Neuroeconomics and Adolescent Substance Abuse: Individual Differences in Neural Networks and Delay Discounting

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Objective: Many adolescents with substance use problems show poor response to evidence-based treatments. Treatment outcome has been associated with individual differences in impulsive decision making as reflected by delay discounting (DD) rates (preference for immediate rewards). Adolescents with higher rates of DD were expected to show greater neural activation in brain regions mediating impulsive/habitual behavioral choices and less activation in regions mediating reflective/executive behavioral choices. **Method:** Thirty adolescents being treated for substance abuse completed a DD task optimized to balance choices of immediate versus delayed rewards, and a control condition accounted for activation during magnitude valuation. A group independent component analysis on functional magnetic resonance imaging time courses identified neural networks engaged during DD. Network activity was correlated with individual differences in discounting rate. **Results:** Higher discounting rates were associated with diminished engagement of an executive attention control network involving the dorsolateral prefrontal cortex, dorsomedial prefrontal cortex, inferior parietal cortex, cingulate cortex, and precuneus. Higher discounting rates also were associated with less deactivation in a "bottom-up" reward valuation network involving the amygdala, hippocampus, insula, and ventromedial prefrontal cortex. These 2 networks were significantly negatively correlated. **Conclusions:** Results support relations between competing executive and reward valuation neural networks and temporal decision making, an important, potentially modifiable risk factor relevant for the prevention and treatment of adolescent substance abuse. Clinical trial registration information—The Neuroeconomics of Behavioral Therapies for Adolescent Substance Abuse, *http://clinicaltrials.gov/*, NCT01093898. J. Am. Acad. Child Adolesc. Psychiatry, 2013;52(7):747–755. **Key Words:** adolescent substance abuse, delay discounting, functional magnetic resonance imaging, neuroeconomics

A primary model of decision making used to explain substance use behavior is intertemporal decision making or choices between 2 alternatives that occur at different points in time.[1] There is a general tendency for rewards to lose value the further away they are in the future, a phenomenon referred to as delay discounting (DD). DD rates generally follow a hyperbolic function, in which reward valuation decreases very rapidly across short delays and then more slowly across longer delays.[2] DD is hypothesized to be particularly relevant to substance use because substance use can be characterized as a choice between the tangible and immediate rewards of consumption and the delayed rewards of abstinence. There is a large literature supporting the association between DD rate and adult and adolescent substance abuse onset and severity.[1,3,4] Further, studies have reported worse adult and adolescent substance abuse treatment outcomes for high discounters.[5-7] For example, the authors previously reported that treatment-enrolled teens with higher DD rates were less likely to achieve abstinence.[8]

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NEURAL MECHANISMS OF DD

A meta-analysis identified 25 regions of significant neural activation during DD tasks.[9] Three

primary regions of robust activation include value-related regions (ventral striatum), value consideration regions (medial prefrontal cortex [PFC]), and future forecasting regions (posterior cingulate cortex). These regions are consistent with the valuation network proposed by Peters and Buchel,[10] who also proposed 2 additional networks important in DD: a cognitive control network, involving activation of the anterior cingulate cortex and decreased top-down regulation of the medial PFC by the dorsolateral PFC, and a prospection/episodic imagery network, involving activity in the medial temporal lobe (hippocampus and amygdala). However, there are developmental differences between adolescent and adults in these regions that may affect DD. Adolescents show maturation similar to adults in limbic and paralimbic "bottom-up" brain regions that function with respect to primary reinforcers[11,12] and slower maturation of the "top-down" frontal cortex and PFC, which regulate executive function and decision making.[11,13] This asymmetric development is theorized to be related to riskier decision making in adolescents than in adults.[14,15] This combination of heightened neural response to reward and motivational cues and delayed behavioral and cortical control may contribute to adolescent preferences for immediate rewards.[16]

There are relatively few studies of neural mechanisms of DD in adolescence. Several studies have examined age-related functional and structural brain changes related to DD, and 2 have identified relations between neural function and structural connectivity and DD rates that were independent of age-related changes.[17,18] For example, strengthening of functional coupling among the ventromedial (vm) PFC, ventral striatum, anterior cingulate cortex, and temporal lobe was associated with decreased discounting, suggesting that developing connectivity between the vmPFC and ventral striatal systems may account for individual differences in DD rates.[17] Increased ventral PFC white matter organization also is associated with decreased DD rates.[18] These results suggest that there may be individual brain and behavioral differences evident in adolescence that confer risk independent of developmental changes.

Several studies also have documented neural structural and activation differences between adolescent substance users and controls.[19,20] There is longitudinal evidence that alcohol use in adolescence may negatively affect memory and attention[21] and evidence of neural activation differences between substance users even at the earliest stages of tobacco use and demographically matched same-age peers.[22] However, most informative for treatment development is identifying the utility of individual neural differences in youth who display problem use and/or who meet diagnostic criteria in predicting individual differences in treatment-relevant constructs such as decision making to ultimately improve treatment outcomes.

The present study was designed to identify individual differences in neural network activation related to decision making (DD) in adolescents with substance use problems. Adolescent substance users were assessed at treatment entry using laboratory and functional magnetic resonance imaging (fMRI) methods while making intertemporal choice decisions. Analyses explored relations between the neural processing patterns that occur when making choices between immediate and delayed rewards and DD rate. The authors hypothesized that the DD task would activate neural networks consistent with reward valuation and cognitive control, and that the patterns of activation in these networks would be correlated with individual differences in DD.

METHOD

Participants

Participants were recruited from 2 ongoing studies investigating behavioral treatments for adolescent substance abuse (marijuana trial and alcohol trial). Fifty-two subjects enrolled in the treatment studies during recruitment for the present study. Two teens refused screening and 9 screened eligible but declined to participate in this study. Six subjects were not eligible for MRI owing to metal in their body (most often braces), and 2 reported claustrophobia and were not scanned. In addition, data for 3 scanned subjects were removed from the dataset because of head movement (n = 1), incomplete discounting data (n = 1), and removal from the scanner owing to claustrophobia (n = 1). Therefore, 30 scanned subjects were included in the analyses. These participants were 12 to 18 years old (mean age 15.7 years, SD 1.7 years; 80% male; 63.3% Caucasian and 36.7% African American).

Teens in the marijuana trial (n = 14) reported marijuana use in the past 30 days or provided a tetrahydrocannabinol-positive urine test and met *DSM* criteria for marijuana abuse or dependence. Teens in the alcohol trial (n = 16) reported alcohol use in the past 30 days and met *DSM* criteria for alcohol abuse or dependence or had had 1 binge episode (≥5 drinks in 1 day) in the past 90 days. A bachelor's level