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Value-Driven Attentional Capture in Adolescence

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Abstract

Adolescence has been characterized as a period of both opportunity and vulnerability. Numerous clinical conditions, including substance-use disorders, often emerge during adolescence. These maladaptive behaviors have been linked to problems with cognitive control, yet few studies have investigated how rewards differentially modulate attentional processes in adolescents versus adults. Here, we trained adults and adolescents on a visual task to establish stimulus-reward associations. Later, we assessed learning in an extinction task in which previously rewarded stimuli periodically appeared as distractors. Both age groups initially demonstrated value-driven attentional capture; however, the effect persisted longer in adolescents than in adults. The results could not be explained by developmental differences in visual working memory. Given the importance of attentional control to daily behaviors and clinical conditions such as attention-deficit/hyperactivity disorder, these results reveal that cognitive control failures in adolescence may be linked to a value-based attentional-capture effect.

Keywords

attentional capture, adolescence, reward, learning

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Adolescence represents a time of considerable psychological and neurobiological change (Dahl, 2004). Although in many ways the most physically healthy period of the life span, adolescence is associated with a sharp increase in morbidity and mortality often due to impulsive and risky behaviors, such as substance use, dangerous driving, and unsafe sexual practices (Eaton et al., 2006). These risky behaviors, although outwardly dissimilar, appear to share a common underlying set of causes (Cooper, Wood, Orcutt, & Albino, 2003). Recent clinical evidence suggests that opioid addicts are prone to attentional capture by non-drug-related yet nonetheless rewarding stimuli (Anderson, Faulkner, Rilee, Yantis, & Marvel, 2013). To that end, characterizing these underlying processes has widespread social and psychological implications.

Early work emphasized deficient cognitive control in adolescence but, as pointed out by Casey, Jones, & Hare (2008), if deficient frontal-lobe-mediated cognitive control processes were primarily driving poor decision making in adolescence, impulsive and risky behaviors would peak in childhood as opposed to adolescence. Current theorizing emphasizes changes in dopamine-mediated reward processes independently (Luciana & Collins, 2012) or in conjunction with cognitive control maturation (Casey et al., 2008). Although functional neuroimaging studies have demonstrated developmental shifts in neural activations in dopamine-rich regions such as the nucleus accumbens (see Galvan, 2010), experimental work examining how rewards differentially bias behavior and cognition in adolescents compared with adults has been limited.

Learned stimulus-reward associations are extraordinarily influential in guiding behavior (Thorndike, 1911). Because reward outcomes fluctuate in concert with a dynamic environment, optimal decision-making processes require great vigilance. Visual attention allows one

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to adapt to moment-by-moment environmental changes because it responds to stimulus salience, current objectives, and reward (Awh, Belopolsky, & Theeuwes, 2012). Optimal attentional deployment helps maximize rewards and minimize losses (see Anderson, 2013, for a recent review).

A number of studies have demonstrated that rewards and other emotionally relevant cues can enhance attention to task-relevant features of a stimulus (Anderson, Laurent, & Yantis, 2011; Della Libera & Chelazzi, 2006). Rewards can enhance selective attention by modulating activity in visual cortices (Hickey, Chelazzi, & Theeuwes, 2010; Serences, 2008). These reward-based attention effects demonstrate the tight linkage between environmental cues and behavior. Further, they suggest that the attentional system can learn to adapt to a dynamic environment (for a review of attentional control, see Vecera, Cosman, Vatterott, & Roper, 2014). Similarly, studies on motivated attention (e.g., Lang, Bradley, & Cuthbert, 1997) have demonstrated that emotional or arousing stimuli, as opposed to neutral stimuli, are more likely to be perceived in attentional blink paradigms that involve rapid presentations of distractors and targets. Learned stimulus-reward associations also enhance the ability to quickly identify and discriminate stimuli (Della Libera & Chelazzi, 2009).

In contrast, previously rewarded stimuli can be distracting and direct attention from target stimuli (Anderson et al., 2011; Hickey & van Zoest, 2012). Furthermore, heightened dopaminergic input leading to increased saliency of reward cues may make cognitive control especially difficult in adolescence (Luciana & Collins, 2012). Although previous work has examined reward processing as a function of performance on complex decision-making tasks, such as the Iowa Gambling Task (e.g., Hooper, Luciana, Conklin, & Yarger, 2004) and the Columbia Card Task (Figner, Mackinlay, Wilkening, & Weber, 2009), few studies have investigated how rewards modulate basic attentional-control processes in adolescents compared with adults. Recently, Grose-Fifer, Hoover, Rodrigues, and Zottoli (2009) demonstrated that adolescents are more distracted than adults by emotionally charged face stimuli when performing a modified flanker task, which suggests that adolescents have greater difficulty resolving conflict in emotionally charged tasks. However, because affective states influence the scope of spatial attention (Huntsinger, Clore, & Bar-Anan, 2010; Rowe, Hirsh, & Anderson, 2007), Grose-Fifer et al.'s (2009) results may not reflect age-dependent differences in attentional processing per se, but rather differences in emotional processing that, in turn, influence spatial attention.

In the current project, we examined how reward influenced early attentional processes that are critical for later, more complex decision making. Specifically, we utilized a task that involves an assessment of attentional control to feature-based cues previously paired with rewards but that were otherwise task irrelevant (Anderson et al., 2011). We hypothesized that adolescents would show a greater tendency than adults toward *value-driven attentional capture* (VDAC); that is, attentional capture by previously rewarding stimuli.

Method

Participants

Forty adolescents (15 males, 25 females) between 13 and 16 years old (M = 14.1, SD = 1.1) and 40 adults (16 males, 24 females) between 20 and 35 years old (M = 27.3, SD = 3.5 years) were recruited from the University of Iowa community. All participants reported normal or corrected-to-normal vision and no color insensitivities. Subjects were compensated $15 for participation and $15 for earnings on the training portion of the task. An appropriate sample size was determined prior to data collection via a power analysis. The power analysis was calculated using an assumed reaction-time (RT) effect of at least 30 ms between subjects in any two conditions, which suggested a sample size of 42 subjects per group. Data collection ceased at 80 participants to accord with the power analysis.

Apparatus

An Apple Mac Mini computer displayed stimuli on a 17-in. LCD monitor and recorded keyboard responses and latencies. The experiment was controlled using MATLAB (The MathWorks, Natick, MA) and the Psychophysics Toolbox (Brainard, 1997). Participants were seated 60 cm from the monitor.

Stimuli and procedure

The experiment was designed to closely replicate Experiment 3 in Anderson et al. (2011). The experiment consisted of two parts: a training phase (see Fig. 1) and a testing phase.

During training, participants viewed a stimulus display consisting of six rings arranged in a circular array. Each of the rings was a different color, and the task was to select a red (RGB value: 255, 0, 0) or green (RGB value: 0, 255, 0) target ring, one of which was present on a given trial. The target was equally likely to be red or green. Each ring subtended a visual angle of 2° with a stroke of 5 pixels. The stimulus array subtended a visual angle of 10° and was centered within the display. Distractor colors were randomly drawn from the

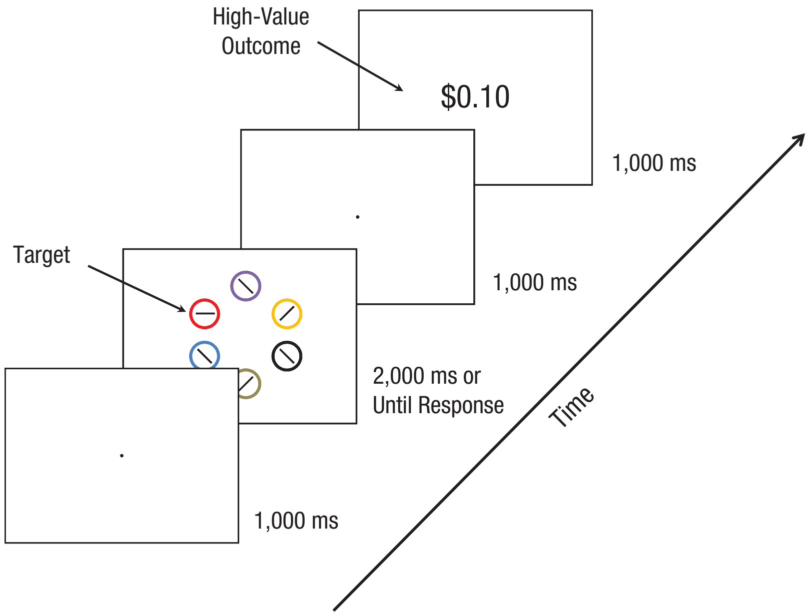

Fig. 1. Example of a training trial. Participants were shown an array of six differently colored rings, one of which (the target) was red or green. Participants then had to report the orientation of the line segment within the target ring (always horizontal or vertical; line segments inside distractors were always diagonal). After making their response, participants were shown feedback. Correct responses garnered a reward of either high value ($0.10) or low value ($0.02). Note that in the actual experiment, backgrounds were black, and text and line segments were white.

following pool of values: blue (RGB value: 0, 0, 255), magenta (RGB value: 255, 0, 255), white (RGB value: 255, 255, 255), tan (RGB value: 237, 199, 114), yellow (RGB value: 255, 255, 0), and cyan (RGB value: 0, 255, 255). The target was equally likely to appear at any of the six locations along the circular stimulus array. Each ring contained a white line segment that subtended a visual angle of 1.2° in length and 0.2° in width. The line segments inside the target were either vertical or horizontal, whereas the line segments within the distractor rings were oriented at a 45° or 135° angle.

Participants were instructed to report the orientation of the line within the target by pressing either the "z" or "?" key. The mapping of these keys to the orientations of the line was counterbalanced. Every trial commenced with a fixation point at the center of the display. This remained on screen for 1,000 ms and was followed by the stimulus array, which was displayed for 2,000 ms or until participants responded. Following every response, feedback was displayed at the center of the screen in 36-point Helvetica font for 1,000 ms. After an incorrect response, the text said "Wrong!" Following a correct response, the text said "Correct!" along with one of two possible monetary reward values ($0.02 or $0.10). Stimulus-reward contingencies were established such that one target color was always associated with an 80% likelihood of the greater reward and a 20% likelihood of the lesser reward. The contingencies were inverted for the other target color. These color/reward-magnitude contingencies were counterbalanced across participants.

Sessions began with a 24-trial practice block in which performance feedback was given without monetary reward. Participants were informed that on the ensuing experimental trials, correct performance would earn them cash at the end of the experiment. Training sessions consisted of 240 trials and were segmented into 60 trial blocks. At the conclusion of each block, participants were informed of their current earnings. A maximum of $14.40 would be earned if accuracy were 100%. At the conclusion of the experiment, participants were given $15 regardless of their performance.

To assess the impact of previously rewarded distractors, we asked participants to complete 240 testing trials at the conclusion of training. The testing sessions were identical to the training sessions except that participants searched for a blue (RGB value = 0, 0, 255), diamond-shaped target among circular distractors. Half of all testing trials contained circles that had been used only as distractors during training; the other half contained, in addition to four distractors, a red or green circle—the very same stimuli that served as targets in the training session. During the test phase, however, these previously rewarding stimuli distracted attention away from the diamond-shaped target. High-value and low-value

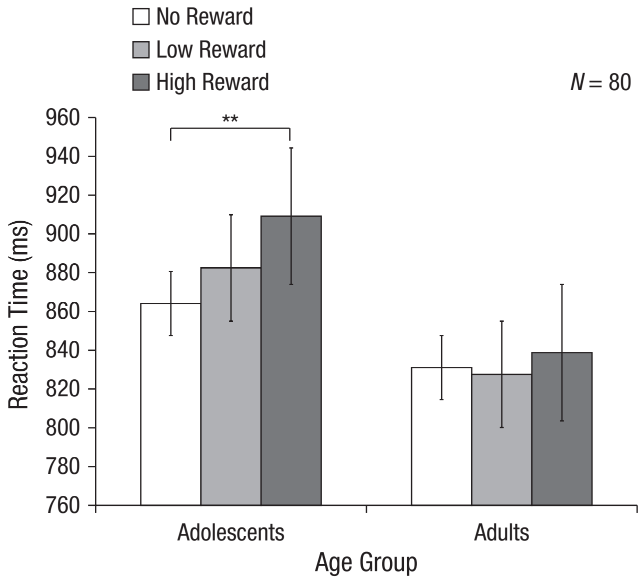

Fig. 2. Mean reaction time as a function of age group and distractor type during the testing phase. Asterisks indicate a significant difference between conditions (**$p < .01$). Error bars represent 95% within-subjects confidence intervals (Cousineau, 2005; Loftus & Masson, 1994).

distractors were equally likely during the testing trials. RT to report the orientation of the line within the diamond served as the dependent variable in our analyses.

Results

Mean correct RT for training trials was computed for each age group (adolescents vs. adults) and for each reward value (low: $0.02 vs. high: $0.10). Response latencies less than 150 ms and trials on which participants made errors were excluded from the analysis. This trimming reduced the amount of analyzed data by 3.7%.

The RT data were analyzed with a mixed-model repeated measures analysis of variance (ANOVA). Neither the effect of reward value, $F(1, 78) = 0.46$, $p = .50$, $\eta^2 = .10$, nor the interaction between age group and reward value, $F(2, 156) = 0.19$, $p = .67$, $\eta^2 = .071$, reached significance (adolescents—high value: $M = 837$ ms, $SD = 208$ ms; low value: $M = 828$ ms, $SD = 190$ ms; adults—high value: $M = 836$ ms, $SD = 165$ ms; low value: $M = 834$ ms, $SD = 167$ ms). These results imply that there was no significant difference between age groups in the strength of the stimulus-reward association established during training.

Mean correct RT for testing trials was computed for each age group (adolescents vs. adults) and distractor type (no value vs. low value vs. high value). Response latencies less than 150 ms and trials on which participants made errors were excluded from the analysis. This trimming reduced the amount of analyzed data by 1.7%.

We applied a mixed-model repeated measures ANOVA on the RT data (see Fig. 2). We observed a main effect of distractor type, $F(2, 156) = 6.42$, $p < .002$, $\eta^2 = .076$. Follow-up analyses revealed that high-reward distractors ($M = 874$ ms, $SD = 211$ ms) produced longer RTs than no-reward distractors ($M = 848$ ms, $SD = 178$ ms), $t(79) = 3.84$, $p < .001$, and low-reward distractors ($M = 855$ ms, $SD = 201$ ms), $t(79) = 2.20$, $p = .031$. RTs on low-reward trials did not significantly differ from RTs on no-reward trials, $t(79) = 0.99$, $p = .32$. Most important, we observed a significant interaction between age group and distractor type, $F(2, 156) = 3.06$, $p = .05$, $\eta^2 = .038$, which revealed that the VDAC effect was exacerbated for younger individuals. A separate analysis revealed that there was no main effect of gender, $F(1, 78) = 0.65$, $p = .42$, $\eta^2 = .008$. The interaction between gender and distractor type was also not significant, $F(2, 156) = 0.18$, $p = .84$, $\eta^2 = .002$. After controlling for visual working memory (VWM) capacity (see the Supplemental Material available online for details), the Distractor Type × Age Group interaction was essentially unchanged, $F(2, 154) = 2.95$, $p = .06$, $\eta^2 = .037$.

We conducted additional analyses to characterize how stimulus-reward associations extinguished as a function of age. VDAC difference scores were calculated for each participant by subtracting the mean RT on no-reward trials from the mean RT on high-reward trials. Anderson et al. (2011) found that raw RTs on high-reward trials differed significantly from those on no-reward trials, but not from those on low-reward trials. Likewise, raw RTs on low-reward trials did not differ significantly from those on no-reward trials. Thus, VDAC is most readily measured by comparing high-reward trials with no-reward trials. These difference scores were derived separately for each quarter of the testing trials. Paired-samples t tests comparing high-reward and no-reward trials were carried out for each age group. Figure 3 depicts the results of this analysis. Adults' reward-modulated behavior extinguished in the 1st quarter, but adolescents' VDAC scores were consistently high throughout the entire testing session. For a final comparison, we divided each group of participants into two groups: Adolescents were divided into 13- to 14-year-olds ($n = 23$) and 15- to 16-year-olds ($n = 17$), and adults were divided into 22- to 28-year-olds ($n = 25$) and 29- to 35-year-olds ($n = 14$). One 20-year-old participant was removed to preserve continuity across the age groups. Figure 4 illustrates a gradual decline in VDAC magnitude as a function of age; 13- to 14-year-olds exhibited greater attentional capture than did 22- to 28-year-olds, $t(46) = 2.54$, $p = .01$, and 29- to 35-year-olds, $t(35) = 2.18$, $p = .04$. No other pairwise comparisons were significant.

Discussion

Attentional control is critical to a host of tasks and is essential for good decision making. Disruptions in

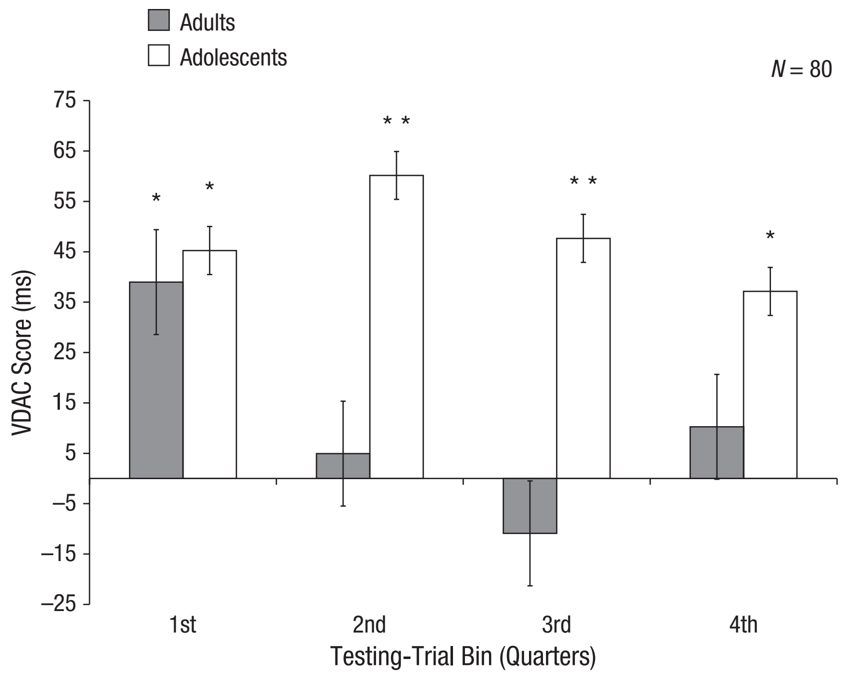

Fig. 3. Mean value-driven attentional-capture (VDAC) magnitude as a function of testing-trial bin and age group. VDAC scores reflect the mean reaction-time (RT) difference between high-reward and no-reward trials. Asterisks denote scores significantly different from zero, as determined using paired-samples *t* tests (**p* < .05, ***p* < .01). Error bars represent 95% within-subjects confidence intervals (Cousineau, 2005; Loftus & Masson, 1994).

attentional processes have been linked to problems with multitasking, sensitivity to cues related to substance use, and developmental disorders such as attention-deficit/hyperactivity disorder. Yet, to date, there has been very limited investigation of how reward cues differentially affect attention in adolescents versus adults. Although stimulus-reward associations are instrumental for optimal decision making and effective behavioral responding (Rescorla & Wagner, 1972), rewards, because of their salient and motivationally relevant nature, may also disrupt behavioral and cognitive processes. Given that adolescence is associated with dramatic changes in the brain's dopamine-mediated reward system, we investigated how previously learned stimulus-reward associations alter attentional control in this sensitive developmental time period. Utilizing a VDAC task recently developed by Anderson and colleagues (2011), we found that adolescents are more susceptible than adults to attentional capture when exposed to previously rewarding stimuli. Furthermore, our analyses demonstrated that the nature of this susceptibility is not necessarily one of magnitude but rather one of longevity. Figure 3 illustrates that adults' attention was initially captured by value-based stimuli, but this effect quickly extinguished. However, value-driven distraction persisted throughout the entire experiment for adolescents. In fact, the magnitude of attentional capture was nearly as large for adolescents at the end of the experiment as it was for adults at the beginning of testing trials. Furthermore, these results could not be accounted for by developmental differences in VWM capacity.

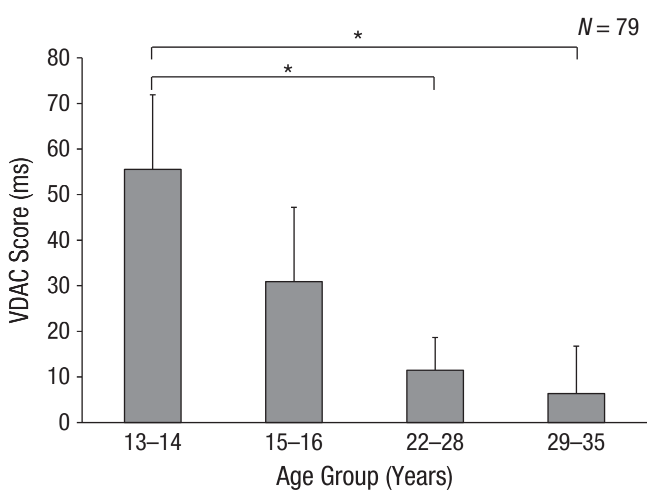

Fig. 4. Mean value-driven attentional-capture (VDAC) magnitude as a function of age group. VDAC scores reflect the average reaction-time difference between high-reward and no-reward trials. For this analysis, participants were divided into four age groups, two for adolescents and two for adults. An asterisk denotes a significant difference between age groups, as revealed by an unpaired-samples *t* test (**p* < .05). Error bars represent +1 *SEM*.

These findings are consistent with recent evidence suggesting that performance on experimental laboratory tasks is likely disrupted in adolescence when there is a "hot," affective component to the task. For instance, Figner and colleagues (2009) demonstrated that adolescents and adults made equally risky choices on a "cold," deliberative version of the Columbia Card Task, but adolescents made significantly more risky choices on the "hot" version of the task. More recently, Somerville, Hare, and Casey (2011), using an emotional go/no-go task, demonstrated that adolescents had more difficulty inhibiting a prepotent button-press response to happy faces than to neutral faces. This deficit was associated with heightened activity in a region encompassing the nucleus accumbens.

Our results extend these findings in two important ways. First, we created a learned association between reward and stimuli. Consequently, performance differences on test trials cannot be attributed to different past experiences with the reward stimulus (as might be the case with happy faces, for instance). Second, contrary to Grose-Fifer et al.'s (2009) finding of distraction by affectively charged faces, our results cannot be readily explained by appealing to the mere scale of attention; our training phase established stimulus-reward associations that are feature-value specific (i.e., red and green target rings). Thus, the attentional capture witnessed in the test phase is not simply attributable to a broadening of attentional scope but reflects how rewards subtly tune the attentional system. More generally, our findings suggest that adolescent differences in performance on "hot" experimental tasks may depend, in part, on early stages of cognitive processing related to attentional cuing. However, this does not preclude the possibility that later cognitive processes, such as the framing effect (Reyna et al., 2011), may also impinge on adolescent behavior during "hot" decision-making episodes.

Overall, these results indicate that the transition from adolescence to adulthood is marked by improvements in top-down control of attentional resources. Ernst, Daniele, and Frantz (2011) suggested that attention in adolescence is motivated by stimulus-driven, as opposed to goal-driven, processes. It is possible that age-group differences in the present experiment were not driven by attentional control but by greater reward saliency acquired during the learning phase in adolescent subjects than in adult subjects (cf. Luciana & Collins, 2012). In this regard, it is noteworthy that the attention of both adults and adolescents was similarly captured by previously rewarded stimuli during the first quarter of the test phase. Also, there was no significant difference between adolescents' and adults' RTs during the training phase. This pattern of results suggests that the age differences in the VDAC effect are driven, at least in part, by top-down cognitive control or executive function processes. In contrast, reward hypersensitivity may also explain age-based attentional differences. The current results are not well suited to distinguish these alternatives. Thus, the exact mechanism driving the observed effect remains an open question for further research. Future work should focus on identifying neuro-maturational as well as experiential processes that promote the development of effective attentional control in the presence of rewarding yet nonetheless task-irrelevant stimuli.

We should acknowledge that adolescents and adults may have different experiences with money, and therefore adolescents may respond more strongly to monetary rewards. It will be important to cross-validate these findings with those involving other rewards (e.g., points to win personally relevant prizes). Furthermore, in order to establish the findings' specificity to reward cues versus all emotionally relevant cues, it will be important for future studies to investigate attention to cues previously associated with punishments or monetary loss. Although Anderson and colleagues (2011) found a correlation between visual working memory and VDAC, we did not observe the same relationship in a wider age range of participants. Indeed, we did not find developmental differences in visual working memory at all. Future studies should include additional working memory and executive function measures to determine whether the VDAC effect relates to other higher order cognitive processes.

Author Contributions

Z. J. J. Roper and S. P. Vecera developed the study concept. All authors contributed to the study design. Testing and data collection were performed by J. G. Vaidya. Z. J. J. Roper and J. G. Vaidya analyzed the data. Z. J. J. Roper drafted the manuscript, and J. G. Vaidya and S. P. Vecera provided critical revisions. All authors approved the final version of the manuscript for submission.

Declaration of Conflicting Interests

The authors declared that they had no conflicts of interest with respect to their authorship or the publication of this article.

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Supplemental Material

Additional supporting information can be found at http://pss.sagepub.com/content/by/supplemental-data

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