = .65$, $BF_{incl} = 0.04$, suggesting no contingent color-identity associative learning. In other words,

high-reward on the color-identity contingency did not improve the performance in general (Figure 1).

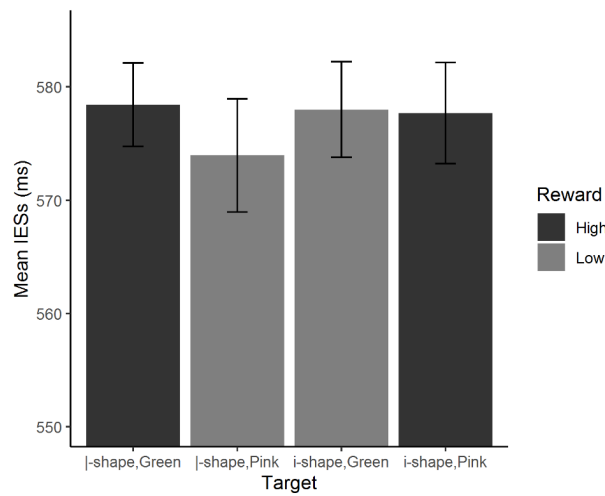


Figure 1. Mean IESs for the four types of targets, separate colors for the high and low rewards in the training phase. The error bar indicates one within-subject standard error.

The failure of reward association for the conjunction features (color and identity) may suggest learning the reward contingent on two dimensions is relatively difficult and slow, and participants may only learn reward association with one simple feature, as most previous studies demonstrated the reward association was effective with the single feature-reward learning (e.g., color) (Anderson et al., 2011a). Given that the high/low reward probability marginalized for the two colors (Pink and Green) or the two identities (“i” and “l”) was equal, this may average out throughout the reward learning. To examine if there was any trial-by-trial reward learning, we further looked into the intertrial effects of the reward value (high/low) from the previous trial that could influence the response time of the current trial. Figure 2A depicts the mean IESs for the intertrial effects of the reward value. By visual inspection, a high-reward in a previous trial boosted the response speed for the current trial (see the black bars). This was confirmed by a one-way repeated-measures ANOVA with the main factor previous reward on the mean IESs. Significant differences were found in previous Reward, $F(1, 23) = 4.65$, $p = .04$, $\eta_p^2 = .17$. The results suggest that indeed there was some short-lived reward learning effect, which was transferred from the previous trial to the current trial, regardless of the associated dimensions. Interestingly, this inter-trial reward effect was not as strong as the standard target repetition effect (Figure 2B), repeating

the same identity color significantly facilitated the search performance, $F(1, 23) = 31.71$, $p < .001, \eta_p^2 = .58$.

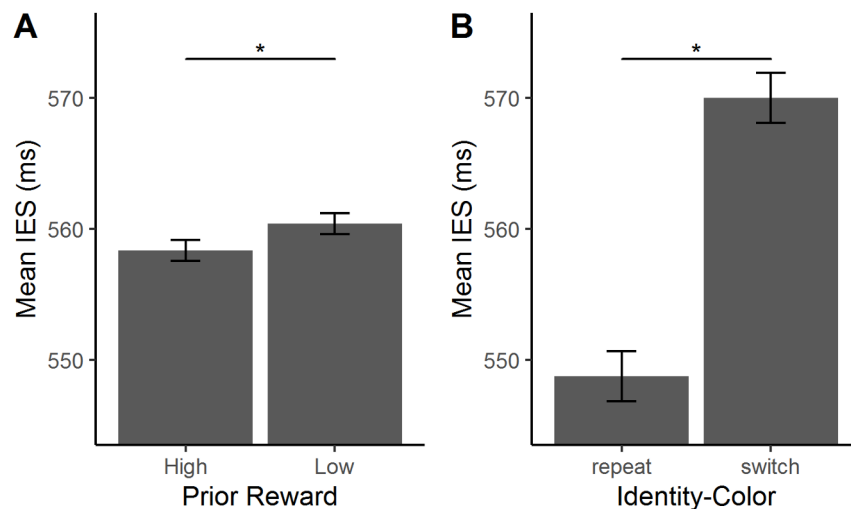


Figure 2. Mean IES as a function of (A) prior reward (high/low value) and (B) identity-color (i-shape-pink, i-shape-green, l-shape-pink, l-shape-green) of Experiment 1. Significant differences were found in the main factor “prior reward”. Significance level “*”: $p < .05$. The error bar indicates one within-subject standard error.

Test phase

It is uncommon that there is no reliable effect in the association phase, but found a transfer value-based attentional capture effect in the test phase (e.g., Anderson, 2016; Kim & Anderson, 2020). Thus, we continue the analysis for the test phase. To investigate whether the cross-dimension conjunction reward-association interferes with the ongoing search task, we separated search displays into two categories: displays with a color singleton (six conditions), displays with an identity-only singleton, or without singleton (see Figure 3). The left panel of Figure 3 shows the mean IES as a function of the reward association for displays with a color singleton, separated for two identities. Small numerical trends were showing slow-down responses when the singleton was previously associated with high-reward relative to low-reward. A two-way repeated-measures ANOVA with singleton distractor identity and color showed a significant difference in distractor color, $F(3, 69) = 4.65, p < .01, \eta_p^2 = .17$, but there was no significant difference in identity, $F(1, 23) = 0.89, p = .35, BF_{incl} = 0.22$, or their interaction: $F(3, 69) = 1.90, p = .14, BF_{incl} = 0.27$. A post hoc t-test for l-shape distractors revealed significant differences between the homogeneous

color turquoise and a distractor pink ($p < .05$), or green ($p < .01$), or orange ($p < .01$), but there was no significant difference among distractor colors for i-shape distractor (all $ps > 0.1$). The findings suggest the color singleton distractor captured attention, regardless of the reward association, while the distractor shape did not contribute to the capture effect when the color singleton was presented.

A further one-way ANOVA with factors of reward-distractor-association (high-reward color, neutral color, low-reward color, Figure 3, left panel) on the mean IES was applied to the trials with i-shape and l-shape respectively. There was neither significant difference for the color, $F(2, 46) = 0.71, p = .50, BF_{incl} = 0.20$, nor significant difference for l-shape distractor either, $F(2, 46) = 0.41, p = .67, BF_{incl} = 0.16$. For the identity-only singleton display, there was also no significant difference between the single present and absent conditions, $F(1, 23) = 2.33, p = .14, BF_{incl} = 0.70$, suggesting the vertical ‘i’ did not significantly capture attention away from the orientation task.

Thus, unlike previous studies with a single feature-reward association, the test phase revealed that there was no significant distractor interference when the reward association was contingent on two features (color and shape identity).

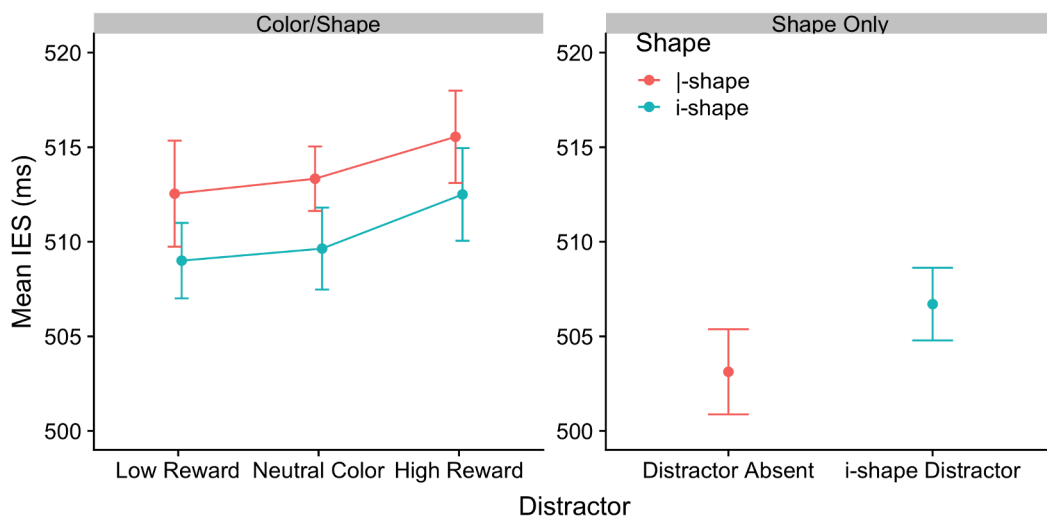


Figure 3. Mean IES as a function of the distractor, separated for the reward value (left) and distractor shape (right) in the test phase of Experiment 2. The error bar indicates one within-subject standard error.

4.5 Discussion

There are ample studies that have shown reward-based association can alter attentional processes in visual search (for a review, see Awh et al., 2012). When the reward is associated with a target feature, attentional selection becomes more efficient (e.g., Della Libera & Chelazzi, 2006), while the reward is associated with a distractor feature, searching a target is impeded by the presence of a reward-associated distractor (e.g., Anderson et al., 2011a). It is important to note that, however, those studies applied a simple reward-feature associative learning, usually only one single feature is reward-related, such as color. In real life, the reward is often ambiguous and might be learned more explicitly. For example, a reward might be associated with multiple conjunction features, or with response modes. Thus, the present study aimed to investigate (i) if reward association could be learned by the conjunction features from different dimensions (here the color and shape), (ii) if this reward-associated conjunction item is presented as a distractor, whether this distractor causes distractor interference similar to those studies with the single-feature association. We designed the reward scheme such that the high and low reward can only be obtained by the conjunction of the color and shape identity, while the color-only or shape-only marginal reward distribution is equally likely.

In the training phase, we observed trial-to-trial reward modulation on search performance. Higher reward led to the facilitation of the next trial, which indicates some short-lived reward learning effect. However, we failed to find any significant reward association to the conjunction of color-shape items. In the test phase, the target in the training became a distractor in an orientation discrimination task and no reward was provided. We found no significant reward-capture effects in the test phase. The distractor interference caused by the singleton distractor was comparable between the reward-associated color-shape distractor and neutral new color-shape distractor, indicating that conjunction reward-feature may not be able to induce reward capture effect as those reported in the literature.

It is not uncommon that the reward association is relatively weak. For example, Sali and colleagues (Sali et al., 2014) showed that if the reward prediction remained the same for the training (either for unique color or two colors), no evidence of developing reward association and value-driven attentional capture. Further, they showed that even though the reward magnitude was coupled with the speed of behavioral responses, there was no reward-feature association if the reward is merely motivational. Rather, a trial-to-trial variation of a unique feature-reward prediction (e.g., high reward for the red color target and

low reward for the green color target) made the associative reward learning possible. Here, however, we indeed varied the high and low reward trial-to-trial, which was consistent with the design of Anderson et al. (2011). What is different here is that the high and low rewards were associated with the conjunction distribution of two dimensions - shape and color. When observers only selected one dimension (either shape or color) for reward association, the selected dimension didn't have a prediction power of the reward. If this was the case, the outcome is consistent with Sali et al. (2014), merely motivational reward did not form a strong feature-reward association. That is, in our case, observers might only pick one dimension for reward learning, which is not effective.

However, one might argue that it might not be enough training for the contingent reward association. In our case, we have 1040 trials in total, and each condition has been repeated 260 times. In comparison, Sali et al. (2014) only have 114 training trials, and Anderson et al. (2011) only had 1008 trials for training. Importantly, Sali et al. (2014) argued that it is not the training that is not enough, rather the unique predictability of the reward-feature association matters. Thus, it is unlikely that in our case the null effect is merely owing to the lack of training. With that said, it remains a possibility that the training is required much more for the conjunction reward associative learning as compared to the single feature reward learning. A future study is warranted if extensive learning is required for contingent reward learning.

It is interesting to note that the reward learning took place at the trial-to-trial level. Trials with high reward facilitated the performance of the next trial, regardless of the target features (color and shape). This effect is consistent with the motivational effect reported in the literature (Asgeirsson & Kristjánsson, 2014; Lak et al., 2020; Wolf & Schütz, 2019). A high reward, in general, arouses participants in a short period to perform better. However, as shown by Sali et al. (2014), merely motivational reward did not guarantee a robust reward-feature associative learning. Besides, the motivational effect is relatively small as compared to the trial-to-trial color feature repetition (Figure 2). The repetition effect is well known in the literature (Hillstrom, 2000; Parks & Werner, 2020), which is a special case of the selection history (Awh et al., 2012). As reviewed in the introduction, there are still ongoing debates concerning whether reward-associative learning is a special kind of selection history. It has been shown that repeated selection of a particular target gives rise to later impairment in visual search if the previous target feature becomes a distractor feature, an effect well similar to the value-driven capture (Sha & Jiang, 2016; Shiffrin & Schneider, 1977). However, the present study showed that the influence of the selection history, if any, is

also weak. In the test session, a neutral color was introduced, together with the colors used in the training phase, for the singleton distractor. If there is any selection history effect, we should observe the difference between the neutral and previous target colors, and the selection history would predict that the previous target colors impede the search performance. However, in our test session, there is no evidence of this. Presences of the singleton distractor with all three colors had comparable performance. Thus, it is unlikely the selection history is strong in our study.

So, what other factors might influence the associative reward learning and distractor interference? One key difference between our paradigm and the paradigm used by Anderson et al. (2011) is that our paradigm is a standard pop-out search, while Anderson used a compound search (i.e., first to identify the location by the shape, and then discriminate the orientation bar inside that shape). In the first study of this doctoral thesis (Chapter 2), we used the crossmodal compound search task and were able to pinpoint the processing stage of the reward-associated distractor interference. The interference occurs at a rather late stage - at the focused selection stage. Thus, it might be that in the present pop-out search paradigm, the pop-out target directly captures the attention, leaving no room for the additional singleton to interfere with. However, the test phase (Figure 3) showed that the additional singleton indeed captures attention, slowing down responses. Thus, it is unlikely that the difference of the search paradigm nullifies the effect, rather the reward associative learning hasn't been established.

Combining those facts and previous studies, we could largely rule out the null effect we observed here due to other nuisance factors (such as motivational, paradigms, or selection history). One potential explanation of the null effect is that the contingent reward scheme is rather difficult to establish a unique reward-feature prediction. Sali et al. (2014) pointed out that the key factor determining if the reward-based attentional capture being observed is the unique prediction of the high /low reward to the feature. Here in our paradigm, the prediction is unique for the two-dimension contingent features, but not for the single dimension feature. The capacity is likely limited to one feature in reward associative learning.

In summary, here in the training phase, we manipulated high/low rewards to the conjunction color/shape items with marginal distribution being equal for individual features (color or shape). We failed to find any significant reward associative learning, and there was no evidence of reward-based distractor interference, albeit we observed local reward-driven motivational enhancement in search performance. The findings suggest that the reward associative learning is rather limited to unique single feature prediction, and contingent

reward association is difficult with implicit learning. Future studies, however, are needed for investigating whether with the aid of explicit instruction the conjunction reward association is possible, and subsequently, the associated conjunction features could interfere with ongoing tasks if the reward-associated features become distractors.

4.6 References

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5 General Discussion

The present dissertation focused on the attentional processing stages and the way of reward-association in reward-based distractor interference. Using visual-tactile search tasks, study 1 aimed to identify the attentional processing stages of reward-driven distractor interference by separating the search stage and identification stage via two modalities and found feature-based reward-driven distractor interference likely occurred at the post-focal-attentional processing stage. Study 2 further investigated the potential level of reward association, particularly on feature-based, response-based, and task-based reward associations. We failed to find the response-based reward association but the other two types were still possible. In addition, previously reward-associated distractors can facilitate search, partly owing to fast rejection of the reward-associated distractor and increased arousal. Study 3 continued to explore the conjunction cross-dimensional reward-association rather than single-feature-reward association to get more clues for complex reward association. Trial-to-trial short-lived reward learning effect was found but there was no general conjunction reward association throughout the whole training phase. Also, previously reward-associated distractors still capture extra attention, though no significant reward-based capture effects were shown, indicating reward-based distractors may only cause interference with a simple single reward-feature association.

5.1 Recapture of the main findings

Generally, based on a disassociation of attentional processing stages (pre-attentional searching stage and post-attentional decision-making stage) with visual-tactile combined tasks, we provided evidence that the reward-driven capture effects based on feature-reward-association occurred at the post (focal) -attentional processing stage (Study 1, Chapter 2), and reward-association is possibly at the task-set level depending at the reward-mapping. In addition, previously reward-associated distractors could facilitate response by fast distractor rejection and increased arousal rather than merely hinder the response to the target (Study 2, Chapter 3). Further, we found trial-to-trial temporally reward-learning effects for consecutive trials under conjunction cross-dimensional reward-association, which suggested that the reward-association under complex conditions (e.g., when reward was associated with two features with a balanced distribution rather than only one feature) might generate counteracting effects that inhabit explicit learning of reward, and reward-driven capture effects diminished as well. However, further studies are needed to

examine if distractors previously associated with multiple features have more interference than their physical salience is supposed to be (Study 3, Chapter 4).

In Study 1 (Chapter 2), the results of Experiment 1 showed great impacts of target-distractor distance, which indicated that the reward-based attentional interference occurred at the post-attentional (identification) stage. This inference was further confirmed by Experiments 2 and 3, in which the pre-attentional stage and the post-attentional stage was dissociated by visual-search & tactile-identification tasks (Experiment 2) and tactile-search & visual-identification tasks (Experiment 3), as no significant reward-capture effects were found in visual-search / tactile-identification tasks while the effects were found in tactile-search / visual-identification tasks.

In Study 2 (Chapter 3), we disassociated feature-based, response-based, and task-set-based reward-association. In Experiment 1, we failed to find response-based reward-association but the presence of previously high-reward associated distractor facilitated the response rather than hinder the distractor-suppression. In Experiment 2, we found a significant interaction between the target and reward assignment, which suggested that the reward-association took place at the level of task-association rather than feature-association.

Study 3 (Chapter 4) explored the conjunction of cross-dimensional reward-association and found the high/low reward of the previous trial had a significant impact on the current trial in the reward-learning process. However, throughout the whole training phase, the reward-learning effects were diminished which was probably due to the contraction effects of the reward-learning under an opposite assignment for the two features of high/low reward association. Besides, the non-significant differences between the previously reward-associated colors and the neutral (non-reward-associated) color of the distractors indicated that selection history had little or no influence on our paradigm.

5.2 Reward-driven capture effect, priority map, and attentional processing stage

As we know, reward facilitates performance with a reward-learning process. The feature which was previously associated with reward can capture attention even when this feature becomes tasks-irrelevant. This reward-driven distractor interference was found in many previous studies (Anderson et al., 2011a; Botvinick & Braver, 2015; Chiew & Braver, 2016; Della Libera & Chelazzi, 2009; Kiss et al., 2009; Notebaert & Braem, 2015; Padmala & Pessoa, 2011, 2014; Pessoa, 2009; Soutschek et al., 2015), but mechanisms underlying the

attentional interference, such as at which level of the priority map and at which attentional processing stages the interference occurs, are not clear. If the reward-driven capture effect occurs at the search-guidance (pre-attentive) stage, the interference should be independent of the target and distractor distance. Conversely, if the reward-driven capture effect occurs at the identification (post/focal-attention stage), a target-distractor positional effect should be found, which indeed we found in Study 1.

In the functional architecture of search guidance, there are three possibilities that the reward-based interference occurs: at the feature level, at the dimension/modality level or the global priority map. As the study of Anderson et al. (2011) found the reward-driven attentional capture was related to reward-associated features rather than interfered by spatial locations of the previously reward-associated-colored distractor, which indicated that the feature-based reward-driven attentional capture is likely modulated at the early feature level (Anderson et al., 2011a). However, some other studies using probability-contingent reward-learning suggested that reward influences at the level of the search-guiding attentional-priority map, which is thought to represent the selection priority associated with particular locations, but not the features of objects at these locations. For instance, in the study of Chelazzi et al. (2014), mapping high/low-probability reward to spatial locations, more attentional bias was found for high-probability-associated locations, which suggested that contingent spatial-probability reward-learning was manipulated at the level of search-guidance attentional-priority map. In the study of Anderson (2015), he proposed that the reward association at the feature level is modulated by the global (spatial) priority map. However, he also admitted that the underlying mechanism is not clear. The interaction of location and feature for value-driven attentional capture might be either reward-location association at the level of priority-map or the location of the distractor with previously reward-associated feature does not affect, only that the signal is suppressed when the location of the previously reward-associated feature was mapped to a low value (Anderson, 2015). Here we reasoned that as in a typical non-search Eriksen flanker task (Eriksen & Eriksen, 1974) if the distractor interference occurs at the post-selective stage, a more marked distractor interference should be found when the conflict distractor is closer to the target. Similarly, if a target-distractor positional effect could be observed, the reward-feature-based distractor interference may occur at the post-selective stage.

In order to separate the attentional processing stage via behavioral tasks, we adopted visual-tactile tasks with pop-out visual search displays in Study 1. In Experiment 1, we replicated Anderson's study (Anderson et al., 2011a) in our tactile-adapted pop-out visual

search display. We found reward-driven capture effects occurred when the visual target and distractor were on the same side of the fixation point. To test if this finding is adapted to visual-tactile combined tasks, we conducted a comparison experiment on two groups of participants: one group of the participants completed the visual-tactile tasks with the search display whose target and distractor were on the different sides of the fixation point, and the other group of the participants completed the visual-tactile tasks with the search display whose target and distractor were on the same side of the fixation point. The visual-tactile tasks were both visual search and tactile discrimination combined tasks. Other experimental conditions were kept the same except that the target and distractor on the search display were on the different sides and the same side of the fixation point respectively. We failed to find reward-driven capture effects for both groups. Then we conducted an experiment of tactile search combined with visual discrimination tasks in Experiment 3, in which the target and distractor were on the same side of the fixation point. Reward-driven capture effects were found in Experiment 3. This suggested that the reward-driven capture effects occurred during the visual discrimination stage, that is, the post-attentive processing stage.

5.3 Task-based and conjunction cross-dimensional reward-association

In most of the previous reward-based studies, reward is mapping to a unique feature or dimension (Anderson et al., 2011a, 2011b; Bucker et al., 2015; MacLean et al., 2016; Roper et al., 2014). However, learning conditions of reward in daily life might be much more complex. Reward-association might be in a combination of both the feature and the task-set response itself, as well as with multiple features. Therefore, it is important to distinguish how different reward associations are formed and whether reward can be learned in a multiple-feature-reward association.

In Study 2 (Chapter 3), we carried two experiments to distinguish feature-based and task-set reward-association. In Experiment 1, high/low reward was associated with task-set left/right response and two colors simultaneously in the training phase and the assignments were balanced within and among participants. In the test phase, the task-set remained the same though no reward was provided. The reward-associated feature in the training phase belonged to the tasks-irrelevant distractor, which was present in half of the trials in the test phase. We hypothesized that if the reward association was mapped to the feature, or the feature-based association plays the main role, we should observe more distractor interference when the feature-singleton distractor was present. By contrast, if task-set reward-association weights more, we should observe more facilitation on the task-set response, given that the

task-set reward mapping remained the same across the training and test phases. The results of Experiment 1 supported neither of the two hypotheses as the mean IES was neither significant for the feature-mapping of the singleton distractor or the task-set response-mapping, though we found the facilitation of the presence of high-reward associated distractor which is consistent with the previous finding of Lee and Shomstein (2014), who argued that the reward association, rather than distractor inference, increased the efficiency of distractor rejection (Lee & Shomstein, 2014). However, the reward may be also associated with the arousal level, thus the presence of salient high-reward color raised the arousal level which further facilitated the response. Besides, it does not rule out that the reward association could take place at the task level just because the absence of the reward association to the motor response suggests that the reward does not promote pure motor priming, we consider the change of task-set response between the training phase (two colors) and test phase (two orientations), which might impede the transfer of the task-level reward-association. Therefore we carried Experiment 2, in which the high/low reward was coupled to the target presence/absence in both the training phase and test phase. A cue-prior pop-out visual search task with the target presence/absence associated with high-low reward in the training phase, and another feature (orientation) as the feature-defined target while the reward-associated feature (color) belonged to the singleton distractor in the test phase. Again, we observed facilitation of response when the color singleton distractor was present, which was consistent with the results of Experiment 1. Distractor presence did hinder the response as we observed in both groups, suggesting that the reward association was unlikely to be established at the feature level. A more interesting find is that we observed facilitation in the high-reward-to-the-absent condition for the target absence condition ('Absence' was previously associated with the high reward), regardless of the singleton distractor presence or not, and the significant interaction between the target and reward assignment suggests that the reward-association rather took place at the level of task-association rather than feature-association.

When the reward to the task-set mapping was changed from the training phase to the test phase but not the reward-response mapping (Experiment 1), we found no significant reward-based distractor interference at the response level. However, when the reward to the task-set mapping was unchanged, we observed the high-reward task response (both the target presence or absence) relative to the low-reward task response was facilitated, indicating the reward-association has been transferred from the pop-out color detection task to the

orientation detection task. Therefore, we concluded that reward association at the task-set level is possible, but only observable when the task set remains the same.

In Study 3 (Chapter 4), we focused on the conjunction cross-dimension reward-association by mapping reward to two features rather than a unique feature with a conversed high/low reward-mapping rule to the two features, that is, high/low reward to pink/green color when the shape identity is i-shape, while the high/low reward mapping to the color was opposite when the shape identity is l-shape. Analysis of inter-trial effects, we found the high/low reward in the prior trial has an impact on the current trial, but this reward-learning facilitation diminished throughout the whole learning process, suggesting a contractive effect in the conjunction cross-dimension reward-learning condition. Also, no reward-capture effect was found in the test phase. It is likely that reward association cannot be well established in the conjunction condition, and only limited to the unique-feature association.

5.4 Conclusions

The current thesis provides evidence for reward-capture interference at the post/focal-attentional processing stage in Study 1 (Chapter 2) and investigates more complex reward-association in Study 2 (Chapter 3) and Study 3 (Chapter 4). Particularly, Study 2 found a facilitation effect of the reward-featured distractor rather than impact effect and showed an inclination to task-set reward-association rather than feature-based and response-based reward association. Study 3 found temporal learning effects under the condition of conjunction cross-dimension reward-association, yet the effects diminished throughout the whole training phase, suggesting that it is likely that reward is rather limited to unique single feature prediction.

6 References (General Introduction and General Discussion)

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Affidavit/Eidesstattliche Versicherung

Hiermit versichere ich an Eides statt, dass ich die vorliegende Dissertation „Reward-based distractor interference: associative learning and interference stage“ selbstständig angefertigt habe, mich außer der angegebenen keiner weiteren Hilfsmittel bedient und alle Erkenntnisse, die aus dem Schrifttum ganz oder annähernd übernommen sind, als solche kenntlich gemacht und nach ihrer Herkunft unter Bezeichnung der Fundstelle einzeln nachgewiesen posnerMuhabe.

I hereby confirm that the dissertation „Reward-based distractor interference: associative learning and interference stage“ is the result of my own work and that I have only used sources or materials listed and specified in the dissertation.

München, den Munich, 25 Mai, 2021

Bing Li

Declaration of author contributions

Manuscript 1:

Bing L., Müller, H. J., Xiaolin Z., Lihan C., Zhuanghua S. (in preparation). On the processing stage of the reward-based distractor interference.

The author of this dissertation was primarily involved in designing and programming the experiment, collecting and analyzing the data, creating plots, interpreting the results, and writing the manuscript.

Hermann J. Müller helped with the interpretation of the results. He commented on and helped revise the manuscript.

Xiaolin Zhou and Lihan Chen commented and helped revise the manuscript.

Zhuanghua Shi conceived and supervised the project, participated in designing the experiments, and interpreted the results. He also commented on and helped to revise the manuscript.

Manuscript 2:

Bing L., Müller, H. J., Zhuanghua S. (in preparation). Reward-based task-association vs. feature-association in visual search.

The author of this dissertation was primarily involved in designing and programming the experiment, collecting and analyzing the data, creating plots, interpreting the results, and writing the manuscript.

Hermann J. Müller helped with the interpretation of the results. He commented on and helped revise the manuscript.

Zhuanghua Shi conceived and supervised the project, participated in designing the experiments, and interpreted the results. He also commented on and helped to revise the manuscript.

Manuscript 3:

Bing L., Müller, H. J., Zhuanghua S. (in preparation). Conjunction Reward-Association in visual search.

The author of this dissertation was primarily involved in designing and programming the experiment, collecting and analyzing the data, creating plots, interpreting the results, and writing the manuscript.

Hermann J. Müller helped with the interpretation of the results. He commented on and helped revise the manuscript.

Zhuanghua Shi conceived and supervised the project, participated in designing the experiments and interpreted the results. He also commented on and helped to revise the manuscript.

The above contributions to the doctoral thesis of Bing Li are all correct as stated above.

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