# The modulation of reward priority by top-down knowledge

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# The modulation of reward priority by top-down knowledge

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Reward-associated features capture attention automatically and continue to do so even when the reward contingencies are removed. This profile has led to the hypothesis that rewards belong to a separate class of attentional biases that is neither typically top-down nor bottom-up. The goal of these experiments was to understand the degree to which top-down knowledge can modulate value-driven attentional capture within (a) the time-course of a single trial and (b) when the reward contingencies change explicitly over trials. The results suggested that top-down knowledge does not affect the size of value-driven attentional capture within a single trial. There were clear top-down modulations in the magnitude of value-driven capture when reward contingencies explicitly changed, but the original reward associations continued to have a persistent bias on attention. These results contribute to a growing body of evidence that reward associations bias attention through mechanisms separate from other top-down and bottom-up attentional biases.

*Keywords*: Attention; Reward; Attentional capture; Top-down; Selection history.

## INTRODUCTION

Rewards are an incredibly important source of information. Stimulus features associated with rewards (e.g., a tree rich in food or a slot machine yielding money) not only bias arousal levels or decision-making processes (Dorris & Glimcher, 2004; Knutson & Greer, 2008; O'Doherty, Buchanan, Seymour, &

Dolan, 2006; Platt & Glimcher, 1999), but also enjoy high attentional priority (Anderson, Laurent, & Yantis, 2011a; Della Libera & Chelazzi, 2006; Della Libera, Perlato, & Chelazzi, 2011; Hickey, Chelazzi, & Theeuwes, 2010; Kiss, Driver, & Eimer, 2009; Lee & Shomstein, 2013; Qi, Zeng, Ding, & Li, 2013; Stankevich & Geng, 2014). Reward-based attentional priority has two main characteristics: rapid stimulus-driven attentional capture and persistence during reinforcement extinction. These effects have been referred to as value-driven attentional capture (Anderson, Laurent, & Yantis, 2011a) and are thought to be distinct from top-down and bottom-up sources of attentional bias (Awh, Belopolsky, & Theeuwes, 2012). However, the extent to which top-down knowledge can modulate value-driven attentional biases remains unclear. In these experiments, we further explore the robustness of reward-based attentional capture by examining the temporal evolution of reward biases on two time scales: (a) within a single trial and (b) during reinforcement extinction.

In traditional characterizations of attention, top-down and bottom-up cues are distinguished by their temporal profiles of efficacy within a single trial. Top-down cues (e.g., a centrally presented arrow) begin to facilitate performance approximately 200 ms after cue onset and can last until the target appears. The delayed onset is attributed to the cognitive processes necessary to interpret the symbolic cue stimulus and to initiate mechanisms of attentional selection (Jonides, 1981; Müller & Rabbitt, 1989; Posner, 1980). In contrast, bottom-up cues (e.g., a peripherally presented stimulus flash or onset) are typically perceptually salient and have a rapid, but short-lived cueing profile. Facilitation begins at cue onset, lasts approximately 200–300 ms (Egeth & Yantis, 1997; Müller & Rabbitt, 1989; Posner, 1980), and is frequently followed by an inhibitory after effect referred to as inhibition of return (IOR; Klein, 1988, 2000).

Value-driven attentional capture is thought to be neither typically top-down nor bottom-up (Awh et al., 2012), but the entire temporal profile of the cueing effect has not been systematically mapped. There is substantial evidence that reward-associated features produce rapid, stimulus-driven, attentional and oculomotor capture similar to that of typical bottom-up cues (Anderson & Yantis, 2012; Anderson, Laurent, & Yantis, 2011a, 2011b; Camara, Manohar, & Husain, 2013; Failing & Theeuwes, 2014; Hickey & van Zoest, 2012, 2013; Hickey et al., 2010; Kiss et al., 2009; Krebs, Boehler, Appelbaum, & Woldorff, 2013; Qi et al., 2013; Schevernels, Krebs, Santens, Woldorff, & Boehler, 2014). For example, in visual search, the presence of a distractor object with a previously rewarded feature interferes with performance, even when it is known to no longer produce rewards (Anderson, Laurent, & Yantis, 2011a). Similarly, the N2pc, an ERP signature of attentional orienting that occurs approximately 200 ms after stimulus onset (Luck & Hillyard, 1994), is larger and earlier contralateral to targets associated with higher value rewards (Kiss et al., 2009). This work provides evidence that value-driven attentional capture can bias attention at the

earliest timescales (i.e., operating between 0 and 200–300 ms following a stimulus), but less is known about the effects of reward based attentional selection later on within a trial when top-down modulations of attention normally occur (i.e., 200 ms or longer). If learned reward associations act primarily through stimulus-driven mechanisms, the strength of reward as an attentional bias should decay as the cue-target SOA increases, possibly even producing IOR (Klein, 1988, 2000). However, if it also reflects top-down processes, then the attentional bias towards an expected reward-associated stimulus should be sustained until the target appears. The first goal of these experiments was to investigate this question using a cued target discrimination paradigm with varying SOAs.

A second characteristic of value-driven capture is that it persists over time, when typical attentional cues are no longer effective. Rewards continue to bias attention even when they are ostensibly irrelevant (e.g., during extinction) and this persistence can last over trials, days, or even months without observer awareness (Anderson & Yantis, 2012, 2013; Anderson, Laurent, & Yantis, 2011a, 2011b; Della Libera & Chelazzi, 2009). For example, trial-by-trial effects have been demonstrated in a variant of the priming of pop-out paradigm (Maljkovic & Nakayama, 1994) in which repetition priming was found to be greater for targets associated with rewards (Kristjánsson, Sigurjónsdóttir, & Driver, 2010). Moreover, behaviour followed the reward schedule, such that differences in priming reversed when the probability of reward associated with two different target colours reversed. On longer timescales, Anderson and Yantis (2013) found that learned reward associations from an experimental session 7–9 months ago continued to influence performance when subjects returned to lab and engaged in a task with no reward contingencies.

However, the effect of rewards is not necessarily dependent on performance outcomes. Even when attentional capture by the reward-associated stimulus is detrimental to collecting rewards (Le Pelley, Pearson, Griffiths, & Beesley, 2014), or unrelated to performance (Della Libera et al., 2011), attentional and oculomotor capture to the reward-associated stimuli continues. For example, Della Libera and colleagues (2011) found that explicit instructions that rewards were unrelated to performance resulted in attention being biased to any stimulus (i.e., targets or distractors) associated with reward. This suggests that reward associations are learned based on simple statistical co-occurrences in addition to being sensitive to performance outcomes. Similar results were found by Le Pelley et al. (2014) in which a salient distractor was more likely to capture attention when it was associated with a high reward target, even when attending to the distractor had a deleterious effect on performance (i.e., decreased the likelihood of reward). The results suggested that attention was captured by stimuli that signalled reward, even if they were irrelevant to the necessary response to gain rewards.

Together, these results suggest that attentional capture by reward-associated stimuli is automatic and largely impervious to extinction. However, it remains unclear the degree to which explicit top-down knowledge can modulate these learned associations, particularly when there is direct evidence that the previously rewarded feature will no longer produce rewards. It may be that learned rewards are impervious to top-down selection entirely, or only partially so. We investigated this second question in Experiments 2 and 3 by making changes in reward contingencies explicit to the observers.

## EXPERIMENT 1

The purpose of Experiment 1 was to examine the temporal profile of reward cues on attentional processing. We used a visual search task in which the colour of the stimuli was task-irrelevant, but indicated the level of monetary reward to be gained if performance was accurate and fast. The critical manipulation of interest was the reward cue-target stimulus-onset asynchrony (SOA). We expected our results to replicate findings that rewarded stimuli would enjoy higher attentional priority (Anderson, Laurent, & Yantis, 2011a; Della Libera et al., 2011; Hickey et al., 2010; Krebs, Boehler, Egner, & Woldorff, 2011; Krebs, Boehler, Roberts, Song, & Woldorff, 2012; Peck, Jangraw, Suzuki, Efem, & Gottlieb, 2009), but the question of interest was whether the strength of the reward priority would change with the cue-target SOA.

### Method

*Participants.*   Seventeen participants were recruited from the University of California, Davis. All had normal or corrected-to-normal vision. Participants received course credit for their participation as well as an additional monetary payout based on performance during the experiment (mean = US$8.43). Informed consent was obtained from all participants in accordance with the University of California, Davis Institutional Review Board.

One participant was removed based on poor performance (i.e., less than 50% accuracy within a condition) and three participants were removed due to poor quality eye-data (i.e., either the subject could not maintain fixation or the calibration quality was so poor that the eye could not be properly tracked). This resulted in the analyses of data from 12 participants (2 males; mean age: 21.09; age range: 18–28; 11 right-handed).

*Apparatus.*   An Intel ® Core ™ i7 equipped with Presentation software (Version 14.9; http://neurobs.com) was used to present the stimuli on a Dell 2408WFP monitor. The participants viewed the monitor from a distance of ~60 cm in a dimly lit room. Responses were entered using a standard 101-key

US layout keyboard. Eye position data for each participant was collected using an Eyelink1000 version 4.56 (SR Research, Canada; sampling rate = 500 Hz).

*Stimuli.* The stimuli were composed of coloured circles, (orange 25.9 cd/m²; or green 25.7 cd/m²; 1.62° × 1.62° visual angle) presented at the centre of the display in the baseline task or bilaterally in the target discrimination task (each 5.30° visual angle from the centre of the screen). Targets were identical to cues, but with a single black dot (0.38° × 0.38°) added above or below the horizontal meridian of the circle (Figure 1A,B). Distractors in the target discrimination task were identical to targets, but the dot was to the left or right of the vertical meridian (i.e., a 90° rotation of the target). The feedback display in both the baseline and target discrimination tasks consisted of white text ("+0.04" or "+0.00") presented 1.05° above a central fixation cross and informed participants of the reward earned on that trial.
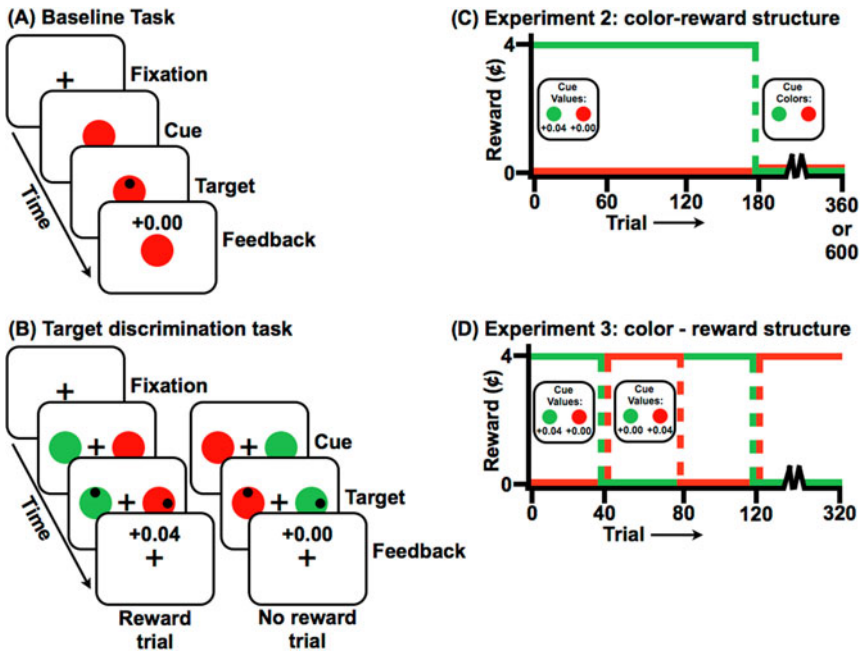


**Figure 1.** (A) Illustration of the trial procedure for the baseline task for Experiments 1 and 2. Cue circle shown in red to illustrate the non-rewarded cue colour. (B) Illustration of the trial procedure for the target discrimination task for Experiment 1 reproduced from Stankevich and Geng, 2014. Cue circles are shown in green and red to illustrate rewarded and non-rewarded cue colours, respectively. (C) Illustration of reward extinction in Experiment 2. Inset illustration depicts instruction screens presented at the outset of reward learning (left) and reward extinction (right) blocks. (D) Illustration of reward reversals across blocks in Experiment 3. Inset illustration depicts instruction screens presented at outset of original (left) and reversed (right) mapping blocks.

*Design and procedure.*   The general sequence of events and time course for the baseline and target discrimination task were previously described (Stankevich & Geng, 2014) and are shown in Figure 1A,B. Briefly, the purpose of the baseline task was to train participants on the task and the colour-reward associations (Figure 1A). Each baseline trial was initiated after 100 ms of continuous central fixation and began with a centrally presented coloured "cue" circle followed by the target. The colour of the cue indicated the potential reward amount for a correct answer on that trial (i.e., rewarded = US$0.04; non-rewarded = US$0.00). The cue was visible for 0–800 ms and the target for 200 ms (i.e., SOA durations of 0, 200, 400, or 800 ms).

Participants indicated whether the target "dot" was in the top or bottom half of the circle by pressing the *k* ("above") or *m* ("below") keys with their right middle and index fingers, respectively. Participants were told that responses must be made within 1000 ms in order to be deemed correct. Responses were followed by a feedback screen lasting 1000 ms (see Figure 1A). The inter-trial interval lasted 800–1200 ms. Each colour was presented in a pseudorandom fashion for a total of 144 trials. The colour-reward pairings were randomly assigned and counterbalanced across participants. Learning of the colour–reward contingencies was verbally assessed at the end of the baseline task. All subjects demonstrated knowledge of the reward contingencies.

The target discrimination task was identical except that the cue and target screens were composed of one orange and one green circle presented bilaterally (each 5.30° visual angle from the centre of the screen; Figure 1B). As in the baseline task, we manipulated the cue-target SOA to test a range of time points relevant for "bottom-up" and "top-down" attentional selection (0–800 ms). Attentional facilitation by rewards during only the early SOAs (i.e., 0 and 200 ms) would suggest that rewards act as a "bottom-up" cue, whereas facilitation during only the later SOAs (i.e., 400 and 800 ms) would suggest that rewards function as a "top-down" cue. The target dot was randomly assigned to either the left or right circle and a distractor dot appeared in the other. The target (above, below) and distractor (left, right) locations were randomly assigned on each trial. Participants made the two-alternative-forced-choice target identification by pressing the *k* ("above") or *m* ("below") keys with their right middle and index fingers, respectively. RTs were measured from the onset of the target display and only considered correct if responses were made within 1000 ms. Correct responses were followed with reward feedback based on the learned reward-colour association (rewarded = US$0.04; non-rewarded = US$0.00). All incorrect or slow responses were followed with a non-rewarded feedback display (Figure 1B). The target discrimination task consisted of 288 trials.

All participants were given written and oral descriptions of the tasks. Participants were instructed that no rewards would be given for responses that were too slow and that they should try to respond as quickly and accurately as possible. Participants were provided with a short break after every 72 trials during

the baseline and target discrimination tasks. During the breaks, participants were informed of the amount of money earned during the previous block of trials as well as the total amount earned. Participants were rewarded on a 1:1 scale (i.e., US$1.00 in the task equalled US$1.00 in the real world). Importantly, the locations of the rewarded and non-rewarded colours were randomly assigned on each trial and this assignment was orthogonal to the location of the target. Thus, the cue circle colour did not predict the location of the target. Each participant was tested individually over the course of a single 1-hour session.

*Analysis.* Only correct answers with RTs less than two *SD*s above or below the individual's condition mean were included for analysis. We included correct trials where the participants responded too slowly (i.e., RT > 1000 ms) and were thus given non-rewarded feedback regardless of cue circle colour-reward pairing. We kept these trials in the analyses because participants were unlikely to know at the time of the button press that their response would be too slow to receive a reward; and we are interested in the effects of reward expectancies on attentional selection not its effects during feedback. Trials where subjects did not hold central fixation were excluded (average number of trials excluded was less than 3% in each experiment). Where pairwise comparisons are done, they are reported with Bonferroni correction for the number of comparisons made, unless stated otherwise.

*Baseline task analysis.* The primary purpose of the baseline, in which a single cue and target was centrally presented, task was to train individuals on the colour-reward mapping. To ensure that the colour-reward mapping did not interact with the overall effect of reward, RT and accuracy data from the baseline task were entered into mixed-effects ANOVAs with the within-subject factors of reward (rewarded, non-rewarded) and SOA (0, 200, 400, 800 ms) and the between-subjects factor of colour-reward mapping. Significant effects were observed for SOA, $F(3,30) = 40.46$, $p < .0001$, and colour mapping on RT, $F(1,10) = 6.67$ $p = .027$. There was no significant main effect of reward, $F(1,10) = .98$, $p = .35$, nor any interactions, all $F(3,30) > 1.25$, all $p > .31$.

The main effect of SOA was due to longer RTs at 0 ms than all other durations, all $t(11)>7.03$, all $p < .001$ with Bonferroni correction. The effect of colour was due to participants in one group (i.e., with green targets $= + 0.04$ and orange targets $= +0.00$) being slower overall. However, there was no interaction between reward and colour mapping, which indicated that the processing time for rewarded and non-rewarded targets was not affected by the precise colour-reward association. We therefore collapsed across colour-reward mapping in the remaining analyses. Furthermore, the lack of a main effect of reward was consistent with our previous findings (Stankevich & Geng, 2014) that perceptual processing of rewarded and non-rewarded stimuli was similar when the stimuli were centrally presented on their own and there was no competition for attention.

## Results and discussion

RT and accuracy data from the target discrimination task were entered into random-effects ANOVAs with factors of reward (rewarded, non-rewarded) and SOA (0, 200, 400, 800 ms). Significant effects were observed for reward, $F(1,11) = 7.83$, $p = .017$, and SOA, $F(3,33) = 18.38$, $p < .0001$, on RT (Figure 2). However, the interaction was not significant, $F(3,33) = .77$, $p = .38$, suggesting that attentional priority enjoyed by rewarded targets did not change as a function of the cue-target SOA (see Figure 2).

RTs were overall shorter to rewarded compared to non-rewarded targets and RTs were significantly longer for the 0 ms SOA compared to 200 and 400 ms SOAs, all $t(11) > 3.36$, all $p < .04$. Additionally, RTs were significantly shorter for 200 ms SOA compared to all other SOAs, all $t(11) > 3.19$, all $p < .05$. There were no other significant differences for the other SOA pairwise comparisons, all $t(11) < 1.65$, $p > .05$. Accuracy was high ($M = 0.98$) and there were no significant effects based on reward, SOA, nor an interaction between the two, all $F < 3.34$, all $p > .09$.

These results replicate previous research showing that reward-associated stimuli capture attention independent of other task goals or perceptual effects. In addition, the current data demonstrate that the RT benefit for rewarded targets was sustained throughout all SOAs (Figure 2). This suggests that the rewarded colour captured attention akin to bottom-up saliency and was also sustained over time similar to top-down cues.

## EXPERIMENT 2

Given the sustained influence of the reward cue on attentional selection over variable SOAs found in Experiment 1, we next investigated whether this pattern
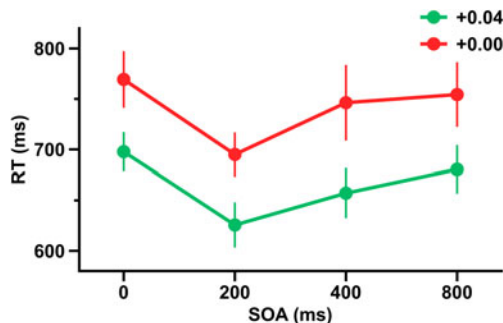


**Figure 2.** Interaction of reward × SOA in Experiment 1 target discrimination task. No interaction between reward and SOA was observed, but both main effects of reward and SOA, were significant. Note that the size of the reward validity effect was equivalent at all SOAs. Error bars reflect SEM.

would also be found during reward extinction. While the colour-reward associations were irrelevant for the task of finding and discriminating the target in Experiment 1, the stimulus colours were motivationally relevant because they had consequences for the accrual of money. The knowledge of monetary reward may have acted as an additional top-down attentional cue. In order to remove the possibility of top-down knowledge acting as an attentional bias towards the rewarded colour, we introduced an extinction phase in Experiments 2ab. During extinction, subjects were explicitly told that the colour-reward mapping would be removed. If the previous effects of reward were due to top-down knowledge, then we would expect there to be no bias towards the previously rewarded colour. However, if the effect of reward was based on learned contingencies only, then we might expect similar effects in the reward and extinction phases of the experiment. Furthermore, we used a range of cue-target SOAs, which measured the within-trial timecourse of the reward-associated attentional bias (if any) as a function of top-down knowledge about the reward association.

## Method

*Participants.*    Thirty new participants were recruited from the University of California, Davis (18 in Experiment 2a and 15 in Experiment 2b). All had normal or corrected-to-normal vision. Participants received partial course credit for their participation as well as an additional monetary payout that participants were told was based on performance during the experiment but in fact all participants received an equal amount (US$10.00). Informed consent was obtained from all participants in accordance with the University of California, Davis Institutional Review Board. Data from six participants were precluded from analysis because of poor quality eye-data; data from three were excluded due to accuracy being less than 50% correct in one, or more, condition(s). This resulted in the analyses of 10 participants in Experiment 2a (5 males; mean age: 20.3; age range: 18–23; 10 right-handed) and 11 participants (3 males; mean age: 20.55; age range: 19–23; 10 right-handed) in Experiment 2b.

*Apparatus and stimuli.*    The apparatus and stimuli were identical to Experiment 1.

*Design and procedure.*    Experiment 2 was identical to Experiment 1 except that partway through the target discrimination task the colour-reward mapping was extinguished. The experiment consisted of 180 rewarded trials (identical to Experiment 1) followed by 180 (Experiment 2a) or 420 (Experiment 2b) extinction trials. During the extinction trials, the reward-based feedback screen ("+0.04" or "+0.00") was replaced with performance-based feedback ("Correct" or "Incorrect"). Participants were informed at the end of the reward phase and immediately preceding the first extinction trial that the colour-reward mappings

were no longer valid and that they would instead receive performance-based feedback. This was done verbally during a rest period where the screen contained the two colour cues (similar to the instruction screen, but without any references to monetary associations; Figure 1C); the verbal instructions from the experimenter were that the colour cues were no longer indicative of monetary reward, that feedback on each trial would indicate accuracy, and that they would receive additional money at the end of the experiment based solely on overall performance accuracy. This was done to equate motivation in the second phase with the first phase of the study without linking the monetary reward to a specific target colour. Participants were provided with a short break after every 60 trials. Participants received the same monetary payout of US$10.00 regardless of performance, but were naïve to this fact until the end of the study.

*Analysis.*   Analysis was carried out identically to Experiment 1 and results from Experiment 2a will be presented alongside the equivalent analysis from Experiment 2b.

*Baseline task analysis.*   We combined the data from the baseline tasks in Experiments 2A and 2B because the tasks were identical and to increase our statistical power. Analysis of the baseline task yielded an RT effect on SOA, $F(3,69) = 49.2$, $p < .0001$. The effect of SOA was due to slower RTs to 0 ms as compared to all other SOAs, all $t(23) > 8.2$, all $p < .0001$. The main effect of reward was not significant, $F(1,23) = 2.98$, $p = .1$, nor was the two-way interaction, $F(3,69) = 1.22$, $p = .3$.

Accuracy was high ($M = 0.99$) and there were no significant differences, all $F < 1.7$, all $p > .18$. Overall, the patterns of results were equivalent to those from Experiment 1, and demonstrated no interactions between SOA, reward, and reward-colour mapping when targets appeared alone.

## Results and discussion

RT and accuracy data from the target discrimination tasks from Experiments 2a and 2b were entered into random-effects ANOVAs with factors target reward (rewarded, non-rewarded), cue-target SOA (0, 200, 400, 800 ms), and block number (six blocks for Experiment 2a; 10 blocks for Experiment 2b; the first three were always learning blocks and the remaining were extinction blocks). Targets in the extinction blocks were labelled as "rewarded" or "non-rewarded" based on their colour association from the first learning blocks with reward feedback.

All three main effects were significant in both Experiment 2a (target reward, $F(1,9) = 18.61$, $p = .002$, cue-target SOA, $F(3,27) = 39.83$, $p < .001$, and block number, $F(5,45) = 10.67$, $p < .001$) and Experiment 2b (target reward, $F(1,10) = 29.45$, $p < .001$, cue-target SOA, $F(3,30) = 39.13$, $p < .001$, and block number,

$F(9,90) = 6.84$, $p < .000$). RTs were shorter to rewarded targets (Experiment 2a: $M = 634.07$ ms; Experiment 2b: $M = 662.97$ ms) than non-rewarded targets (Experiment 2a: $M = 759.50$ ms; Experiment 2b: $M = 703.98$ ms). The main effect of SOA was represented by a U-shaped curve (similar to Experiment 1) with the longest RTs for the 0 ms condition, followed by the 800, 400, and 200 ms conditions, respectively (Experiment 2a: only pairwise comparisons between 0 ms SOA and the other SOAs survived correction, all $t(9) > 4.57$, all $p < .008$; Experiment 2b: pairwise comparisons between the early SOAs (0 and 200 ms) and all other SOAs survived correction, all $t(10) > 5.49$, all $p < .002$). RTs became progressively shorter across blocks (first block Experiment 2a: $M = 758.51$ ms; Experiment 2b: $M = 683.64$ ms; last block Experiment 2a: $M = 643.75$ ms, Experiment 2b: $M = 610.02$ ms), first block vs. last block Experiment 2a: $t(9) = 3.57$, $p = .006$, Experiment 2b: $t(10) = 3.61$, $p = .005$. The pattern of main effects observed here are in line with those from Experiment 1.

More importantly, there was a significant two-way interaction of target reward × block number, Experiment 2a: $F(5,45) = 10.67$, $p < .001$, Experiment 2b: $F(9,90) = 4.31$, $p < .001$, reflecting a reduction in the reward cueing effect during the extinction blocks (Figure 3A,C; Table 1). This significant interaction between block number and target reward suggested that the effect of the learned association on attentional priority did extinguish to some extent. The change in attentional priority seemed to go through two phases, an initial decrease in RTs to the previously non-rewarded targets, followed by a secondary phase of persistent value-driven attentional capture, which lasted the remainder of the task. All comparisons during the learning blocks were highly significant (see Table 1); almost all the pairwise comparisons within the extinction blocks remained significant without Bonferroni correction, Experiment 2a: all $t(9) > 1.83$, $p < .099$; Experiment 2b: all $t(10) > 2.45$, $p < .04$, but varied with correction (see Table 1). The weaker statistical effects during the extinction blocks reflected a decrease in reward priority. Nevertheless, even in the last extinction block, the advantage for the previously rewarded colour was 63 ms and 42 ms in Experiments 2a and 2b, respectively. This reflected a maintenance of 36% and 35% of the validity effect (i.e., RT to previously non-rewarded—RT to previously rewarded targets) from the learning blocks (Figure 3A,C).

In order to examine the initial drop in the reward validity effect during the extinction blocks in more detail, we conducted an additional analysis on the data from blocks 3 and 4 (i.e., the last block with reward feedback and the first block without reward feedback). The two experiments were identical during these blocks and therefore the data were combined. The data were divided into 12 equal bins of 10 trials each (Figure 4) and pairwise $t$-tests were conducted between the rewarded and non-rewarded targets in each time bin (see Table 2). This analysis demonstrated there was a significant decrease in value-driven attentional capture when the extinction blocks began: the reward validity effect
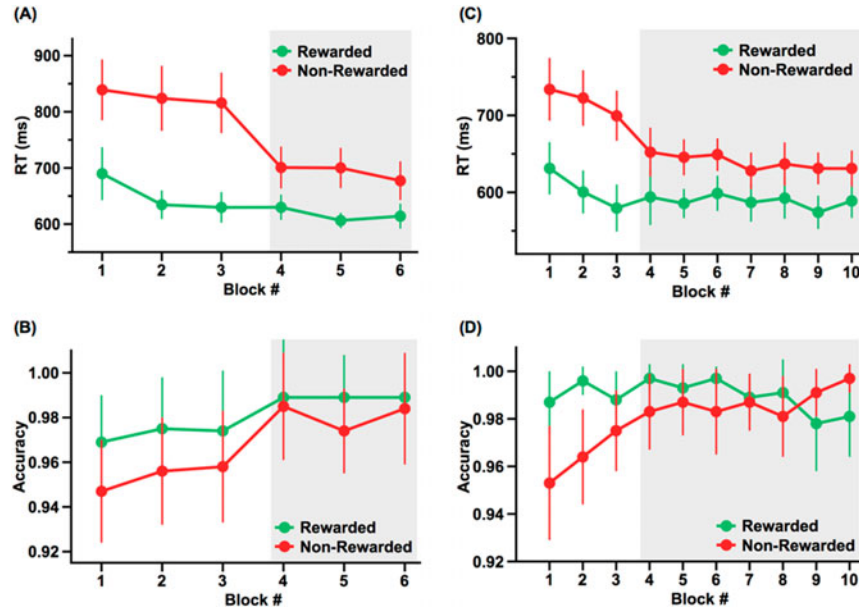
**Figure 3.** Interaction of reward × block in Experiments 2a and 2b. (A) RT data from Experiment 2a. (B) Accuracy data from Experiment 2a. (C) RT data from Experiment 2b. (D) Accuracy data from Experiment 2b. During extinction blocks (grey box), RTs to previously non-rewarded targets became shorter, but the change in RT preserved the reward-associated bias from the learning phase. Green = rewarded targets; Red = non-rewarded targets. Bars reflect SEM.

TABLE 1

Pairwise comparisons from the interaction of reward × block from Experiments 2a and 2b. Values in the table are the *t*-values and uncorrected *p*-values from pairwise comparisons between RTs to rewarded and non-rewarded targets across blocks. Values with an asterisk (*) survived Bonferroni correction.

| | | Block | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* |
| Experiment 2a | *t*-value | 5.64 | 4.33 | 4.52 | 3.09 | 2.68 | 1.84 | | | | |
| | *p*-value | <.001* | .002* | .001* | .013 | .026 | .099 | | | | |
| Experiment 2b | *t*-value | 4.28 | 5.2 | 5.47 | 6.01 | 5.04 | 2.95 | 2.91 | 2.88 | 4.34 | 2.46 |
| | *p*-value | .002* | <.001* | <.001* | <.001* | <.001* | .015 | .016 | .016 | .001* | .034 |

decreased from 174.63 ms in bin 6, to 97.36 ms in bin 7 (first extinction bin) and reached a plateau at 49.77 ms in bin 8. The validity effect dropped by 72.5% within 20 trials.

None of the interactions involving SOA were significant, all $F < 1.4$, all $p > .2$. The value-driven attentional capture was stable across all SOAs, replicating the effects found in Experiment 1.

Accuracy was high (Experiment 2a: $M = 0.99$; Experiment 2b: $M = 0.97$) and there were no significant main effects based on reward, block, or SOA, all $F < 4.15$, all $p > .069$. The two-way interactions of SOA × block and of SOA × reward were not significant, and neither was the three-way interaction, all $F < .96$, all $p > .38$. The only significant difference was a two-way interaction between block and reward in Experiment 2b, $F(9,90) = .2.26$, $p = .02$; this was not significant in Experiment 2a, $F(15,45) = .28$, $p = .92$. During the extinction blocks of Experiment 2b, there was an increase in the accuracy to the non-rewarded targets, mirroring the results from the RT analysis (Figure 3B,D).

There were two main conclusions from these data. The first was a replication of Experiment 1, which demonstrated that reward cues influenced attentional priority across all cue-target SOAs tested. This suggested that reward cues have an early and sustained effect on attentional priority consistent with a mixed profile of top-down and bottom-up cueing. The second was in regard to extinction of the learned reward associations once the reward contingencies were removed. While there was an immediate decrease in the strength of the reward association bias on attention, it continued to enjoy higher priority for the entirety of the task. This suggests that there was a top-down modulation of the reward priority that reduced its influence, but that full extinction may rely on a different mechanism such as statistical evidence from selection history
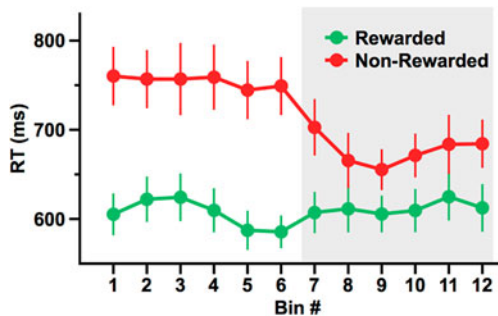


**Figure 4.** Interaction of reward × bin number from blocks 3 and 4 in Experiments 2a and 2b. The combined data were split into 10 trial bins for better visualization of the initial extinction phase. A sharp decrease in RTs to non-rewarded targets occurred within 20 trials after extinction began and was followed a sustained bias towards the previously rewarded colour. Green = rewarded targets; Red = non-rewarded targets. Grey box denotes the rewards extinction blocks. Bars reflect SEM.

TABLE 2

Pairwise comparisons from the interaction of reward × bin for the combined data from Experiment 2. Values in the table are the $t$-values and uncorrected $p$-values from pairwise comparisons between RTs to rewarded and non-rewarded targets. Values with an asterisk (*) survived Bonferroni correction.

| | Bin | | | | | | | | | | | |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* | *9* | *10* | *11* | *12* |
| $t$-value | 5.07 | 4.42 | 4.49 | 4.99 | 6.61 | 6.94 | 4.12 | 2.03 | 2.57 | 3.82 | 3.13 | 4.64 |
| $p$-value | <.001* | <.001* | <.001* | <.001* | <.001* | <.001* | <.001* | .06 | .02 | .001* | .005 | <.001* |

(Awh et al., 2012). In the next experiment, we test a boundary condition of selection history vs. top-down knowledge by oscillating the reward-associated colour between blocks.

## EXPERIMENT 3

In Experiment 3 we used a reversal paradigm and switched the colour-reward mapping from block-to-block in order to further test the interaction between top-down knowledge and learned reward associations. If the selection history of rewarded stimuli always dominates attentional priority, then we would expect a reduction in the reward cueing effect over blocks (as the overall probability history for each cue colour drops to chance). However, if top-down knowledge controls reward learning, then we would expect attentional priority to oscillate in phase with the explicit reward structure. A third alternative is that there will be a mixture of effects such that explicit knowledge will set priority towards the currently rewarded colour, but selection history will modulate the timecourse or size of the reversal in attentional priority. This latter possibility would be most consistent with the results from Experiment 2 where we observed a reduction in the strength of value-driven attentional capture during the extinction phase, which emerged over about 20 trials.

## Methods

*Participants.*    Eighteen participants were recruited from the University of California, Davis. All had normal or corrected-to-normal vision. Participants received partial course credit for their participation as well as an additional monetary payout that participants were told was based on performance during the experiment but in fact all participants received an equal amount (US$10.00). Informed consent was obtained from all participants in accordance with the University of California, Davis Institutional Review Board. One participant was removed based on poor central fixation (e.g., requiring multiple calibrations within a short run of trials), two participants were removed for missing values in a condition, and two participants were removed due to computer issues resulting in the analyses of 13 participants (four males; mean age: 21.2; age range: 18–21; 13 right-handed).

*Apparatus and stimuli.*    The apparatus and stimuli were identical to Experiments 1 and 2 except for the few differences described below.

*Design and procedure.*    Experiment 3 consisted of 320 trials in the target discrimination task. The target discrimination task was identical to Experiment 1 except that the colour-reward mapping alternated every 40 trials (Figure 1D).

Unlike in Experiments 1 and 2, in Experiment 3 there was no baseline task as the colour-reward mapping alternated throughout the target discrimination task. Instead, participants were informed of the colour-reward mapping change in between blocks both verbally and visually (Figure 1D). As was the case for Experiment 2, participants received the same monetary payout of US$10.00 regardless of performance, but were naïve to this fact until the end of the study.

*Analysis.*    Analysis was carried out identically to Experiments 1 and 2.

## Results and discussion

RT and accuracy data from the target discrimination task were entered into random-effects ANOVAs with factors target reward (rewarded, non-rewarded), cue-target SOA (0, 200, 400, 800 ms), and block number (8 blocks). Labelling of target reward was based on the colour-reward mapping from the first block of the experiment. There were main effects of SOA, $F(3,36) = 36.12$, $p < .001$, and block number, $F(7,84) = 5.14$, $p < .001$. As in the previous experiments, participants had longer RTs in the 0 ms SOA condition as compared to all other SOAs, all $t(12) > 5.95$, all $p < .001$ shorter RTs in the 200 ms SOA condition as compared to 0 ms (see above) and 800 ms SOA, $t(12) = 3.3$, $p = .04$, and marginally shorter compared to the 400 ms SOA, $t(12) = 2.85$, $p = 0.09$. The final pairwise comparison between 400 and 800 ms SOA was not significant, $t(12) = 1.45$, $p = .1$. Also as observed in the previous experiments, the effect of block number was due to an overall decrease in RTs as the task progressed, first block vs. last block: $t(12) = 3.57$, $p = .004$. There was no main effect of reward, $F(1,12) = .02$, $p = .9$, reflecting the fact the colour-reward mapping switched each block.

More importantly, as in Experiment 2, the two-way interaction of block × reward was significant, $F(7,84) = 7.79$, $p < .001$. This interaction reflected the fact that RTs followed the reversal pattern such that value-driven attentional capture was based on the currently rewarded target colour (Figure 5). None of the other interactions were significant, all $F < 1.06$, all $p > .38$.

In order to better understand the timecourse of the reversal, we divided the data into bins of 10 trials each, just as in Experiment 2 (Figure 6). Data from the blocks with the same reward mappings were collapsed to increase statistical power. As before, we performed pairwise $t$-tests on the non-rewarded against the rewarded targets at each time bin (see Table 3). The reward validity effect was significant by the third bin on blocks with the original reward mapping, but was not significant (even without correction) until the fourth bin in the reversal blocks. This suggested that the original mapping was easier to reinstate, even though the two mappings oscillated back and forth repeatedly.

Accuracy was high ($M = 0.97$) and none of the main effects of reward, block, or SOA were significant, all $F < 3.0$, all $p > .1$. There was a significant two-way
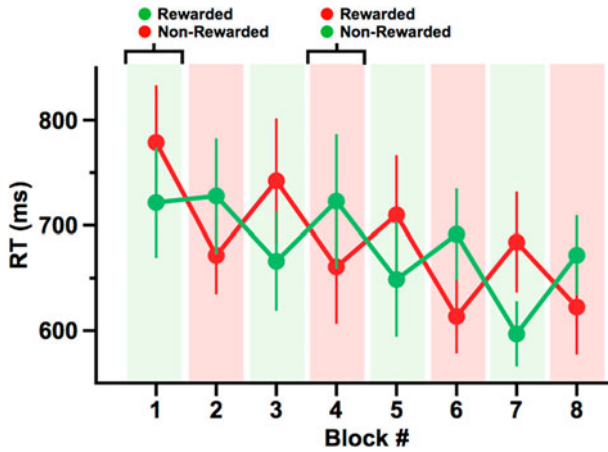
**Figure 5.** Interaction of block number × reward in Experiment 3. RTs oscillated with the switches in the colour-reward contingency from block-to-block. Coloured boxes indicate the target colour that was rewarded in each block. Line colour indicates the trial-by-trial target colour. Bars = SEM.

interaction between reward and SOA, $F(3,36) = 4.98$, $p = .005$ due to differences in target reward at the 200 ms SOAs, $t(12)2.97$, $p = .05$. However, this result was difficult to interpret due to the fact that "target reward" was defined by the original reward mapping and not the actual reward values. The two-way
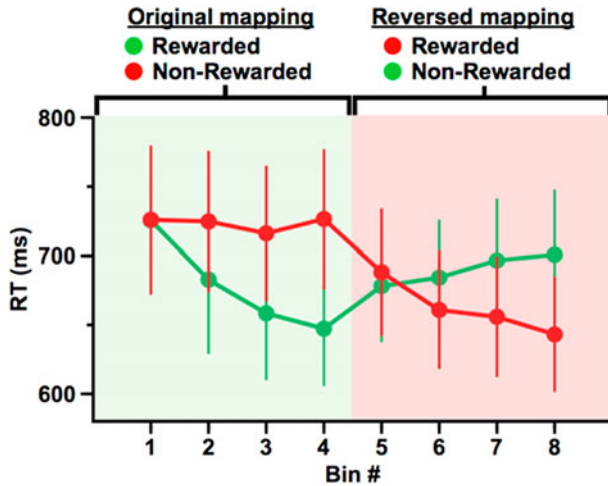


**Figure 6.** Interaction of bin number × reward in Experiment 3. Data from each block were split into 10 trial bins that were collapsed across blocks with the same colour-reward mapping. Data show growth of reward-associated attentional benefit before and after reversal of colour-reward mapping. Coloured boxes indicate the target colour that was rewarded. Note that the experiment began with the "green" target rewarded (counterbalanced between participants). Bars/shading = SEM.

TABLE 3

Pairwise comparisons from the interaction of reward × bin from Experiment 3. Values in the table are the *t*-values and uncorrected *p*-values from pairwise comparisons between RTs to rewarded and non-rewarded targets (see Figure 6). Values with an asterisk (*) survived Bonferroni correction.

| | Bin | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | *1* | *2* | *3* | *4* | *5* | *6* | *7* | *8* |
| *t*-value | 3.93 | 41.97 | 57.65 | 79.12 | 9.99 | −23.47 | −40.8 | −57.55 |
| *p*-value | .87 | .09 | .005* | .001* | .52 | .27 | .15 | .03 |

interactions of SOA × block and of reward × block were not significant, and neither was the three-way interaction, all $F < 2.0$, all $p > .069$.

## GENERAL DISCUSSION

Work in the last few years has firmly established reward associations as a powerful attentional bias. Features and objects associated with rewards capture attention automatically and rapidly, and continue to do so even when the reward contingencies are removed (Anderson, Laurent, & Yantis, 2011a; Della Libera & Chelazzi, 2006; Della Libera et al., 2011; Hickey & van Zoest, 2013; Hickey et al., 2010; Kiss et al., 2009; Krebs et al., 2011; Kristjánsson et al., 2010; Lee & Shomstein, 2013; Peck et al., 2009; Raymond & O'Brien, 2009). Strikingly, this value-driven attentional capture appears to be resistant to extinction and can appear even when observers are tested 7–9 months after original learning (Anderson & Yantis, 2013). This profile of bias on attention has led to the hypothesis that rewards belong to a separate class of attentional biases that is neither typically top-down nor bottom-up (Awh et al., 2012). However, it may be that the strength of attentional bias in these previous studies persisted so robustly in part because there was not direct counter-evidence in the same task and with the same stimuli (Stankevich & Geng, 2014). Thus, the primary goal of these experiments was to understand the limits to which value-driven attentional capture is impervious to top-down attentional control, within (a) the timecourse of a single trial and (b) when the reward contingencies change explicitly.

In Experiment 1, we manipulated the SOA between the onset of a cue indicating the potential reward level of targets at two locations, and the target. If value-driven attentional capture is purely "bottom-up", then we would have expected attentional capture by the reward-associated object to be strong immediately after cue onset and to decay over time. In contrast, we found that the strength of the cueing effect did not change over time (from 0–800 ms). Although there were overall differences in the effectiveness of the cue at the different

SOAs, the size of the value-driven capture was uniform across all SOAs tested. This effect was replicated in Experiments 2 and 3. This result was somewhat surprising and suggested that attentional capture by reward-associated stimuli is immediate and sustained over time. This temporal profile is unlike either traditional bottom-up (stimulus-driven) or top-down (voluntary) attentional control and provides another source of evidence that reward associations are part of a unique third class of attentional cues that include other sources of selection history (Awh et al., 2012; Geng & Behrmann, 2005; Jiang, Swallow, & Rosenbaum, 2013; Stankevich & Geng, 2014).

In Experiments 2 and 3 we employed the same experimental design, but now included explicit extinction (Experiment 2) or a reward reversal (Experiment 3). Interestingly, in both tasks, we found that an explicit change in the reward contingency resulted in an immediate decrease in the strength of the value-driven attentional capture. There are several possibilities for why RTs to previously non-rewarded targets and previously rewarded targets could come together during extinction. First, it may be that RTs in both conditions should have sped up (e.g., due to practice effects), but RTs to previously rewarded targets were already at performance ceiling. However, this does not explain why the initial drop in RT to non-rewarded targets was sharp since practice effects are gradual. Second, it could be that the facilitation for rewarded targets was removed when the contingencies changed. However, this would have resulted in an increase in RT for previously rewarded targets, which was not the observed pattern. The third possibility is that the previously non-rewarded colour was released from top-down inhibition, allowing RTs to speed up rapidly. The last alternative fit best with our data in Experiment 2, but there was potentially a blend of the latter two in Experiment 3 where the reward contingency changed rapidly.

However, the decrease in value-driven attentional priority following a change in explicit instructions did not follow a purely top-down profile: this effect occurred gradually over 10–20 trials and began to asymptote when the cueing effect was approximately 30% of the original size in Experiment 2. To our surprise, in Experiment 3 when the value-driven cueing effect switched every block (i.e., every 40 trials) to favour the currently rewarded colour, the speed of the switch was context-dependent: in blocks where the contingency returned to the original mapping it took about 10–20 trials to reach its peak, but on reversal blocks it took the entire 40 trials meaning the learned reward association from the previous block lingered for some time despite clear knowledge that the rewarded colour had switched. This profile was again consistent with the idea that reward associations biased attention through mechanisms of statistical learning and selection history. That is, even though top-down knowledge that the reward contingency was no longer valid reduced the size of attentional capture by the previously rewarded colour, the extinction was incomplete, leaving a small, but significant bias towards the originally rewarded colour.

Experiments 2 and 3 examined how top-down information (in the form of explicit instructions) can alter the extinction of learned reward associations. We found that there was a large and rapid change in attention to the reward-associated colour when it was no longer relevant, but that there was also a consistent and persistent bias that remained. Our findings dovetail nicely with those of Della Libera et al. (2011) in suggesting that while there is a "top-down" knowledge component that drives attention towards objects expected to produce positive outcomes, there is also a second mechanism that biases attention towards stimuli that were simply previously associated with rewards. Interestingly, both studies suggest that the two mechanisms operate simultaneously when both are present, but that removing explicit knowledge reveals the effect of the learned associations alone, which is smaller, but persistent.

Our results are consistent with the view that rewards bias attention via two mechanisms, one reliant on explicit knowledge (or expectations) and one on implicit statistical learning. The removal of explicit knowledge of reward outcomes was responsible for an initial rapid drop in priority for the previously rewarded colour (Experiments 2 and 3), but a smaller bias persisted within the timecourse of a single trial and across trials. Thus, the profile of reward cueing neither matches that of traditional top-down attentional cues nor that of traditional bottom-up cues (Awh et al., 2012).

In conclusion, these results provide novel evidence that reward associations bias attention with a profile that is unique from traditional characteristics of top-down and bottom-up cues. The temporal profile of value-driven attentional capture is immediate and sustained over the period of time when bottom-up cues typically fade and top-down cues become effective. Moreover, even when there are explicit instructions that the reward contingency is no longer present, value-driven attentional capture still persists. However, the persistence of this cueing effect is reduced (e.g., by 65% in Experiment 2), suggesting that reward-associated cues bias attention through a blend of informational sources that operate through explicit knowledge and statistical learning (Stankevich & Geng, 2014).

## REFERENCES

Anderson, B. A., & Yantis, S. (2012). Value-driven attentional and oculomotor capture during goal-directed, unconstrained viewing. *Attention, Perception, & Psychophysics*, *74*(8), 1644–1653. doi:10.3758/s13414-012-0348-2

Anderson, B. A., & Yantis, S. (2013). Persistence of value-driven attentional capture. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(1), 6–9. doi:10.1037/a0030860

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011a). Value-driven attentional capture. *Proceedings of the National Academy of Sciences*, *108*(25), 10367–10371. doi:10.1073/pnas.1104047108

Anderson, B. A., Laurent, P. A., & Yantis, S. (2011b). Learned value magnifies salience-based attentional capture. *PLoS One*, *6*(11), e27926. doi:10.1371/journal.pone.0027926.g001

Awh, E., Belopolsky, A. V., & Theeuwes, J. (2012). Top-down versus bottom-up attentional control: a failed theoretical dichotomy. *Trends in Cognitive Sciences*, *16*(8), 437–443. doi:10.1016/j.tics.2012.06.010

Camara, E., Manohar, S., & Husain, M. (2013). Past rewards capture spatial attention and action choices. *Experimental Brain Research*, *230*(3), 291–300. doi:10.1007/s00221-013-3654-6

Della Libera, C., & Chelazzi, L. (2006). Visual selective attention and the effects of monetary rewards. *Psychological Science*, *17*(3), 222–227. doi:10.1111/j.1467-9280.2006.01689.x

Della Libera, C., & Chelazzi, L. (2009). Learning to attend and to ignore is a matter of gains and losses. *Psychological Science*, *20*(6), 778–784. doi:10.1111/j.1467-9280.2009.02360.x

Della Libera, C., Perlato, A., & Chelazzi, L. (2011). Dissociable effects of reward on attentional learning: from passive associations to active monitoring. *PLoS One*, *6*(4), e19460. doi:10.1371/journal.pone.0019460.g002

Dorris, M. C., & Glimcher, P. W. (2004). Activity in posterior parietal cortex is correlated with the relative subjective desirability of action. *Neuron*, *44*(2), 365–378. doi:10.1016/j.neuron.2004.09.009

Egeth, H. E., & Yantis, S. (1997). Visual attention: control, representation, and time course. *Annual Review of Psychology*, *48*, 269–297. doi:10.1146/annurev.psych.48.1.269

Failing, M. F., & Theeuwes, J. (2014). Exogenous visual orienting by reward. *Journal of Vision*, *14*(5), 6–6. doi:10.1167/14.5.6

Geng, J. J., & Behrmann, M. (2005). Spatial probability as an attentional cue in visual search. *Perception & Psychophysics*, *67*(7), 1252–1268.

Hickey, C., & van Zoest, W. (2012). Reward creates oculomotor salience. *Current Biology*, *22*(7), R219–R220. doi:10.1016/j.cub.2012.02.007

Hickey, C., & van Zoest, W. (2013). Reward-associated stimuli capture the eyes in spite of strategic attentional set. *Vision Research*, *92*, 67–74. doi:10.1016/j.visres.2013.09.008

Hickey, C., Chelazzi, L., & Theeuwes, J. (2010). Reward changes salience in human vision via the anterior cingulate. *Journal of Neuroscience*, *30*(33), 11096–11103. doi:10.1523/JNEUROSCI.1026-10.2010

Jiang, Y. V., Swallow, K. M., & Rosenbaum, G. M. (2013). Guidance of spatial attention by incidental learning and endogenous cuing. *Journal of Experimental Psychology. Human Perception and Performance*, *39*(1), 285–297. doi:10.1037/a0028022

Jonides, J. (1981). Voluntary vs. automatic control over the mind's eye's movement. In J. B. Long & A. D. Baddeley (Eds.), *Attention and Performance IX*. Hillsdale, NJ: Lawrence Erlbaum Associates.

Kiss, M., Driver, J., & Eimer, M. (2009). Reward priority of visual target singletons modulates event-related potential signatures of attentional selection. *Psychological Science*, *20*(2), 245–251. doi:10.1111/j.1467-9280.2009.02281.x

Klein, R. (1988). Inhibitory tagging system facilitates visual search. *Nature*, *334*(6181), 430–431.

Klein, R. M. (2000). Inhibition of return. *Trends in Cognitive Sciences*, *4*(4), 138–147.

Knutson, B., & Greer, S. M. (2008). Anticipatory affect: neural correlates and consequences for choice. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *363*(1511), 3771–3786. doi:10.1098/rstb.2008.0155

Krebs, R. M., Boehler, C. N., Appelbaum, L. G., & Woldorff, M. G. (2013). Reward associations reduce behavioral interference by changing the temporal dynamics of conflict processing. *PLoS One*, *8*(1), e53894. doi:10.1371/journal.pone.0053894.t001

Krebs, R. M., Boehler, C. N., Egner, T., & Woldorff, M. G. (2011). The neural underpinnings of how reward associations can both guide and misguide attention. *Journal of Neuroscience*, *31*(26), 9752–9759. doi:10.1523/JNEUROSCI.0732-11.2011

Krebs, R. M., Boehler, C. N., Roberts, K. C., Song, A. W., & Woldorff, M. G. (2012). The involvement of the dopaminergic midbrain and cortico-striatal-thalamic circuits in the integration

of reward prospect and attentional task demands. *Cerebral Cortex*, *22*(3), 607–615. doi:10.1093/cercor/bhr134

Kristjánsson, A., Sigurjónsdóttir, O., & Driver, J. (2010). Fortune and reversals of fortune in visual search: Reward contingencies for pop-out targets affect search efficiency and target repetition effects. *Attention, Perception, & Psychophysics*, *72*(5), 1229–1236. doi:10.3758/APP.72.5.1229

Le Pelley, M. E., Mitchell, C. J., & Johnson, A. M. (2013). Outcome value influences attentional biases in human associative learning: Dissociable effects of training and instruction. *Journal of Experimental Psychology: Animal Behavior Processes*, *39*(1), 39–55. doi:10.1037/a0031230

Le Pelley, M. E., Pearson, D., Griffiths, O., & Beesley, T. (2014). When goals conflict with values: Counterproductive attentional and oculomotor capture by reward-related stimuli. *Journal of Experiment Psychology: General*. Advance online publication.

Lee, J., & Shomstein, S. (2013). The differential effects of reward on space- and object-based attentional allocation. *Journal of Neuroscience*, *33*(26), 10625–10633. doi:10.1523/JNEUROSCI.5575-12.2013

Luck, S. J., & Hillyard, S. A. (1994). Spatial filtering during visual search: evidence from human electrophysiology. *Journal of Experimental Psychology. Human Perception and Performance*, *20*(5), 1000–1014.

Maljkovic, V., & Nakayama, K. (1994). Priming of pop-out: I. Role of features. *Memory & Cognition*, *22*(6), 657–672.

Müller, H. J., & Rabbitt, P. M. (1989). Reflexive and voluntary orienting of visual attention: time course of activation and resistance to interruption. *Journal of Experimental Psychology. Human Perception and Performance*, *15*(2), 315.

O'Doherty, J. P., Buchanan, T. W., Seymour, B., & Dolan, R. J. (2006). Predictive neural coding of reward preference involves dissociable responses in human ventral midbrain and ventral striatum. *Neuron*, *49*(1), 157–166. doi:10.1016/j.neuron.2005.11.014

Peck, C. J., Jangraw, D. C., Suzuki, M., Efem, R., & Gottlieb, J. (2009). Reward modulates attention independently of action value in posterior parietal cortex. *Journal of Neuroscience*, *29*(36), 11182–11191. doi:10.1523/JNEUROSCI.1929-09.2009

Platt, M. L., & Glimcher, P. W. (1999). Neural correlates of decision variables in parietal cortex. *Nature*, *400*(6741), 233–238. doi:10.1038/22268

Posner, M. I. (1980). Orienting of attention. *Quarterly Journal of Experimental Psychology*, *32*(1), 3–25.

Qi, S., Zeng, Q., Ding, C., & Li, H. (2013). Neural correlates of reward-driven attentional capture in visual search. *Brain Research*, *1532*, 32–43. doi:10.1016/j.brainres.2013.07.044

Raymond, J. E., & O'Brien, J. L. (2009). Selective visual attention and motivation: the consequences of value learning in an attentional blink task. *Psychological Science*, *20*(8), 981–988.

Schevernels, H., Krebs, R. M., Santens, P., Woldorff, M. G., & Boehler, C. N. (2014). Task preparation processes related to reward prediction precede those related to task-difficulty expectation. *NeuroImage*, *84*, 639–647. doi:10.1016/j.neuroimage.2013.09.039

Stankevich, B. A., & Geng, J. J. (2014). Reward associations and spatial probabilities produce additive effects on attentional selection. *Attention, Perception, & Psychophysics*, *76*(8), 2315–2325. doi:10.1037/xge0000037