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Research report

Cerebral white matter correlates of delay discounting in adolescents

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HIGHLIGHTS

- Younger adolescents showed greater preference for immediate rewards during delay discounting.
- Preference for immediate rewards correlated with white matter brain volume differences in prefrontal and motor cortices.
- Reduced white matter maturity in brain regions vital for cognitive control may underlie greater impulsivity.

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ABSTRACT

The adolescent brain undergoes extensive structural white matter (WM) changes. Adolescence is also a critical time period during which cognitive, emotional and social maturation occurs in transition into adulthood. Compared to adults, adolescents are generally more impulsive with increased risk-taking behaviors. The goal of this study is to examine whether adolescent impulsivity may be related to cerebral WM maturation. In 89 healthy adolescents, we assessed impulsivity using the delay discounting task, and MRI WM volumes in brain regions previously implicated in delay discounting behaviors. We found that smaller delay discounting AUC (area under the curve) was associated with larger WM volumes in orbitofrontal, dorsolateral and medial prefrontal cortices (PFC) and motor cortex. There were no significant effects of AUC on WM volumes within somatosensory brain regions. In our sample, younger age was significantly associated with greater WM volumes in orbitofrontal and dorsolateral PFC subregions. Even after accounting for age-related effects, preference for immediate rewards (or greater impulsivity) still correlated with larger WM volumes in prefrontal regions known to mediate cognitive control. Our findings lend further support to the notion that reduced brain WM maturity may limit the ability in adolescents to forgo immediate rewards leading to greater impulsivity.

1. Introduction

Impulsivity, regarded as dysfunctional inhibition of impulses [32], encompasses a wide range of complex behavioral phenotypes [23]. One category of impulsive behaviors is the failure to consider future consequences when making decisions [1]. This form of impulsivity is often assessed using the delay discounting task [16,42] (DDT). During DDT, test subjects are presented with a series of hypothetical forced-choice scenarios offering a smaller immediate reward over a larger but delayed one (e.g. Would you rather have $2 now or $10 in 180 days?). Delay discounting refers to the phenomenon where the current value of a future reward reduces as the delay to that reward increases. In animal studies, lesions in the ventral striatum [9] or in specific regions within the orbitofrontal cortex [36,43] have been shown to increase impulsivity. Although the rate of discounting provides a measure of impulsivity, DDT likely also entails decision-making, cognitive control and quantitative valuation of future rewards that are subserved by cortico-striatal and prefrontal brain networks. For example, McClure and colleagues have shown that greater BOLD signal changes in the ventral striatum, medial orbitofrontal, medial prefrontal, and cingulate cortices were associated with immediate monetary reward choices [38]. On the other hand, delayed reward choices correlated with greater activations in the dorsolateral prefrontal cortex (PFC), motor cortex and somatosensory brain regions. These findings are therefore consistent with the notion that fronto-parietal regions exert cognitive control and top-down support [7,39,40] over limbic brain structures that mediate reward evaluation [20,34,47,50]. Predominant prefrontal influence over limbic activation leads to "safe" behaviors while the converse may manifest as "risky" impulsive conduct [12,41,57]. An imbalanced frontal-striatal interaction favoring the latter may bias toward the

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Table 1
Sociodemographic characteristics of 89 adolescent subjects with valid delay discounting.

Mean age (years (SD))	14.4 (1.32)
Sex (M/F (% males))	43/46 (48.3)
Race (% caucasian)	92.1
Handedness (R/L/mixed (% right))	76/1/12 (85.4)
Mean educational level (grade (SD))	8.2 (1.49)
Mean parental education (years (SD))	15.2 (2.31)
Mean delay discounting (AUC proportion (SD))	0.49 (0.29)

drive for immediate rewards, maladaptive decision-making and impulsivity.

The nodes within brain neural circuits subserving delay discounting (i.e. ventral striatum, prefrontal, medial orbitofrontal, anterior cingulate and parietal cortices) are interconnected by short and long white matter (WM) fiber tracts. Previous studies have examined brain WM correlates of delay discounting but findings have been mixed. Individuals with steeper delay discounting rates (or more impulsive) have smaller right prefrontal subgyral WM volumes and larger WM volumes in the right parahippocampus/hippocampus [67]. Olson and colleagues found that greater impulsivity on the DDT correlated with lower WM tract integrity (i.e. lower fractional anisotropy (FA) and higher mean diffusivity (MD)) in diffuse brain regions corresponding to the inferior and superior longitudinal fasciculi, anterior thalamic radiation, uncinate fasciculus, inferior fronto-occipital fasciculus, corticospinal tract, and splenium of the corpus callosum [48]. Olson and colleagues further reported that many of these impulsivity-WM tract associations (except in the right frontal and left temporal regions) were age-dependent suggesting that there are likely complex interrelationships with adolescent brain maturation.

A hallmark of adolescence is accelerated remodeling of the brain leading to cognitive, emotional and social maturation. Changes in the adolescent brain include pruning of neuronal axons leading to thinning of prefrontal and parietal cortical gray matter [29,49,51,59,60]. There is concurrent increased neuronal myelination associated with WM volume enlargements during adolescence which do not plateau until the fourth decade of life [37,58]. Adolescents are frequently perceived to be more impulsive and prone to engage in increased risk taking leading on to drug use, car accidents and unprotected sexual activity [3]. Adolescent predisposition to impulsivity is thought to be related to a “maturational gap” [10,46]; such that the relatively late maturing prefrontal-based control brain regions are inadequate in regulating the earlier maturing frontostriatal reward circuits [27]. An emerging body of literature supports the view that WM maturation during adolescence increases the efficiency of prefrontal inhibitory interactions on the striatum, and may underlie reductions in impulsivity as adolescents progress into adulthood [5,63].

The goal of this study is to investigate the relationships between cerebral WM volumes and delay discounting rates so as to assess how WM maturation during adolescence may correlate with variability in impulsivity. We hypothesize that reduced maturity in WM connecting brain regions known to mediate delay discounting behaviors will be associated with preference for immediate rewards.

2. Materials and methods

2.1. Sample

Of the 99 adolescents (aged 12–17 years) recruited from the community through advertisements, 10 subjects (M:F = 3/7) did not have valid delay discounting data (see below) and were omitted from further analyses leaving 89 adolescents (Table 1) in the current study. Participants and their parents/legal guardians gave written informed consent approved by the University of Iowa Human Subjects Institutional Review Board. All subjects were assessed using the CAPA (Child and Adolescent Psychiatric Assessment, Child Interview [2]), a semi-structured interview instrument to rule out lifetime history of psychiatric or substance use disorders. Participants with intellectual disability (WRAT3 Reading Score [65] <30), serious medical/neurological disorders or contraindications for magnetic resonance imaging were also excluded. Sociodemographic characteristics of the sample are summarized in Table 1. The sample comprised predominantly of right-handed (85.4%) Caucasians (92.1%) in mid-adolescence (Mean age = 14.4 years (SD = 1.32)) with approximately equal gender distribution (48.3% males).

2.2. Delay discounting task (DDT)

The DDT was based on an experimental paradigm previously developed by Richards et al., [53]. It was administered on a computer monitor screen. The software program controlling the DDT was written in Inquisit scripting language installed on Inquisit 4 Lab software (Version 4.0.3; Millisecond Software LLC, Seattle, Washington) running Windows 7 operating system. In our computerized DDT, subjects chose between a series of two hypothetical monetary rewards, i.e. a smaller (ranging $0.50 to $10) immediately available reward versus a $10 standard reward in the future (2, 30, 180 or 365 days later). Detailed task instructions appeared onscreen. Each study participant was supervised by a research team personnel verifying that the participant had understood the experimental task. Before starting the DDT, subjects were also told that they would receive a cash reward based on one of their answers but that the reward would be chosen randomly by the computer program.

The DDT script used a random adjustment algorithm to determine an indifference point for each of the 5 different delays (i.e. 0, 2, 30, 180 and 365 days). Area under the curve (AUC) and discounting constant k were then derived based on the indifference point at each delay to the standard $10 reward. AUC was calculated by summing the resulting trapezoids [44] while discounting constant k calculation used a nonlinear regression least-squares fit approach. Smaller AUC or larger k indicate preference for immediate rewards or higher impulsivity [44]. Similar results were found regardless of whether AUC or natural log-transformed k (due to its skewed distribution) was used in the statistical analyses. Because AUC provides a more straightforward interpretation of discounting behavior that is not linked to a specific theoretical framework [44], only AUC findings will be presented in this report. Results based on log-transformed k are available in Supplemental materials.

Consistent discounting behavior was defined as having at least two decreases and not more than one increase in indifference points as time increased [19]. A proportion of study participants inevitably do not show discounting behavior, i.e. their indifference points do not consistently decrease with increased time to reward delivery. As with previous studies [19,52], subjects (N = 10) who did not show consistent discounting behavior were excluded leaving 89 study participants who had valid discounting data. Subjects with versus without valid delay discounting did not differ significantly on age, gender distribution, race, handedness, education, parental education or AUC ($p \geq 0.13$).

2.3. Brain MR image acquisition and processing

Each participant underwent a brain MRI scan on the same day the DDT was administered. High-resolution, multimodal imaging of the whole brain was obtained in a single scanning session using a research-dedicated Siemens 3-Tesla TIM Trio scanner equipped with a 12-channel head coil. Each scan included T1-weighted