

OBSERVATION

Persistence of Value-Driven Attentional Capture

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Stimuli that have previously been associated with the delivery of reward involuntarily capture attention when presented as unrewarded and task-irrelevant distractors in a subsequent visual search task. It is unknown how long such effects of reward learning on attention persist. One possibility is that value-driven attentional biases are plastic and constantly evolve to reflect only recent reward history. According to such a mechanism of attentional control, only consistently reinforced patterns of attention allocation persist for extended periods of time. Another possibility is that reward learning creates enduring changes in attentional priority that can persist indefinitely without further learning. Here we provide evidence for an enduring effect of reward learning on attentional priority: stimuli previously associated with reward in a training phase capture attention when presented as irrelevant distractors over half a year later, without the need for further reward learning.

Keywords: attentional capture, reward, learning, incentive salience

Attention must select stimuli that are important for promoting the survival and well-being of an organism, so that the organism can detect and perceive these stimuli and arrive at appropriate responses. To facilitate selection, attention and eye movements are biased toward reward-related stimuli (Della Libera & Chelazzi, 2006, 2009; Della Libera, Perlato, & Chelazzi, 2011; Hickey, Chelazzi, & Theeuwes, 2010a, 2010b, 2011; Hickey & van Zoest, 2012; Krebs, Boehler, & Woldorff, 2010; Peck, Jangraw, Suzuki, Efem, & Gottlieb, 2009; Raymond & O'Brien, 2009; Serences, 2008; Serences & Saproo, 2010). Furthermore, learning to associate visual stimuli with reward leads to the development of an attentional bias that continues to involuntarily drive attentional selection in favor of previously rewarded stimuli, even when those stimuli are task-irrelevant and no longer rewarded (Anderson, Laurent, & Yantis, 2011a, 2011b, 2012; Anderson & Yantis, 2012). We refer to this phenomenon as *value-driven attentional capture*; it reflects a distinct form of attentional control in which reward learning modifies the attentional priority of stimuli.

Value-driven attentional capture has only been assessed immediately or several days following initial reward learning (Anderson et al., 2011a, 2011b, 2012; Anderson & Yantis, 2012), and typically does not evidence significant extinction over the course of several hundred trials (Anderson et al., 2011b, 2012; Anderson & Yantis, 2012). Thus, it is unknown how long the learned biases that

underlie value-driven attentional capture persist, and whether these biases eventually extinguish in the absence of continued reinforcement. This is an important theoretical question with implications for our understanding of the mechanisms that underlie how reward learning modifies attentional priority.

One possibility is that value-driven attentional biases are plastic and constantly evolve to reflect only recent reward history. According to such a mechanism of attentional control, only consistently reinforced patterns of attention allocation persist for extended periods of time. Another possibility is that reward learning creates enduring changes in attentional priority that can persist indefinitely without further learning. According to this mechanism of attentional control, organisms maximize their ability to capitalize on prior learning in the guidance of attention, at the possible expense of maintaining attentional biases that are no longer useful. In the present study, we document a strikingly robust and persistent attentional bias for stimuli as a consequence of reward learning: the effects on attention of repeatedly pairing a stimulus with monetary reward are evident several months after the reward learning has taken place, with no additional training.

We recruited people who had previously participated in a study that included reward learning. They had experienced repeated pairings of each of two color stimuli with different amounts of monetary reward during a *training phase*. Our previous results showed that both immediately and several days following these pairings, previously reward-associated stimuli captured attention when presented as irrelevant distractors in an unrewarded visual search task (referred to as the *test phase*), and the magnitude of attentional capture by a given stimulus depended on its value during training (Anderson et al., 2011a, 2011b, 2012; Anderson & Yantis, 2012). In the present study, 13 participants returned to complete the test phase again, 7–9 months following their initial participation in the training phase, without any further reward learning.

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Method

Participants

Thirteen individuals from the Johns Hopkins University community were recruited to participate. Six had participated in Experiment 1 and four had participated in Experiment 3 of Anderson et al. (2011b), and three had participated in Experiment 1 of Anderson and Yantis (2012). These prior experiments involved 1,008, 240, and 300 training phase trials on which one of two color targets (either red or green) was associated with a high reward on 80% of the trials on which it was presented and a low reward on the remaining 20% (high-value color). For the other color (low-value color), these percentages were reversed. Eight participants had experienced red as the high-value color in their previous participation, and the other five had experienced green as the high-value color. High rewards were 5¢, 10¢, and 15¢ in these three training phases, respectively, while low rewards were 1¢, 2¢, and 3¢ (note that the high reward was always 5 times larger than the low reward).

Between 7 and 9 months had elapsed between the initial training phase and participation in the present study. None of these participants had completed any study involving reward since participation in the initial study from which they were recruited. Participants were compensated with \$10 for 1 hour of participation.

Apparatus

A Mac Mini equipped with Matlab software and Psychophysics Toolbox extensions (Brainard, 1997) was used to present the stimuli on a Dell P991 monitor. The participants viewed the monitor from a distance of approximately 75 cm in a dimly lit room. Responses were entered by participants using a standard 101-key U.S. layout keyboard. Head position was stabilized using a chinrest.

Stimuli, Design, and Procedure

All participants experienced the same sequence of trial events in the present experiment that was used in the test phase of the study they previously participated in (Anderson et al., 2011b; Anderson & Yantis, 2012). In all cases, the test phase consisted of a modified, multicolor version of the additional singleton paradigm (Theeuwes, 1991, 1992) in which participants searched for the unique shape (e.g., diamond among circles) and reported the orientation of a line segment inside of it using the keyboard (see Figure 1). On a subset of the trials, one of the nontarget items (referred to as the distractor) was rendered in the color of a formerly rewarded target from a training phase experienced 7–9 months earlier. Trials were categorized as containing no distractor (50% of all trials), a formerly low-value distractor (25% of all trials), or a formerly high-value distractor (25% of all trials).

The test phases differed only slightly in the timing, number of trials, and positions of the stimuli on the screen. For the participants recruited from Anderson et al. (2011b), the test phase consisted of 480 trials involving the presentation of six shape stimuli in a circular array (as in Figure 1) for 1,500 ms or until a response was made; for the participants recruited from Anderson & Yantis (2012), the test phase consisted of 320 trials during which the six

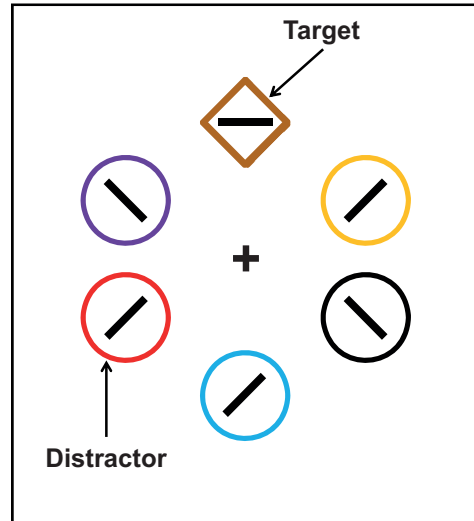


Figure 1. Example stimulus display from the test phase. Participants reported the orientation (vertical vs. horizontal) of the line segment within the unique shape (in this example, diamond among circles). On half the trials, one of the nontarget shapes was rendered in a color that had been associated with different amounts of monetary reward during training 7–9 months earlier.

shape stimuli were presented bilaterally with three shapes on the left of the screen and three on the right for 1,500 ms, regardless of when participants executed their response. The methods for these test phases were identical to those reported in their respective sources.

Assessment of Explicit Memory

At the end of the experiment, participants were reminded that they had been rewarded during the original learning phase of the experiment for finding red and green colored items, and were asked if they recalled which of the two colors tended to be followed by higher reward than the other. All of the participants reported no memory for which color had been the high-value color.

Results

Despite the fact that over half a year had passed since their experience with the training phase, irrelevant but previously reward-associated stimuli still exerted a robust influence on response time (reaction time [RT]) in target identification [Figure 2; $F(2, 24) = 7.74, p = .003, \eta_p^2 = .392$] in the absence of explicit memory for the previously learned stimulus-reward associations. Whether the formerly high-value stimulus was red or green did not interact with the effect of the distractors on performance [$F(2, 22) = 1.01, p = .380$], which is consistent with prior studies from our lab (Anderson et al., 2011a, 2012; Anderson & Yantis, 2012). The effect of the distractors on performance also did not differ based on the specific training phase participants experienced previously ($F < 1$), so we collapsed across these two variables.

Post hoc comparisons revealed that the formerly high-value stimulus slowed RT both compared to when no formerly rewarded stimulus was present [$t(12) = 3.79, p = .003, d = 1.05$] and when

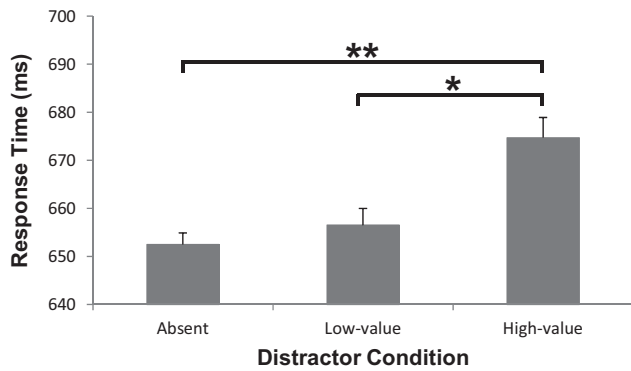


Figure 2. Response time as a function of distractor condition. The presence of a formerly high-value distractor significantly slowed responses compared to the other two conditions (* $p < .05$. ** $p < .01$). Error bars reflect within-subjects SEM.

a formerly low-value stimulus was present [$t(12) = 2.45$, $p = .031$, $d = .68$]. The difference in response slowing in the presence of formerly high- and low-value distractors can only be explained in terms of a difference in learned value, as that is all that differed between the two conditions. Accuracy was high and did not differ significantly among the three distractor conditions [absent: 92.6%, low-value: 93.1%, high-value: 91.6%; $F(2, 24) = 1.24$, $p = .307$].

Discussion

Attentional biases develop for stimuli that have previously been followed by the delivery of reward, causing these stimuli to capture attention involuntarily (Anderson et al., 2011a, 2011b, 2012; Anderson & Yantis, 2012). Such attentional biases have been shown to persist for hundreds of unrewarded trials soon after the reward learning has taken place (Anderson et al., 2011b, 2012; Anderson & Yantis, 2012), but whether value-driven attentional biases are capable of persisting for long periods of time without continued reinforcement is unknown.

In the present study, we show that stimuli previously associated with reward capture attention as long as 7–9 months following reward learning, without any additional pairings with reward. This suggests that the attentional priorities of the visual system are modified in an enduring way by reward learning, without the updating of such priorities as a function of their utility. More broadly, the present results suggest that implicit memories are formed between a stimulus and reward that are stored in the brain in such a way that the stimulus will retain a heightened attentional priority whenever it is experienced, leading to the capture of attention.

The precise mechanism by which stimulus–reward pairings give rise to attentional biases is not fully understood. Prior research using otherwise equivalent training phases without reward feedback show that the observed attentional biases specifically depend on reward history (Anderson et al., 2011a, 2011b, 2012). However, more extended experience searching for target stimuli in the absence of reward feedback, often for thousands of trials over several days, is also known to create persistent selection biases as a consequence of perceptual learning (e.g., Kyllingsbaek, Schneider, & Bundesen, 2001; Shiffrin & Schneider, 1977). One possibility is

that value-driven attentional biases operate through similar mechanisms of perceptual learning, but with reward-driven motivation substantially accelerating the perceptual learning. Another possibility is that the stimulus–reward associations are themselves stored in memory, either directly or indirectly modifying attentional priority. Additional research will be needed to distinguish between these and other possible explanations of the mechanisms underlying value-driven attentional biases.

The magnitude of value-driven attentional capture was greater for high-value than for low-value distractors; this difference was larger here than in previous studies (Anderson et al., 2011b; Anderson & Yantis, 2012). One possible account for this observation is that associations between stimuli and high reward are better remembered and are thus more robust to extinction over extended time periods than associations between stimuli and low reward. Nevertheless, these data show that the reward associated with visual stimuli is maintained in such a way that it can exert a persistent influence on attentional priority.

Although participants had experience with the test phase of the present study from prior participation, the red and green distractors were always irrelevant and unrewarded in this context. However, the test phase did involve a visual search task that was similar to the previously experienced training phase in certain respects; in particular, both tasks involved visual search among multicolored outline shapes. Whether the observed attentional capture is capable of generalizing to situations and stimuli less similar to the training phase is unclear. We have previously shown that value-driven attentional biases generalize to novel stimuli in a novel task when those stimuli possess a previously reward-associated feature, but such an effect has only been demonstrated immediately following training (Anderson et al., 2012).

The implications of the persistence of value-driven attentional capture may well extend to other domains of cognition. For example, drugs of abuse powerfully activate the dopaminergic reward centers of the brain. According to the theory of incentive salience, pairing a drug-related cue with the dopamine response causes the cue to become motivationally salient, thereby automatically eliciting approach behavior (Berridge, 2012). It is well documented that drug-related visual cues come to involuntarily capture attention, an effect that can persist for long periods of time without any additional exposure or learning (Field & Cox, 2008; Lubman, Peters, Mogg, Bradley, & Deakin, 2000), which contributes to addiction relapse (Field & Cox, 2008; Marissen et al., 2006). Here, we show similarly persistent effects of reward learning on attention using arbitrary, nondrug stimuli. Our results suggest the possibility that relapses into addiction following abstinence may be precipitated by normal learning processes in which incentive salience is persistently ascribed to stimuli associated with value. Such a mechanism would have broad implications for our understanding of the basis for normal and disordered cognitive control.

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