Value-driven attentional capture

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Attention selects which aspects of sensory input are brought to awareness. To promote survival and well-being, attention prioritizes stimuli both voluntarily, according to context-specific goals (e.g., searching for car keys), and involuntarily, through attentional capture driven by physical salience (e.g., looking toward a sudden noise). Valuable stimuli strongly modulate voluntary attention allocation, but there is little evidence that high-value but contextually irrelevant stimuli capture attention as a consequence of reward learning. Here we show that visual search for a salient target is slowed by the presence of an inconspicuous, task-irrelevant item that was previously associated with monetary reward during a brief training session. Thus, arbitrary and otherwise neutral stimuli imbued with value via associative learning capture attention powerfully and persistently during extinction, independently of goals and salience. Vulnerability to such value-driven attentional capture covaries across individuals with working memory capacity and trait impulsivity. This unique form of attentional capture may provide a useful model for investigating failures of cognitive control in clinical syndromes in which value assigned to stimuli conflicts with behavioral goals (e.g., addiction, obesity).

Effective deployment of attention is critical to the successful performance of any cognitive task. Attention determines what aspects of the sensory input are selected for cognitive processing, memory storage, and awareness. Two modes of attentional control are widely believed to determine perceptual priority: a voluntary, goal-directed mode, in which attention is guided by contextually appropriate goals and intentions, and an involuntary, stimulus-driven mode, in which attention is captured by physically salient stimuli (1–4) or by task-irrelevant stimuli that share identifying features with a searched-for target (5, 6). Each of these modes of control present concomitant benefits and costs: voluntary control of attention is goal-specific but potentially slower to implement; involuntary attentional capture can rapidly orient the organism to unexpected changes that could signal danger or opportunity, but has the potential to cause distraction from intended acts of perception.

Goal-directed and stimulus-driven modes of attentional control have long been a focus of intense investigation, and much has been learned about the operating principles of each mode of control and their interaction (1, 4). However, there is growing evidence that these are not the only influences on attentional deployment. To promote survival and well-being, the brain is optimized to learn about perceptual stimuli that signal the potential for procuring reward (7, 8). Voluntary attention to stimuli that predict reward is an effective mechanism for efficiently selecting valuable stimuli (9). Many studies have shown that reward facilitates voluntary attention to task-relevant stimuli, and that reward-based strategies and priorities strongly influence attentional performance (10–19).

Attentional capture by valuable but task-irrelevant stimuli could also confer adaptive advantages in many circumstances, leading the perceiver to orient to inconspicuous and/or unexpected reward-related stimuli. At the same time, however, attentional capture by reward-related stimuli (e.g., drugs of abuse, excessive food, or even irrelevant but rewarding information like an e-mail chime) can be maladaptive when it conflicts with contextually appropriate goals (e.g., intended abstinence from a drug or food) (20–25). This raises the possibility that valuable but inconspicuous stimuli capture attention involuntarily as a consequence of reward learning. Several recent studies have investigated this possibility, but in each case, when arbitrary stimuli were associated with reward delivery during a learning procedure and then made entirely task-irrelevant during extinction, they did not cause distraction (10–12, 26). Although it is known that task-irrelevant drug-related stimuli draw attention in addicted populations (27–30), and that motivationally salient stimuli, such as happy faces and erotic pictures, can capture attention (31, 32), it is unclear to what extent this reflects a general-purpose mechanism of attentional capture by stimuli imbued with value through reward learning. To date, no clear demonstration of such a mechanism of attentional capture, particularly in healthy individuals, has been reported.

We examined whether an irrelevant, unrewarded, and nonsalient distractor, previously associated with reward, captures attention when both stimulus-driven and goal-driven accounts predict that a physically salient and task-relevant target should instead solely determine the locus of attention. Critically, we associated value with a basic stimulus feature—color—rather than more complex conjunctions of features that have failed to capture attention during extinction in previous studies (10–12, 26). The results show that reward-related stimuli do cause significant and persistent distraction as a consequence of reward learning, and thereby reveal an involuntary mechanism of attentional selection that is uniquely value-driven, operating at an earlier level of representation than previously documented.

Results

Experiment 1. During an initial training phase, participants searched for a red or green target among differently colored nontargets (Fig. 1A), and received visual feedback at the end of each trial indicating an accumulating monetary reward for a correct response. Importantly, the participant's response did not depend on color; rather, they discriminated the orientation of a bar within the target stimulus; thus reward was associated with color, and not with a particular behavioral response. One target color (red for half the participants, green for the rest, to control for possible differences in physical salience) was associated with a high probability ($P = 0.8$) of a high reward (5¢) and a low probability ($P = 0.2$) of a low reward (1¢); for the other target color, this mapping was reversed. Participants were not explicitly informed of this reward contingency, but had to learn it over the course of 1,008 trials. Training thus imbued one color with high value and the other color with lower (but positive) value. After the training phase was complete, a test phase began, comprising 480 trials during which no reward was provided: participants searched for a unique shape in an array of six differently colored shapes (Fig. 1B). On half of these trials, one of the nontarget elements— termed the distractor—was rendered in red or green (each equally often); the target was never red or green, and participants
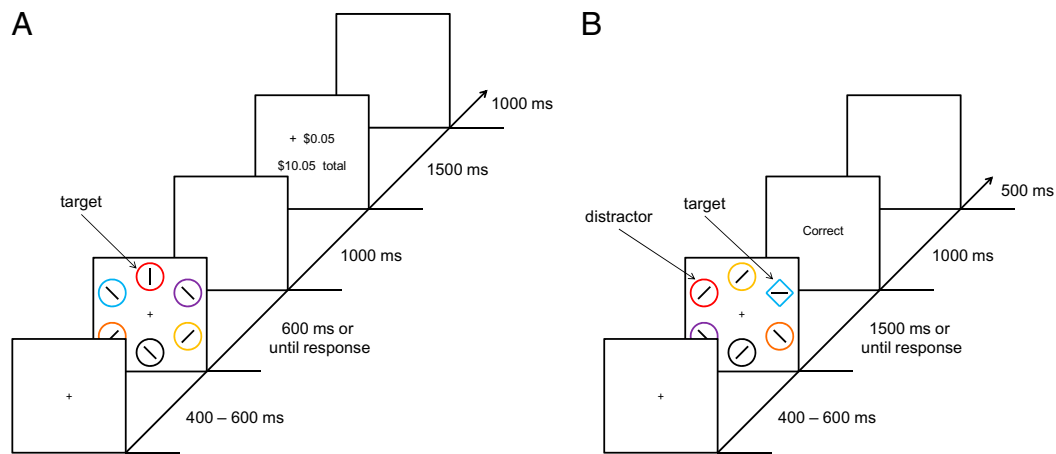
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Fig. 1. Sequence of trial events. (*A*) Targets during the training phase were defined by color (red or green, exactly one of which was present on each trial), and participants reported the identity of the line segment inside of the target (vertical or horizontal). Correct responses were followed by the delivery of monetary reward feedback. One of the target colors was followed by a high reward on 80% of the trials and a low reward on 20% of the trials; for the other target color, this mapping was reversed. (*B*) During the test phase, the target was defined as the unique shape, and no reward feedback was provided. On half of the trials, one of the nontarget items—the distractor—was rendered in the color of a formerly rewarded target (each color equally often).

were informed that color was irrelevant to the task and should be ignored.

Based on the reward contingencies to which participants were exposed during the training phase, trials during the test phase were classified as containing a high-value distractor, a low-value distractor, or neither. A repeated-measures ANOVA revealed that response times (RTs) differed significantly among these three conditions [$F(2, 50) = 6.07$, $P = 0.004$] (Table 1). High-value distractors slowed RT relative to when neither value-related distractor was present [$t(25) = 3.49$, $P = 0.002$], and the effect of reward on performance exhibited a linear trend [$F(1, 25) = 12.19$, $P = 0.002$]. There was no significant difference in error rate between the three distractor conditions [$F(2, 50) = 0.41$, $P = 0.667$]. These results are striking in that they clearly violate the predictions of both a salience-driven and goal-driven account of attentional capture: the data mirror the well-documented distracting effect of physically salient stimuli (2, 4, 33), despite the fact that the distractors were neither physically salient nor goal-relevant, and did not have any identifying features in common with the searched-for target (5). Even the fastest 25% of RTs in the high-value distractor condition were slower than those in the distractor-absent condition [$t(25) = 3.07$, $P = 0.005$], suggesting that the high-value distractor captured attention consistently, rather than on only a small proportion of the trials (34). To confirm that red and green were

not more physically salient than the other colors we used (and equally salient to each other), eight naive participants completed a separate control experiment that consisted only of the test phase of experiment 1. Mean RT did not differ for the three conditions containing a red distractor, a green distractor, or neither [$F(2, 14) = 0.13$, $P = 0.880$] (Table 2).

Visual working memory (WM) capacity is correlated with the magnitude of attentional capture by salient, task-irrelevant stimuli (35, 36), an effect that is thought to reflect individual differences in a general ability to resist distraction and thus to maintain items in working memory. Trait impulsivity also provides a broad measure of the degree to which people can successfully exercise control over behavior (37). We therefore measured visual working memory capacity using a change-detection task (35) and trait impulsivity using the Barratt Impulsiveness Scale (BIS-11) (38), and entered them as predictors of value-driven attentional capture in a simultaneous regression model. These two factors accounted well for individual differences in value-driven attentional capture ($R^2 = 0.355$, $P = 0.006$); each variable uniquely contributed to the predictive power of the model ($\beta = -0.554$, $P = 0.004$, and $\beta = 0.378$, $P = 0.038$, for WM capacity and impulsivity, respectively; Fig. 2). Greater impulsivity and smaller working memory capacity were associated with greater vulnerability to distraction by high-value stimuli. The relationship between visual working memory capacity and the magnitude of value-driven capture cannot be explained by a general slowing of response times by lower-capacity individuals, because visual working memory capacity was not correlated with RT in the no-distractor condition (Pearson's $r = 0.073$, $P = 0.723$).

Experiment 2. An alternative account for our findings is that participants deliberately continued to search for the red and green items in the test phase even though those items were no longer task-relevant or rewarded. Although it is known that attentional priorities are rapidly adjusted with changing task demands (39), former targets can attract attention under certain circumstances (40, 41). To rule out this account, we tested 10 new participants who engaged in the same training and test phases of the experiment, but with no reward feedback during training. Instead, participants were compensated with a flat rate that matched the average earnings of participants in the main experiment ($25). We found that removing trial-by-trial reward feedback from the training phase completely abolished any effect of distractors at test [$t(9) = -0.39$, $P = 0.707$] (Table 2). There was

Table 1. Mean response time (in milliseconds) and error rate, respectively, in the test phase of the experiments in which reward was delivered for each of three training conditions: long training (1,008 trials) with low and high reward of 1¢ or 5¢ per trial, brief training (240 trials) with rewards of 2¢ and 10¢ per trial, and brief training followed by a delay of 4–21 d

Training phase	Distractor condition in the test phase		
	None	Low value	High value
1,008 trials	665 (2.8)	673 (2.8)	681 (2.6)
	0.11 (0.004)	0.10 (0.004)	0.11 (0.004)
240 trials	667 (2.0)	675 (3.0)	682 (2.9)
	0.12 (0.005)	0.12 (0.006)	0.12 (0.006)
4–21 d ago	614 (1.8)	624 (2.7)	630 (3.3)
	0.06 (0.004)	0.07 (0.006)	0.08 (0.005)

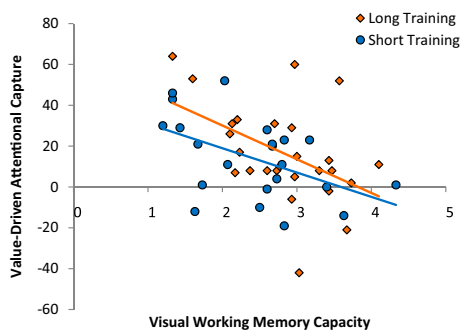The error terms, in parentheses, reflect the within-subjects SEM.

Fig. 2. Magnitude of value-driven attentional capture (indexed as response time when a high-value distractor was present minus response time when no distractor was present) as a function of visual working memory capacity following the long (yellow) and short (blue) training regimen. Pearson product-moment correlations for the long and short training experiments were −0.468 (P = 0.016) and −0.468 (P = 0.021), respectively.

no significant difference in error rate between the red, green, and no-distractor conditions [$F(2, 18) = 2.30, P = 0.139$].

Experiment 3. To assess the robustness of value-driven attentional capture, we shortened the training phase and test phase to 240 trials each and doubled the reward magnitude (2¢ and 10¢, respectively, for low and high reward) with 24 new participants. We replicated the effect of prior reward on performance during the test phase [repeated-measures ANOVA: $F(2, 46) = 5.17, P = 0.009$; linear trend: $F(1, 23) = 14.09, P = 0.001$] (Table 1). The magnitude of slowing caused by high-value distractors was again correlated with visual working memory capacity (Pearson's $r = -0.468, P = 0.021$; Fig. 2), but not with trait impulsivity (Pearson's $r = 0.093, P = 0.666$). Again, there was no correlation between visual working memory capacity and RT in the no-distractor condition (Pearson's $r = 0.027, P = 0.900$). We then invited these participants back after several days had passed (4–21 d, mean = 8.8, SD = 3.9) to carry out the same test phase with no additional training; 19 of the 24 participants returned. The influence of prior reward on performance remained [repeated-measures ANOVA: $F(2, 36) = 5.81, P = 0.007$; linear trend: $F(1, 18) = 11.55, P = 0.003$]. In none of these experiments did error rates differ significantly among the three conditions (all Ps > 0.25). These results show that high-value stimuli have a rapidly learned and long-lasting influence on attentional priority, and the magnitude of this effect is negatively correlated with working memory capacity. The influence of trait impulsivity was only evident for well-learned associations provided by the longer training regimen of the first experiment, which may be a manifestation of habit learning (42).

Finally, we tested whether value-driven attentional capture entails a spatial deployment of attention to the distractor's location or, instead, a nonspecific filtering cost—that is, an overall slowing caused by the presence of a high-value stimulus. Previous

studies have shown that attentional capture by a physically salient distractor inhibits perception of a stimulus that subsequently appears in the distractor's location (33). We examined response times in trials on which no distractor was presented that were preceded by a trial containing a high-value distractor. Responses were on average 66 ms slower when the target appeared in a location formerly occupied by a high-value distractor than when it appeared in another location [$t(23) = 3.13, P = 0.005$], confirming that high-value distractors indeed capture attention in a spatially specific manner.

Discussion

Two modes of attentional control have long been known to play a role in the adaptive deployment of selective attention (1–6). Several recent studies have shown that the voluntary deployment of attention is influenced by reward (10–19). In contrast to the ample evidence that voluntary deployment of attention to task-relevant stimuli is affected by reward, the evidence for an influence of the value assigned to stimuli through reward learning on involuntary attentional capture is negative or equivocal (10–12, 26). The experiments reported here provide clear evidence that arbitrary reward-related stimuli capture attention involuntarily and persistently as a result of associations that develop rapidly during learning.

Value-driven attentional capture is distinct from the well-established role of salience and ongoing goals in the control of attention. Our findings establish that nonsalient, task-irrelevant stimuli previously associated with reward slow visual search during extinction, and that the magnitude of slowing is spatially specific: when a target appears in a location occupied by a high-value distractor on the previous trial, slowing is especially prolonged. This result strongly suggests that high-value distractors draw spatial attention, and the subsequent act of disengagement leaves an inhibitory trace at that location (33). Furthermore, a control experiment showed that the effect could only be attributable to reward feedback during training, ruling out the persistence of a deliberate attentional strategy as an explanation; this confirms a recent report that top-down goals in visual search can be adjusted flexibly within seconds (39), and further distinguishes value-driven capture from goal-directed attentional deployment.

In previous studies that have investigated whether valuable stimuli capture attention as a consequence of reward learning (10–12, 26), the types of stimuli used were complex (e.g., faces and words). We observed evidence of value-driven attentional capture operating on a basic stimulus feature—color—that can provide a basis for the efficient detection of valuable stimuli. This is consistent with the level of selectivity seen in contingent involuntary orienting (5, 6), and may reflect a general underlying principle of involuntary attentional selection.

In a classic investigation of attentional control, Shiffrin and Schneider (41) reported that following extensive training in search for a specific target letter, that letter subsequently captures attention even when it is no longer task-relevant. However, this effect required a great deal of consistent training. The significant slowing caused by value-driven attentional capture reported here required as little as 240 trials during training. Furthermore, if reward was omitted during training, the effect disappeared. Value-driven capture is clearly a distinct phenomenon.

Individual differences in visual working memory capacity are thought to reflect variation in a general ability to resist distraction; in a change-detection task, this manifests as the efficient and selective processing of a capacity-limited number of to-be-remembered items, with minimal interference from irrelevant and supracapacity items (35, 36). Individual differences in change-detection performance thus reflect variation in the ability to restrict visual and mnemonic processing to goal-relevant features and locations. We found that individual differences in visual working memory capacity are strongly correlated with suscepti-

Table 2. Mean response time (in milliseconds) and error rate, respectively, in the test phase of the experiments in which no reward was delivered

Training phase	Distractor condition in the test phase		
	None	Red	Green
None	698 (4.1)	696 (4.7)	700 (3.4)
	0.13 (0.004)	0.13 (0.006)	0.14 (0.006)
1,008 trials (unrewarded)	602 (3.9)	606 (2.1)	593 (3.9)
	0.14 (0.004)	0.17 (0.006)	0.15 (0.005)

The error terms, in parentheses, reflect the within-subjects SEM.

bility to value-driven attentional capture: individuals with low working memory capacity tend to exhibit stronger value-driven attentional capture. This finding echoes recent reports that WM capacity is correlated with the degree to which physically salient, contingently relevant stimuli capture attention despite competing goals (35, 36), and further extends previous demonstrations of a correlation between verbal measures of working memory capacity and the efficiency of goal-directed attentional selection (43–45).

The influence of reward in motivated behavior has been a focus of intense investigation in recent years. A wide variety of stimuli are rewarding—sweet taste, positive facial expression, erotic pictures, money, and illicit drugs such as cocaine, among others. The receipt of a rewarding stimulus is accompanied by subjective pleasure, and associative learning mechanisms in the brain give rise to incentive salience—a desire or "wanting" response when reward-associated stimuli are present (22). In susceptible individuals, the learned wanting response can override cognitive intentions to avoid the rewarding stimulus, and lead to impairment of cognitive control and ultimately to addiction and related syndromes.

Although it is known that irrelevant drug-related stimuli draw attention in addicted populations (27–30), it is unclear to what degree such effects might be explained by attentional capture driven by associations between stimuli and reward that arise through associative learning. Drugs of abuse usurp the brain's reward system, making drug addiction more than just a consequence of normal reward learning. Motivationally salient stimuli, such as happy faces and erotic pictures, are also known to capture attention (31, 32), but it is unclear whether such attentional preferences reflect arbitrary associations between stimuli and reward outcomes that develop through basic learning processes, or an evolutionarily conserved attentional bias. Our results clearly demonstrate that learned stimulus-reward associations are sufficient to involuntarily drive attention allocation, suggesting that maladaptive attentional biases found in drug addiction (27–30) may reflect, in part, the disordered influence of an otherwise normal cognitive process.

Value-driven attentional capture may play a key role in a variety of clinical syndromes in which both attention and reward have been critically implicated, including drug addiction (20–22), obesity (23), attention-deficit hyperactivity disorder (24), and obsessive-compulsive disorder (25). These conditions are highly comorbid (23, 25), suggesting common underlying causal factors. We observed clear individual differences in, and patterns of correlation with, the magnitude of value-driven attentional capture: individuals with low visual working memory capacity and high trait impulsivity were the most vulnerable to the effect of stimulus value on involuntary attentional selection. These individual differences may provide insights into the traits and states that jointly influence susceptibility to these conditions.

Methods

Experiment 1. *Participants.* Twenty-six participants were recruited from the Johns Hopkins community. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were provided monetary compensation based on performance (mean = $25.11), in addition to $5 compensation for completing an initial session. Informed consent was obtained from all participants, and all of the experimental procedures were approved by the Johns Hopkins University Institutional Review Board.

Initial session. Participants first filled out a questionnaire (BIS-11) and performed a change-detection task designed to measure visual working memory capacity. The questionnaire and change-detection task were performed the day before the experiment in a single 20-min session. The method for the change-detection task has been previously described (35). In the change-detection task, participants were presented with a brief unmasked display consisting of four, six, or eight colored squares, which was followed by a probe display in which a single colored square appeared in a previously occupied location. Participants indicated, via an unspeeded key press, whether this probe square was the same or different in color than the square previously presented in the probed location. Visual working memory capacity was measured separately for each display size by multiplying the

display size by the difference between the hit rate and false alarm rate, and then averaged across set sizes to obtain a global estimate (35).
Apparatus. A Mac Mini equipped with Matlab software and PsychToolbox extensions was used to present the stimuli on a Dell P991 monitor. The participants viewed the monitor from a distance of ~50 cm in a dimly lit room. Reponses were entered by using a standard 101-key US layout keyboard.
Stimuli. The sequence of events and time course for the training and test phases are shown in Fig. 1 *A* and *B*, respectively. Each trial consisted of three displays: a fixation display, a search display, and a feedback display. During both the training and test phases, the fixation display consisted of a white fixation cross (0.5° × 0.5° visual angle) presented in the center of the screen against a black background, and the search display consisted of the fixation cross surrounded by six shapes (2.3° × 2.3° visual angle) placed at equal intervals along an imaginary circle with a 5° radius.
Training phase. During the training phase, the six shapes in the search display were all circles of different colors (red, green, blue, cyan, pink, orange, yellow, and white). Targets were defined as a red or a green circle, exactly one of which was presented on every trial. Inside the target, a white line segment was oriented either vertically or horizontally, and inside each of the nontargets, a white line segment was tilted at 45° to the left or to the right. The feedback display informed participants of the reward earned on the previous trial, as well as total reward accumulated thus far.
Test phase. During the test phase, the search display consisted of a circle among diamonds or a diamond among circles, and the target on each trial was defined as the unique shape. Each item in the display had a unique color. On half of the trials, one of the nontarget elements, the distractor, was rendered in red or green; the target was never red or green, and participants were informed that color was irrelevant to the task and should be ignored. The feedback display at test informed participants only whether their response on the previous trial was correct. That is, no reward was provided during the test phase.
Design. The experiment consisted of 1,008 training trials and 480 test trials. Participants were provided with 50 practice trials before the training trials, and 20 practice (distractor absent) trials before the test trials. The practice trials were identical to the experimental trials except that no reward feedback was provided to the participants. After each 100 experimental trials and between the tasks, participants were provided with a short break. Target identity, target location, distractor color, and distractor location were fully crossed and counterbalanced.

Correct responses were followed by visual feedback indicating monetary reward in the training phase. High-reward targets were followed by high-reward feedback (5¢) on 80% of trials and low-reward feedback (1¢) on the remaining 20%; for low-reward targets, the percentages were reversed. High-reward targets were red for half of the participants, and green for the other half. No reward feedback was provided during the initial practice block, and no reward feedback was provided during the test phase. Upon completion of the experiment, participants were given the cumulative monetary reward they had earned.
Procedure. Each participant was tested individually over the course of a single 2-h session. Each session took place inside a dimly lit laboratory room. The experimenter familiarized all participants with each task by providing written and oral descriptions of the stimuli and procedures. Participants were instructed to respond "as quickly as possible while minimizing errors."

Each trial began with the presentation of the fixation display for a randomly varying interval of 400, 500, or 600 ms. The search display then appeared and remained on screen until a response was made or the trial timed out. The training task was performed under time pressure, with trials terminating after 600 ms; during the test, time pressure was lifted by lengthening this time limit to 1,500 ms.

Participants made a forced-choice target identification by pressing the *z* and *m* keys for the vertically and horizontally orientated targets, respectively. Response time was measured from the onset of the target display until a response was made or the trial timed out. The computer emitted a 500-ms, 1,000-Hz feedback tone to inform the participant when a trial timed out. Only correct responses were included in the analysis, and all RTs more than three SDs above and below the mean for each subject and condition were excluded from the analysis.

Experiment 2. *Participants.* Ten participants were recruited from the Johns Hopkins community. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were compensated with a flat amount of $25. None of the participations had participated in experiment 1.
Apparatus and stimuli. The apparatus and stimuli were identical to experiment 1, with the exception that the feedback display during training informed

participants only whether their previous response was correct. Critically, no reward feedback was provided.

Design and procedure. The design and procedure were identical to experiment 1, with the exception that no monetary rewards were provided for correct responses. Also, participants did not perform the change detection task or complete the BIS-11.

Experiment 3. *Participants.* Twenty-four new participants were recruited from the Johns Hopkins community. All were screened for normal or corrected-to-normal visual acuity and color vision. Participants were provided monetary compensation based on performance (mean = $13.24).

Apparatus and stimuli. The apparatus and stimuli were identical to experiment 1.

Design and procedure. The design and procedure were identical to experiment 1, with the following exceptions. The experiment consisted of a single 1-h session. The training and test phases consisted of 240 trials each, with a short break every 120 trials. Trials terminated after 800 ms in the training phase and 1,200 ms in the test phase. High and low rewards were increased to 10¢ and 2¢, respectively. Participants performed the change detection task and completed the BIS-11 at the beginning of the session. Four to 21 d after the initial session (mean = 8.8, SD = 3.9), 19 of the participants returned to complete the test phase again, and were compensated with an additional $5.

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