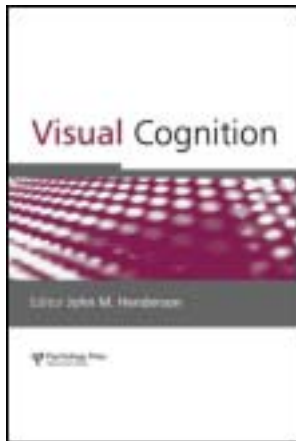


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Reward has a residual impact on target selection in visual search, but not on the suppression of distractors

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Reward has a residual impact on target selection in visual search, but not on the suppression of distractors

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In the reinforcement learning literature, good outcome following selection of a visual object is thought to bias perception and attention in favour of similar objects in later experience. This impact of reward might be instantiated in two ways: Reward could prime target features or it could act to facilitate suppression of distractors present when reward was received. Here we report results from an experiment in which reward outcome was selectively associated either with the colour defining a visual search target or with the colour defining a salient distractor in the display. Reward's impact on search was evident only when it was tied to the target; reward made it no easier to ignore a distractor when it subsequently reappeared as a distractor. This suggests that reward acts largely to prime target representations, consistent with the idea that objects associated with good outcome become visually salient.

Keywords: Attention; Distractor suppression; Priming; Reward.

Theories of reinforcement learning and animal approach behaviour suggest that reward feedback has a direct impact on perception and attention, automatically biasing vision such that perceptual features associated with reward are processed preferentially. This is thought to involve the dopamine system, with the release of mesolimbic dopamine causing a sequence of neural events that leads to visual priming (e.g., Berridge & Robinson, 1998).

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The idea here is that reward biases vision in favour of environmental stimuli that are likely to be beneficial, and that this mechanism plays a role in motivating approach towards these objects (see Ikemoto & Panksepp, 1999).

We have recently developed an experimental paradigm designed to investigate this idea in humans (Hickey, Chelazzi, & Theeuwes, 2010a, 2010b). Our task is broadly based on the *additional singleton paradigm* of Theeuwes (1991). In this paradigm observers search for a uniquely shaped target presented among a number of homogenous nontargets and, sometimes, one uniquely coloured distractor. This salient distractor is often red, with all other stimuli green, or vice versa, and this changes from trial to trial. As a result, the colours defining the target and distractor can be the same as in the previous trial or can have swapped. The pervasive finding is that responses to the target are slowed by the presence of the task-irrelevant *colour singleton* (e.g., Theeuwes, 1991), and this has been linked to the misallocation of attention to the location of this object (Hickey, McDonald, & Theeuwes, 2006).

To determine the impact of reward on vision we modified this paradigm slightly, adding reward feedback at the end of every trial (see Figure 1). Reward could be either of high (10 points) or low magnitude (1 point) and participants were paid based on the number of points they accumulated throughout the experiment (though reward magnitude was actually randomly determined for each trial and thus not tied to performance characteristics). In our initial work with this paradigm we approached experimentation with two expectations. First, high-magnitude reward should reinforce the selective processes that garner good outcome such that attention is biased towards similar objects in the next trial. Participants should accordingly be quick to

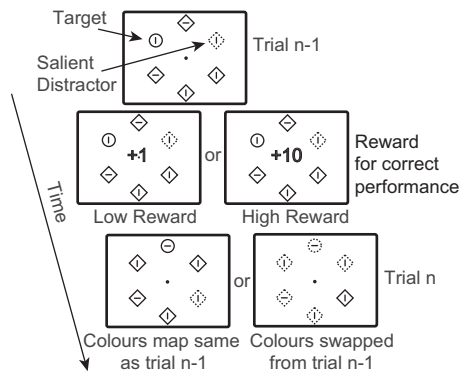


Figure 1. The general paradigm with target and salient distractor denoted.

respond when the same colour characterizes the target in the next trial. When the colours change, and the colour that previously characterized the target comes to characterize the distractor, this should increase the chances that attention will be misallocated to the distractor and performance should suffer. Second, low-magnitude reward should result in a devaluation of the selective processes that garnered suboptimal outcome such that attention is biased away from similar objects in the next trial. Participants should thus be slow to respond when the same colour characterizes the target in the next trial and faster when the colours swap.

As illustrated in Figure 2 (which is a reproduction of Figure 1b from Hickey, Chelazzi, & Theeuwes, 2010a), these expectations were confirmed in experimental results. Importantly, we have found that the behavioural pattern illustrated in Figure 2 is evident under circumstances where it is strategically counterproductive for participants to attend to stimuli characterized by reward-associated colours. This suggests that reward has an impact on vision that is independent of its role in the strategic establishment of endogenous attentional set.

Selection in visual search is known to operate through mechanisms that act on both target and distractor representations (for review, see Hickey, Di Lollo, & McDonald, 2009; Reynolds & Chelazzi, 2004). In this context there are three ways to interpret the impact of reward on attention illustrated in Figure 2. It may be that reward acts on targets, with high-magnitude reward reinforcing target representations (making subsequent discrimination easier) and low-magnitude reward devaluing them (making subsequent discrimination more difficult). If this were the case, the reward priming effect should be evident even when there is no variance in the perceptual features that define the salient distractor, so long as the target colour still changes

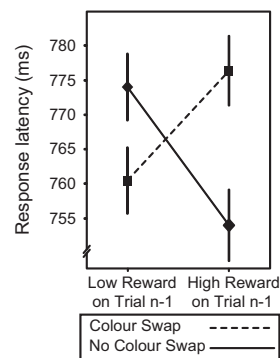


Figure 2. Behavioural results from Hickey et al. (2010a). Error bars in all figures reflect within-subject 95% confidence intervals (Cousineau, 2005).

from trial to trial and thus can be primed. Alternatively, it may be that reward acts to facilitate the suppression of distractors. This would have the effect of reducing ambiguity in neural coding and therefore would benefit target discrimination (e.g., Desimone & Duncan, 1995; Luck, Girelli, McDermott, & Ford, 1997). The expectation here is that reward priming should be apparent even when there is no variance in the features that define the target, so long as the distractor colour changes from trial to trial and thus can be affected by reward. Finally, it may be that reward modulates both target enhancement and distractor suppression such that some aspect of reward priming is evident under both circumstances.

The current experiment was designed to discriminate between these possibilities. We had two groups of participants take part in the modified versions of the reward priming task outlined previously. In the “static distractor” condition the colour of the target and homogenous distractors could be red or green, with these colours randomly determined for each trial, but the distractor was always blue. In the “static target” condition the colour of the target and homogenous distractors was consistently blue and the distractor could be red or green.

METHOD

Participants

Thirty-two neurologically typical students of the Vrije Universiteit Amsterdam gave informed consent before participation. Data from two participants was discarded due to excessively slow and inaccurate response (> 1.5 standard deviations from the mean). Four of the remaining 30 participants (11 men; age 19.8 ± 1.9 years, mean ± 1 *SD*) were left-handed. All participants were paid for their participation.

Experimental stimuli and procedure

The experiment took place in a sound-attenuated room and all stimuli were presented to participants via a CRT monitor located 60 cm from the eyes. Participants viewed stimuli arrays consisting of six shapes presented in a circle formation (see Figures 1 and 3). Each shape was 9.1° of visual angle away from a central fixation point and 12.9° away from each of its neighbouring stimuli. The shapes were thinly outlined (0.3°) diamonds ($4.2^\circ \times 4.2^\circ$) and circles (1.7° radius). A grey line ($0.3^\circ \times 1.5^\circ$) that could be randomly oriented either vertically or horizontally was presented in the centre of each item.

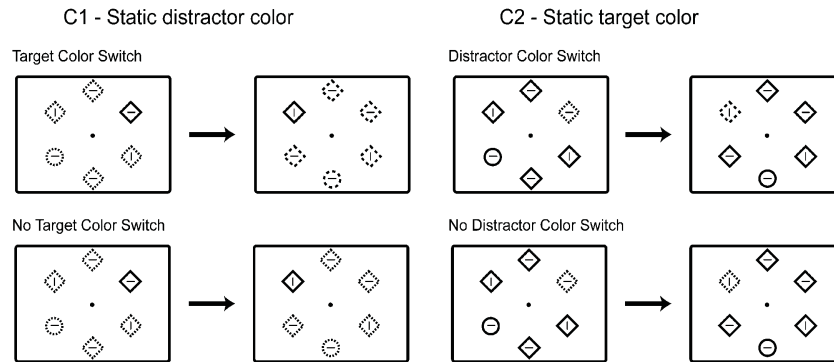


Figure 3. Schematic of current experimental design. In Condition 1, the colour of the distractor was always blue; in Condition 2, the colour of the target was always blue.

The colour and shape of the stimuli were pseudorandomly varied within the following confines. In each trial one of the objects was a circle with all other stimuli diamonds. In a quarter of trials this shape singleton was the only unique stimulus in the display but in the remaining trials an additional singleton was defined by giving one of the identically shaped objects a unique colour. In the “static distractor colour” condition the target and homogenous distractors could be either red or green in colour, but the colour singleton distractor was always blue. In the “static target colour” condition the target and homogenous distractors were always blue, but the colour singleton distractor could be either red or green. Participants were randomly assigned such that 15 took part in each condition.

The experiment consisted of 30 blocks of 30 trials, which took approximately 1 hour. Each trial began with the presentation of a fixation point for 400–1400 ms, followed by the presentation of a visual search array. Participant response was based on orientation of the line contained within the shape singleton; instructions were to press the “z” key on a standard computer keyboard with their left index finger when the target line was vertical and the “m” key with their right index finger when the target line was horizontal, and to do so as quickly as possible while maintaining an average accuracy of 90% or better. Feedback regarding accuracy and response latency was provided at the end of each experimental block. Participants were instructed to maintain eye fixation throughout the experiment and informed that eye movements were being periodically monitored via closed circuit camera. Correct responses to the search target were immediately followed by the replacement of the central fixation dot with an indication of reward feedback in blue text (65 point font; 5° height), either “+10”, denoting the receipt of 10 points, or “+1”, denoting the receipt of 1 point. Incorrect

responses were followed by “–10”, denoting the loss of 10 points. The visual search display remained onscreen during the presentation of feedback and the search display and feedback were presented together for 1000 ms. Reward value was randomized on a per-trial basis, such that correct response was as equally likely to garner low-magnitude reward as it was high-magnitude reward.

RESULTS

The salient distractor slowed response in both the static distractor condition (absent: 700 ms; present: 716 ms) and the static target condition (absent: 638 ms; present: 644 ms). A repeated measures analysis of variance (RANOVA) with a within-subject factor for salient distractor presence (present vs. absent) and a between-subject factor for condition (static distractor vs. static target) revealed a main effect of distractor presence, $F(1, 28) = 17.42, p < .001$, a marginally significant main effect of condition, $F(1, 28) = 4.03, p = .054$, and a marginally significant interaction between the factors, $F(1, 28) = 3.38, p = .077$. A similar analysis of accuracy revealed no effects (distractor present: 96.62%; distractor absent: 96.60%), condition: $F(1, 28) = 1.58, p = .220$; all other F s < 1 . Analysis of accuracy is perhaps limited by a ceiling effect; one subject had an average accuracy of 85% but all other subjects performed at 95% or better.

In order to determine how reward in one trial affected visual processing in the next we examined the RT results as a function of two factors: The reward magnitude received in the immediately preceding trial and whether the target or distractor colours had switched between trials. Analysis was limited to trials where the distractor was present and had been present in the immediately preceding trial. Because feedback can impact response priming in ways that are in addition to their impact on perception (e.g., Rabbitt & Rodgers, 1977), we were particularly interested in trials where the response was the same as that in the preceding trial. As illustrated in Figure 4a, the reward priming effect was clearly evident in these “same-response” trials in the static distractor colour condition: Responses were faster when high reward had been received in the previous trial and the target colour had stayed the same, and faster when low reward had been received in the previous trial and the target colour had switched. This pattern is not evident in results from the static target colour condition, where there is only a generic slowing of responses (Figure 4b), or in conditions where response has switched from the immediately preceding trial (Figure 5). We conducted a RANOVA with within-subject factors for reward (high-magnitude vs. low-magnitude), colour switch (switch vs. no-switch), and response repetition (same response vs. opposite response) and a between-subject factor for

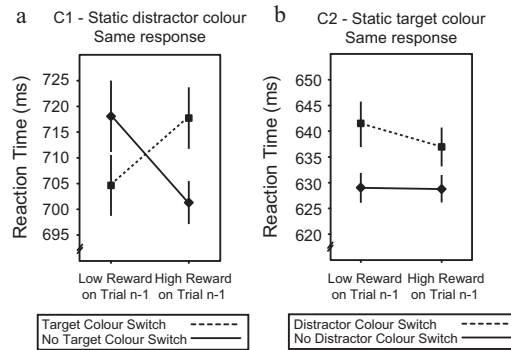


Figure 4. The impact of prior reward and colour switch on visual search in each of the *static distractor* and *static target* conditions. These results reflect performance in trials where response was the same as in the immediately preceding trial.

condition (static distractor vs. static target) in order to statistically assess these results. Importantly, this revealed a significant four-way interaction, demonstrating that the interactive pattern of RTs observed in Figure 4a was reliably different from the patterns observed in all other levels of the response repetition and condition factors, $F(1, 28) = 6.18, p = .019$. A main effect of condition was revealed, $F(1, 28) = 4.71, p = .039$, reflecting faster RTs in the static target colour condition, as was a main effect of reward, $F(1, 28) = 4.51, p = .043$, reflecting faster RTs in trials that followed receipt of high-magnitude reward. No other effects were significant: Response repetition, $F(1, 28) = 1.41$; Reward \times Condition, $F(1, 28) = 1.53$; Colour switch \times Condition, $F(1, 28) = 1.12$; Response repetition \times Reward, $F(1, 28) = 1.16$; Response

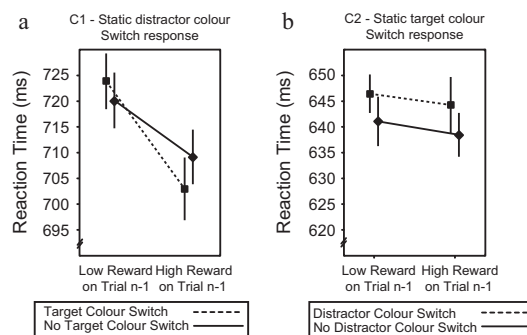


Figure 5. The impact of prior reward and colour switch on visual search in each of the *static distractor* and *static target* conditions. These results reflect performance in trials where response had switched from the immediately preceding trial.

repetition \times Reward \times Condition, $F(1, 28) = 1.14$; Reward \times Colour switch \times Condition, $F(1, 28) = 1.48$; Response repetition \times Reward \times Colour switch, $F(1, 28) = 3.89$; all other $F_s < 1$.

Planned follow-up ANOVAs demonstrated that the interaction between reward and colour switch factors in the static distractor condition was reliable when examined in isolation (Figure 4a), $F(1, 14) = 6.06$, $p = .027$; all other $F_s < 1$. No trend towards a similar pattern was identified in the static target condition (Figure 4b), $F < 1$, where a main effect of colour switch was revealed, $F(1, 14) = 12.56$, $p = .003$; reward, $F < 1$.

DISCUSSION

As is evident in Figure 4a, reward priming occurs when the target colour can vary from trial to trial but the distractor colour is static (and response is repeated between trials; more on this later). Under these circumstances reward can prime target selection but cannot differentially impact distractor suppression. In contrast, when the distractor characteristics can vary from trial to trial but the target colour is static there is no hint of the reward priming pattern; participants are consistently slower when the distractor colour has switched between trials, but this does not interact with the magnitude of reward feedback in the previous trial (Figure 4b). The results thus demonstrate that reward has a residual impact on target selection—guiding attention to targets associated with high magnitude reward—but does not facilitate later suppression of salient distractors that were present in the search array when reward was received.

The current results are broadly consistent with those of Della Libera and Chelazzi (2009, Exp. 2). Participants in that study trained extensively on a task that associated reward with visual stimuli. During training, stimuli consistently acted either as target or as distractor, but in a subsequent test phase objects that had acted as distractors could act as targets and vice versa. As in the present study, when reward-associated distractors reappeared as distractors during the test phase there was no impact on behaviour.

Importantly, Della Libera and Chelazzi (2009) did show that responses were slow when reward-associated distractors reappeared as targets. It thus appears that reward makes distractors hard to select as targets, but does not make them easier to suppress. Why would this be the case? One possibility is that reward has a selective influence on early stages of visual processing that precede distractor suppression. Spatial attention in visual search is thought to initially operate through the rapid detection and localization of target features (e.g., Hopf, Boelmans, Schoenfeld, Luck, & Heinze, 2004), which is followed by the suppression of distractors such that detailed target features can be resolved (e.g., Desimone & Duncan, 1995; Luck et al., 1997; see also

Hickey et al., 2009). We believe that reward may impact the first of these processes but leave the second unchanged.

This proposal is perhaps best described in reference to a simple schematic. We think that search in our paradigm begins with target detection and localization (Stage 1), which is followed by a process of distractor suppression responsible for the resolution of fine target details (Stage 2). Response and reward feedback follow. When outcome is good, the target representation is enhanced and the distractor representation is devalued (Stage 3). Importantly, distractor suppression during visual search is distinct from distractor devaluation that occurs in response to reward feedback.

We think that the process of detection and localization (Stage 1) is sensitive to reward-mediated modulation of representation (which occurs at Stage 3). This means that the target enhancement that follows good outcome (Stage 3) will facilitate detection and localization when the target reappears as a target in subsequent trials (Stage 1). It also means that the distractor devaluation that occurs following good outcome (Stage 3) will make detection and localization problematic when the distractor reappears as a target in subsequent trials (Stage 1). This is consistent with results from Della Libera and Chelazzi (2009) showing that responses to a good-outcome distractor are slowed when it reappears as a target.

In contrast, distractor suppression involved in the resolution of target features (Stage 2) does not appear to be impacted by reward-mediated changes in representation (Stage 3). This means that the distractor devaluation that occurs following good outcome (Stage 3) does not make it any easier to resolve target features, because the underlying process of distractor suppression occurs as normal (Stage 2). In essence, we believe that once the target is detected and localized, a blanket suppression of nontarget features occurs with no regard for reward status. This is consistent with results from both Della Libera and Chelazzi (2009) and the present study showing that search is unchanged when a good-outcome distractor reappears as a distractor in subsequent trials.

The idea that reward selectively impacts very early visual processes that precede distractor suppression is in line with our electrophysiological work with this paradigm (Hickey, Chelazzi, & Theeuwes, 2010a). There we found that the P1 component of the event-related potential was larger in magnitude contralateral to a reward associated stimulus regardless of whether this object was the target of search or a salient distractor. The P1 is generally insensitive to manipulations of visual attention: When elicited by a target singleton its magnitude is the same as when elicited by an equally salient nontarget singleton (e.g., Luck & Hillyard, 1994). Modulation of the lateral P1 as a function of reward thus suggests that reward acts to change perceptual processes that precede the deployment of attention, possibly those processes involved in initial detection and localization of the target.

The reward priming effect may be similar in nature to another phenomenon in visual search known as priming of popout (POP). In POP, selection of a singleton target is facilitated when the colour defining this target is the same as was the case in preceding trials (e.g., Maljkovic & Nakayama, 1994). Recent results from Kristjansson, Sigurjonsdottir, and Driver (2010) have shown that the POP effect is sensitive to reward; the facilitation associated with repetition of a target feature is larger when selection of the target garners good outcome. We have proposed that the receipt of reward may begin a series of cognitive events, starting in the mesencephalic dopamine system, that lead to the reinforcement of representations in visual cortex (Hickey, Chelazzi, & Theeuwes, 2010a, 2010b). It seems likely that this same system underlies the change in POP identified by Kristjansson et al. However, at least two caveats need to be attached to this proposal. First, performance in POP tasks is better not only when the target is repeated between trials, but also when distractors are repeated (e.g., Geyer, Mueller, & Krummenacher, 2007; Kristjansson & Driver, 2008). This suggests a residual influence of distractor suppression plays a role in POP, though the current study demonstrates that reward does not make it easier to suppress a distractor. At first glance it seems odd that reward might influence the target enhancement aspect of POP but leave the distractor suppression aspect unchanged. However, this possibility is consistent with recent modelling work in the perceptual learning literature. Roelfsema, van Ooyen, and Watanabe (2010; see also Roelfsema & van Ooyen, 2005) have suggested that reinforcement learning in visual cortex may be contingent on the application of spatial attention at the same time as reward is received. According to this idea, spatial attention renders object representations plastic, opening the possibility for a reward signal to “burn” these codes into visual cortex such that their processing is facilitated in subsequent experience. At the same time, attention also acts to inhibit the plasticity of unattended stimuli such that the representation of these objects is not inadvertently reinforced. With reference to POP, this raises the possibility that the deployment of attention to a target may make the target representation sensitive to reward feedback while at the same time inhibiting the impact of reward on unattended distractors. Reward may thus have a discrete impact on targets, even if POP reflects changes in both target processing and distractor suppression.

The idea that reward priming and POP might reflect the same underlying mechanisms requires a second caveat. As is evident in Figure 5 of the present study, the reward priming pattern is absent under conditions where response switches from one trial to the next. This suggests that reward priming may be more akin to *dimension priming* in visual search than it is to the *feature priming* thought to underlie POP. Dimension priming is observed in experiments where there are multiple manners in which the target can be defined (for example, when red items of any shape are targets and so are diamonds

of any colour). Performance is better when the target is defined in the same dimension in sequential trials (e.g., Found & Mueller, 1996; Mueller, Krummenacher, & Heller, 2004). Importantly, this effect is reliably observed only under circumstances where response is also repeated between trials (e.g., Kingstone, 1992; Mueller & Krummenacher, 2006; Toellner, Gramman, Mueller, Kiss, & Eimer, 2008). One account for this relationship between dimension priming and response priming is that the cognitive system may be optimized to change both parameters at the same time (Kingstone, 1992; Mueller & Krummenacher, 2006). As such, change in either parameter initiates a reset and creates the need for reestablishment of both systems. Something similar appears to be happening in reward priming, with change in the response parameter extinguishing the propensity to select objects characterized by reward-associated visual features.

We would like to conclude by noting that a visual bias towards reward-associated perceptual features is clearly adaptive; perceptual features that have characterized beneficial objects in the past are likely to do so again in the future. We have suggested elsewhere that this propensity in humans might reflect the action of a very old cognitive mechanism centred on the dopamine reward circuit (Hickey, Chelazzi, & Theeuwes, 2010a). In simple animals an attentive bias towards reward-associated features may constitute the primary source of attentional control. Humans have clearly acquired the ability to deploy attention in the absence of immediate reinforcement feedback, but this does not mean that the old, reward-driven system no longer has a say in attentional control.

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