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Adolescent Brain Response to Reward Is Associated with a Bias toward Immediate Reward

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Abstract

The current study examines associations between neural activation to the receipt of monetary reward in a rewarding game task and bias toward immediate reward measured in a behavioral delay discounting task among early adolescents (N = 58, 12–14 years). As expected, heightened brain activation in reward-related regions were correlated with higher bias toward immediate reward. This suggests that bias toward immediate reward in delay discounting tasks may be linked to heightened activation to reward in reward processing regions. This interplay between neural reward processing and bias toward immediate reward might explain the sharp increases in bias toward immediate reward that occur in early adolescence.

Introduction

Early adolescence is a period characterized by the initial emergence of risky behaviors, such as alcohol and substance use, and other risk-taking behaviors such as staying out late (Rew, Horner, & Brown, 2011; Sikora, 2016). In addition, bias toward immediate reward as measured in delay discounting tasks is associated with substance use, externalizing behavioral disorders (Olsen et al., 2007; Scheres et al., 2006). Thus, bias toward immediate reward may be important in predicting the onset of substance use during middle adolescence (Audrain-McGovern et al., 2009). In contrast, lower levels of bias toward immediate reward during early childhood is predictive of better social competence, planning, and better coping skills during middle adolescence (Mischel, Shoda, & Peake, 1988). Given bias toward immediate rewards' associations with externalizing disorders, such as substance use, and cognitive and social competencies, further exploring the neural mechanisms of bias toward immediate reward in adolescence is important and can help in the development of interventions to prevent substance use during middle adolescence.

One neural factor that might underlie bias toward immediate reward is neural responses in reward-related regions to rewarding stimuli, such as a monetary reward. Similar to bias to immediate reward, neural responsivity to rewarding stimuli in reward-related regions increases during early adolescence, peaks during mid-adolescence, and then declines into adulthood (Steinberg et al., 2009). Critical regions for reward processing during adolescence include striatal regions, including the nucleus accumbens (NAc) which is responsible for

(proportion of choices in which smaller immediate rewards were selected). While it remains unclear if enhanced or blunted neural reward-related activity is associated with bias toward immediate reward as measured in delay discounting tasks, these studies demonstrated that altered activation in reward-related regions, including the ventral striatum, are linked with a bias toward immediate reward in adolescents. In addition, a few studies with adults find that increased neural activation in reward regions, including the ventral striatum, caudate, putamen, and nucleus accumbens, during decision-making and reward receipt tasks, are associated with increased bias toward immediate reward measured in delay discounting tasks (Kable & Glimcher, 2007; McClure, Laibson, Loewenstein, & Cohen, 2004; Hariri et al., 2006; Wittmann, Leland, & Paulus, 2007; Ballard et al., 2009). However, studies are needed that examine brain responses to reward and bias toward immediate reward specifically during early adolescence (not including childhood and middle adolescence), given the importance of this developmental period and studies are needed that use developmentally appropriate measures of bias toward immediate reward.

In the current study, we aimed to examine associations in early adolescents between neural activation in four bilateral reward-related regions of interest (ROIs) (caudate, putamen, NAc, and vmPFC) to the receipt of monetary reward in a rewarding game task in scanner and bias toward immediate reward measured in a behavioral delay discounting task, The Delay and Probability Discounting Task (DPDT; Richards, Zhang, Mitchell, & Wit, 1999). The present study contributes to the literature in two ways. First, the present study investigated how neural response to reward relates to bias toward immediate reward during in 12–14 year olds who are in *early adolescence*, a period of time characterized by increases in bias toward immediate reward and increases in risk behavior. We chose 12–14 year old participants to reflect the time period after middle childhood, but before middle adolescence and also to map on to the middle school period. Second, the present study used a widely used, valid, and developmentally appropriate measure of delay discounting. Findings from the present study can help inform prevention efforts by identifying potential neural mechanisms underlying bias toward immediate reward, which may be related to risk-taking behaviors.

We hypothesized that heightened activation in the neural reward processing ROIs during receipt of monetary reward in the fMRI scanner will be associated with a heightened bias toward immediate reward measured in a behavioral delay discounting task in the laboratory.

Materials and methods

Participants

We recruited early adolescents ranged from 12–14 years old from a larger study investigating early adolescent risk behavior. Participants were recruited through newspaper ads, flyers, and mailings distributed to representative households in a suburban area in the Mid-Atlantic United States. Families were screened for inclusion criteria. Families that had children between the ages of 12–14, parent and child with adequate English proficiency to complete questionnaires, a child with $IQ > 80$, and no diagnosis of psychotic or autism spectrum disorders for the child, were recruited into the larger study. If interested, adolescents were invited to participate in a fMRI session if they met MRI inclusion criteria (MRI safe, not pregnant, no history of traumatic brain injury).

Participants were drawn from a larger study, which included 197 early adolescents. Out of this larger study, the first 89 adolescents who were interested and eligible for a fMRI scan participated in an additional fMRI scan. Out of the 89 adolescents, 13 were excluded due to an inability to complete the scan (excessive motion, discomfort, and feeling sick). Due to concerns around inattention and lack of motivation, delay discounting scores were examined for inconsistent response styles. Indifference point should decrease over time, and if not, responses are considered erratic. Erratic responses are usually removed from data (Olsen et al., 2007; Dixon et al., 2005; Reynolds, Richards, de Wit, 2006). In order to be considered consistent, participants must have at least two indifference point decreases and not more than one increase in indifference points (Dixon et al., 2005; Dixon, Marley, & Jacobs, 2003). Sixteen additional adolescents were excluded for inconsistent discounting on the behavioral delay discounting task. These excluded adolescents were not significantly different from the larger sample of 89 adolescents. Adolescents were not excluded due to current, or previous, psychiatric medication use, and 10% of the adolescents in the sample were using medication on the day of the scan. We examined psychiatric medication use as a possible covariate (see below). Additionally, fMRI data were examined for excessive head motion, with results indicating no outliers.

Procedures

As noted, adolescents were recruited from a larger, longitudinal study of youth emotion. From this larger study, adolescents completed three baseline sessions, with informed consent and assent being obtained prior to beginning the first session. The larger study included two study sessions where adolescents completed questionnaires, interviews, behavioral tasks, a parent-adolescent interaction task and physical measures that included urine and breath drug screens. During the third session, adolescents who were eligible participated in the fMRI scan.

fMRI scan

Adolescents arrived 30 min before the scan. During this time, adolescents were acquainted with a mock scanner and informed of the fMRI procedure. Adolescents completed a practice trial of the reward task, which lasted approximately 1 min. After completing the practice trial, adolescents were questioned about medication use and drug use within the last month. Adolescents were informed to not use alcohol, tobacco or any other substance on the day of the scan. All 60 adolescents in the current sample refrained from substance use, confirmed by their self-report.

Following this, adolescents and their guardian met with a certified MRI technician for a final safety scan. Once cleared by the technician, adolescents were set up in the scanner and provided with head padding for comfort, and protective ear wear to protect against loud sounds emitted by the scanner. For the scan, first, structural images were obtained (approx. ~5 min). Then, adolescents completed three functional task-based scans (including the reward task scan; approx. ~30 min), a functional resting state scan (~6 min) and a T2 weighted structural scan (MPRAGE) (~8 min). Upon departure, adolescents completed exit questionnaires and received payment for participation.

Neural measure of reward: card guessing task

An event-related card guessing game was used to measure neural response to reward anticipation and reward feedback (Forbes et al., 2009)(Figure 1a). This task was adapted from Delgado, Nystrom, Fissell, Noll, and Fiez (2000) to probe reward-related processing regions, with one run including 24 trials (12 trials for each of the two possible anticipation trial types and 6 trials for each of the four possible outcome trial types for use with adolescents) (Forbes et al., 2009). This task was originally two runs but was shortened after finding that reward processing can be established within the first run, which is important in minimizing fatigue and habituation (Forbes et al., 2009). Several studies have used this one run task with 24 trials and were successful in assessing reward-related brain function (Forbes et al., 2009; Holm et al., 2009; Nusslock et al., 2012).

During each trial, adolescents used a button box to guess whether a card on the screen would be greater than or less than five (2 s). Next, they were presented with shuffling hands with an up or down arrow that indicated a possible win or possible loss trial (500 ms). Then, they saw the actual card and were told that they either won a dollar (win feedback), lost 50 cents (loss feedback), or neither (neutral feedback) (500 ms) and then saw a cross-hair for an inter-trial interval of 11 s. Analyses will focus on the contrast between win feedback and neutral feedback trials (win-neutral). Furthermore, although adolescents were informed their earnings were random, all adolescents won and lost a set number of trials, and all adolescents received \$6 at the end of the session.

fMRI image acquisition, preprocessing and analysis—Participants were scanned using a Siemens Allegra 3-T scanner, equipped with a one-channel birdcage head coil. BOLD functional images during the reward task were acquired by using gradient-echo echoplanar images (EPI) (TR/TE: 2250/30 ms; flip = 70°; FOV: 192 mm; matrix size: 64 × 64; 40 axial 3 mm thick slices). Before analyses, fMRI images were preprocessed using FSL (FMRIB, Oxford, UK) and assessed for quality.

Analyses were performed using FSL (www.fmrib.ox.ac.uk/fsl). To allow the scanner to reach its equilibrium magnetization, the first three volumes were removed before analysis. Data were smoothed with a 6 mm full width half maximum (FWHM) Gaussian kernel, and noise frequencies lower than 1/96 Hz were removed. Data were co-registered to that participant's MPAGE image, and then to the MNI template.

Behavioral measure of bias toward immediate reward: delay discounting task

To assess bias toward immediate reward behaviorally, youth completed a computerized Delay and Probability Discounting Task (DPDT; Richards et al., 1999)(Figure 1a). In this task, adolescents were asked to choose their preference between a smaller immediate/certain monetary reward and a \$10 delayed reward/\$10 probabilistic reward. Fluctuating amounts of smaller immediate/certain reward in each trial were determined by using a random adjusting procedure (Richards, Mitchell, Wit, & Seiden, 1997). When the participant considered the variable amounts (immediate/certain monetary reward) equally as attractive as the standards (delayed/probabilistic monetary reward), an indifference point (or “subjective value”) was established. For this study, the measure we are using of bias toward immediate reward is the

indifference point. Typically, lower discounting scores reflect individuals with a relatively higher bias toward immediate/certain rewards. However, to make our results easier to interpret, delay discounting data were reversed scored; where higher scores now reflect individuals with a relatively high bias toward immediate reward.

Analysis plan

Data inspection—Data were examined for outliers. ROI extracted data with values greater than 3 SDs above the mean were winsorized and set to equal 3 SDs above the mean, following previous MRI studies (e.g., Price et al., 2014). L Putamen and R Caudate data each had two outliers, while L Caudate data had one outlier. Data were motion corrected, slice-time corrected, and B0 unwarped. Four children had 1–4 TR spikes of between 3 and 6 mm. Those spikes were scrubbed with FSL motion outlier function.

Covariates.: Due to sex differences found in brain response, analyses covaried for child sex. Age, IQ, race, psychiatric medication use and socioeconomic status were also considered as covariates if they were significantly correlated with discounting scores and ROIs. None of these variables were significantly correlated with discounting scores and ROIs; therefore, none were included in the final models.

Analyses.: Analyses focused on BOLD responses in the apriori ROIs (bilateral regions of the putamen, caudate, vmPFC and NAc). These regions were chosen as they are primary areas for reward processing and are typically examined during adolescence (Knutson & Greer, 2008). ROIs were defined on an MNI template brain and applied to each participant's MNI transformed data using standard anatomical criteria. ROIs were created from the Harvard-Oxford Atlas. Mean parameter estimate values were extracted from ROIs for the win and neutral trials. Next, win minus neutral scores were calculated. To test the hypotheses, ROI scores were regressed on delay discounting scores, with child sex as a covariate. To control for multiple comparisons across the ROIs, a Benjamini-Hochberg False Discovery Rate (FDR) correction was applied at $p < .05$. Both FDR-corrected and uncorrected p -values, in addition to estimates of effect size, are reported.

Results

Our final sample included 58 adolescents (32 boys), ranged from 12 to 14 years old ($M = 12.58$, $SD = .64$). The average discounting rate was similar to that found in adolescent literature ($M = .43$, $SD = .29$) (Figure 4). The majority of the adolescents were European American (71.7%, 8.3% Latin American, 6.7% Asian, 6.7% Multiracial and 6.7% Other or Unknown) and most had family incomes above 100,000 (75.9%; 8.3% between 75,000 and 100,000; 11.7% between 60,000 and 74,999; 1.7% between 35,000 and 59,999 and 1.7% < 35,000; $n = 57$). Ethnicity and income were representative of the community from which families were recruited.

R and L putamen activation to win minus neutral trial was significantly associated with discounting scores, $t(56) = 3.361$, $p = .001$; $t(56) = 3.232$, $p = .002$, respectively (Figure 2). R and L caudate activation to win minus neutral trials was significantly associated with discounting scores, $t(56) = -2.967$, $p = .004$; $t(56) = 2.908$, $p = .005$, respectively (Figure

2). R and L nucleus accumbens activation to win minus neutral trials was significantly associated with discounting scores, $t(56) = 2.231$, p value = .03; $t(56) = 2.533$, $p = .002$, respectively (Figure 3). R and L ventromedial prefrontal cortex activation to win minus neutral trials was significantly associated with discounting scores, $t(56) = -2.399$, p value = .02; $t(56) = 2.808$, $p = .007$, respectively (Figure 3). Thus, our findings indicate that higher BOLD response in reward-related regions was associated with higher levels of bias to immediate reward (measured in the behavioral delay discounting task), as predicted.

Discussion

Early adolescence is a developmental period where risk behavior first emerges. Relative to children and adults, bias toward immediate reward is strongest during adolescence (Steinberg et al., 2009;

Whelan & McHugh, 2009). Heightened bias toward immediate reward during early adolescence is predictive of risk-taking tendencies during mid-to-late adolescence (Audrain-McGovern et al., 2009; Gardiner et al., 2018; Heinrich et al., 2016; Nees et al., 2012). Thus, given that bias toward immediate reward increases in adolescence and is related to risk behaviors, it is important to understand associations between brain responses to reward and bias toward immediate reward. Critical brain regions that are implicated in the processing of reward during adolescence include the caudate, vmPFC, NAc, and putamen. These reward-related regions show increased activation during adolescence and may underlie increased bias toward immediate reward (Christakou et al., 2011; Benningfield et al., 2014). However, there are few studies examining associations between behaviorally measured bias toward immediate reward and activation in reward-processing brain regions during early adolescence. Those studies that examine these associations during adolescence used small sample sizes included wide age ranges that crossed middle childhood, early adolescence, and middle adolescence. Further, those studies also used uncommon behavioral measures of delay discounting (e.g. Monetary Choice Questionnaire) and non-traditional approaches to measuring discounting behavior (proportion of choices in which smaller immediate reward was selected rather than area under the curve). The present study addressed these limitations by uniquely examining a large sample of early adolescents, with a well-validated behavioral measure of delay discounting and traditional approaches to measuring delay discounting scores (area under the curve). Results from the current study revealed that heightened brain responses in reward processing regions to receipt of monetary reward was significantly associated with a greater bias toward immediate reward, as measured by a behavioral measure of delay discounting during early adolescence. Furthermore, this relationship remained significant after controlling for adolescent sex.

Our findings are consistent with the adult literature and one study of 11–18 year old early to late adolescents by Christakou and colleagues (2011) that find that an increased bias toward immediate reward measured in delay discounting tasks is associated with heightened activation in reward processing regions to rewarding stimuli (or reward-related decision making), including in NAc, caudate, and putamen (Hariri et al., 2006). Both Christakou and colleagues (2011) and our study found that increased activation in the caudate during reward processing was correlated with a heightened bias toward immediate reward in a delay

discounting task in adolescents, although our delay discounting task was in the lab and theirs was in the scanner. It is interesting that they found their main findings between bias toward immediate reward and caudate responses, whereas we also found associations with NAc, vmPFC, and putamen responses to reward. The NAc and vmPFC are implicated in readying the body for reward and processing rewarding stimuli. Thus, it might be that these particular areas are more heavily involved in processing the receipt of reward (as measured in our study), rather than in reward-related decision making (as assessed in the Christakou et al. 2011). Although the putamen and caudate are similar in function, the putamen is more heavily involved in evaluating actions in term of rewards. Given that our task was stimulus-action-response based, it is possible that the putamen demonstrated increased activation because adolescents were evaluating their future actions (what button they would press in the next trial to guess the next card during card game) in response to receiving a rewarding outcome (winning a trial). Benningfield et al. (2014) study of 10–14 year olds found that children/early adolescents' increased bias toward immediate reward was associated with decreased activation in the left ventromedial caudate during the anticipation phase of reward (when the youth learn that the trial is a possible win trial, but have not yet received a reward), but not during the receipt of reward. These results are counter to our results and the literature that finds increased activation in the caudate is associated with a bias to immediate reward (Christakou et al., 2011; Hariri et al., 2006; McClure et al., 2004). These discrepant results might be explained through several aspects of the Benningfield study. First, Benningfield et al. (2014) sampled participants aged 10–14 years. As noted, relative to adolescents, children are less reward responsive and show less bias toward immediate reward, and so the inclusion of pre-adolescent participants might have weakened their results. Second, delay discounting was measured through the Monetary Choice Questionnaire, which has a limited amount of trials (27), and might have not been sufficient enough to capture discounting tendencies. In terms of their reverse finding for reward anticipation, it is possible that there may be a dip in reward system activation before the reward arrives, particularly for children/adolescents with greater bias toward immediate reward, which might explain this finding. Our study did not examine reward anticipation and this would be interesting to examine in future research.

Implications

The present findings of associations between heightened brain activation to rewarding stimuli in reward processing regions and increased bias toward immediate in early adolescence may have significant implications for clinical interventions. Interventions that work to try to strengthen decision-making capabilities and decrease bias toward immediate reward during adolescence to prevent risk behaviors may be improved by this understanding of potential neural mechanisms of their effects. In addition, it is notable that we found that bias toward immediate reward in early adolescence was linked to higher activation in caudate, putamen and NAc and also in vmPFC. The caudate and putamen are related to signaling to the vmPFC that there is a reward present and to facilitate the PFC's involvement in using the rewarding information to help promote self-regulation and decision-making. Our finding may indicate that heightened caudate and putamen responsiveness during early adolescence might overwhelm the gradually developing vmPFC's ability to regulate activation in order to control behavior, and thus; adolescents might be more influenced to act

on urges to pursue immediate reward. Given the relationship of both heightened neural sensitivity and bias toward immediate reward to externalizing disorders, such as substance use, our findings suggest that interventions during early adolescence should target this neural sensitivity to reward and bias toward immediate reward to prevent increases in substance use and externalizing behaviors during middle and late adolescence. Through strengthening brain regions involved in self-regulation and decision-making, interventions can disable adolescent's strong urges to pursue immediate reward and reduce the likelihood of risk behaviors. Second, bias toward immediate reward was linked to higher NAc activation, which is involved in preparing the body to engage in reward-seeking behaviors. Given that adolescents are sensitive to reward, increased activation in the NAc may drive the behavioral orientation toward immediate reward. With this, interventions should work to develop strategies that strengthen adolescents' abilities to delay gratification. Lastly, our results demonstrate that bias toward immediate reward is related to heightened activation in vmPFC to the receipt of reward. The vmPFC is responsible for integrating reward information into decision-making. However, in early adolescence, vmPFC is rapidly developing and may be more associated with increased bias toward immediate reward. Future studies should examine brain function in reward-related regions longitudinally as they relate to bias toward immediate reward to understand how increased activation in regions responsible for processing reward information is related to stronger bias toward immediate reward during adolescence.

Limitations

The current study was not without limitations. For instance, while our sample size was larger when compared to the other two studies with adolescents, it included predominately white and middle to upper-income families. Thus, interpretations of these findings may not be generalizable to other populations. Furthermore, it would be useful to examine how neural responses to reward and behavioral bias toward immediate reward are related to actual risk behavior. However, given our young sample, there was not enough variability in the data to examine risk behavior. In the future, it would be useful to have longitudinal studies that examine the development from childhood through early to late adolescence of neural reward processing, bias toward immediate reward, and risk behavior.

Conclusion

The current study examined associations between neural responses to reward and bias toward immediate rewards in a behavioral delay discounting task. Our findings indicated that adolescents who displayed increased neural activation in reward-related regions upon receipt of monetary reward demonstrated greater bias to immediate reward outside of the scanner. By identifying critical neural mechanisms associated with a bias toward immediate reward, research can be better equipped to target and intervene with adolescents who may be more likely to engage in risk-taking behaviors.

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a. Reward Task

b. Delay Discounting Task

Figure 1.
 (a) Reward task. (b) Delay discounting task.

Figure 2.

Plots show the relationship between bilateral putamen and caudate activation to delay discounting scores. R and L Putamen to win minus neutral trials, $t(56) = 3.361$, $p = .001$; $t(56) = 3.232$, $p = .002$, respectively. R and L Caudate to win minus neutral trials, $t(56) = -2.967$, $p = .004$; $t(56) = 2.908$, $p = .005$, respectively.

Figure 3.

Plots show the relationship between bilateral nucleus accumbens and vmPFC to delay discounting scores. R and L Nucleus Accumbens to win minus neutral trials, $t(56) = 2.231$, p value = .03; $t(56) = 2.533$, $p = .002$, respectively. R and L Ventromedial Prefrontal Cortex to win minus neutral trials, $t(56) = -2.399$, p value = .02; $t(56) = 2.808$, $p = .007$, respectively.

Figure 4.

Subjective value as a function of delay until a reward is received. Subjective value is established when the participant considers the immediate reward equally as attractive as the delayed reward.