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Neural mechanisms of individual differences in temporal discounting of monetary and primary rewards in adolescents

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ABSTRACT

Adolescents are generally characterized as impulsive. However, impulsivity is a multi-dimensional construct that involves multiple component processes. Which of these components contribute to adolescent impulsivity is currently unclear. This study focused on the neural mechanisms underlying individual differences in distinct components of temporal discounting (TD), i.e., the preference for smaller immediate rewards over larger delayed rewards. Participants were 58 adolescents (12–16 years-old) who performed an fMRI TD task with both monetary and snack rewards. Using mixed-effects modeling, we determined participants' average impatience, and further decomposed TD choices into: 1) amount sensitivity (unique contribution of the magnitude of the immediate reward); and 2) delay sensitivity (unique contribution of delay duration). Adolescents' average impatience was positively correlated with frontoparietal and ventral striatal activity during delayed reward choices, and with ventromedial prefrontal cortex activity during immediate reward choices. Adolescents' amount sensitivity was positively associated with ventral striatal and dorsal anterior cingulate cortex activity during immediate reward choices. Delay sensitivity was positively correlated with inferior parietal cortex activity during delayed reward choices. As expected, snacks were discounted more steeply than money, and TD of both reward types was associated with overlapping activation in the inferior parietal cortex. Exploring whether testosterone or estradiol were associated with TD and its neural correlates revealed no significant associations. These findings indicate that distinct components contribute uniquely to TD choice and that individual differences in amount sensitivity are uniquely associated with activation of reward valuation areas, while individual differences in delay sensitivity are uniquely associated with activation of cognitive control areas.

Introduction

Adolescents are typically characterized as impulsive. For instance, compared to children and adults, they show increased levels of substance use and other reckless behaviors (Steinberg, 2008). However, not all adolescents are equally impulsive. Importantly, adolescents who are highly impulsive are at a heightened risk to develop behavioral problems, such as substance abuse (Audrain-McGovern et al., 2009), with substantial costs across all domains of life (i.e., social, financial, health) (Mertens et al., 2003). Therefore, it is important to understand the mechanisms underlying individual differences in adolescent impulsivity, as this could inform prevention and intervention programs.

A key component of impulsivity, namely the preference for smaller, more immediate rewards over larger delayed ones has been widely studied with temporal discounting (TD) tasks (see Scheres et al. (2013), for a review). TD refers to the decrease in subjective value of a reward as the delay preceding its delivery is increased. TD tasks involve choices between smaller, more immediate rewards (e.g., $2 today) and larger, delayed rewards (e.g., $10 in 90 days). Adolescents with psychiatric disorders whose core symptom includes impulsivity (e.g., Attention-Deficit/Hyperactivity Disorder (ADHD), substance abuse, gambling, and conduct disorders) have been found to show steeper TD than typically developing adolescents (Demurie et al., 2012; Jackson and MacKillop, 2016; MacKillop et al., 2011; Patros et al., 2016; Reynolds, 2006; Scheres et al., 2010; White et al., 2014). Typically developing adolescents also show steeper TD than adults (de Water et al., 2014; Olson et al., 2007; Scheres et al., 2006; Steinberg et al., 2009; van den Bos et al., 2015; but see Scheres et al. (2014)).

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Studies investigating the neural correlates of TD have implicated both frontoparietal and limbic brain areas in TD, including the lateral prefrontal cortex (PFC), parietal cortex, ventral striatum (VS), medial PFC (mPFC) and posterior cingulate cortex (PCC) (Scheres et al., 2013). The few studies that have explored the neural mechanisms of individual differences in TD in adolescents (Benningfield et al., 2014; Ripke et al., 2012; Stanger et al., 2013) have found that differential functioning of both frontoparietal and limbic areas contributes to these individual differences. One study reported that adolescents who exhibit relatively steep TD show increased activation of lateral prefrontal and parietal brain areas during delayed reward choices, and increased activation of the VS and ventromedial PFC (vmPFC) during immediate reward choices (Stanger et al., 2013). However, other studies reported *decreased* VS activation during decision-making (Ripke et al., 2012) or reward processing (Benningfield et al., 2014) in adolescents who show relatively steep TD.

In the present study, we used mixed-effects modeling (Baayen et al., 2008) to determine individual differences in adolescents' average preference for immediate rewards (i.e., *average impatience*) and two distinct components of TD choice: 1) *amount sensitivity*, or the unique effect of the amount of the immediate reward; and 2) *delay sensitivity*, or the unique effect of the delay duration. The first goal of this study was to investigate the neural mechanisms underlying individual differences in adolescents' average impatience, and amount and delay sensitivity. We hypothesized that average impatience would be positively associated with superior parietal cortex activity (Stanger et al., 2013), and either positively (Stanger et al., 2013) or negatively (Figner et al., 2010; Gianotti et al., 2012) associated with dorsolateral PFC (DLPFC) activity during delayed reward choices. Further, we predicted that average impatience would be positively associated with activation of the vmPFC (McClure et al., 2004; Stanger et al., 2013) and with differential recruitment of the VS (Benningfield et al., 2014; Ripke et al., 2012) during immediate reward choices. We expected that amount sensitivity would be positively associated with VS and vmPFC activity during immediate reward choices (Kable and Glimcher, 2007; van Duijvenvoorde et al., 2015). We anticipated that delay sensitivity would be positively associated with amygdala and insula activation during delayed reward choices (Lemiere et al., 2012; Plichta et al., 2009; Wilbertz et al., 2013).

The second goal of this study was to directly compare the neural correlates of TD of money and snacks in adolescents, and to explore whether amount and delay sensitivity contributed differently to TD of both reward types. We expected that adolescents would discount delayed snack rewards more steeply than monetary rewards (Demurie et al., submitted for publication; Estle et al., 2007; Jimura et al., 2011). We also expected that TD choices for money and snacks would both activate frontoparietal regions (McClure et al., 2004, 2007), and that monetary choices would activate the medial orbitofrontal cortex (mOFC) more than snack choices, whereas snack choices would activate the anterior insula more than money choices (Sescousse et al., 2013).

The third goal of this study was to explore whether testosterone and estradiol levels might be associated with TD components and their neural correlates. When investigating the neural mechanisms underlying individual differences in TD in adolescence, it is important to account for pubertal hormone levels (e.g., testosterone and estradiol), as they increase rapidly in adolescence (Peper and Dahl, 2013), and have been reported to stimulate impulsive behaviors (de Water et al., 2013) by influencing brain activity in reward-related brain areas, such as the VS (Braams et al., 2015; Op de Macks et al., 2011). We expected that higher testosterone and estradiol levels would be associated with increased discounting of delayed rewards (Bromberg et al., 2015), and increased VS activation during decision-making (Braams et al., 2015; Op de Macks et al., 2011).

Methods

Participants

Participants were 61 adolescents (all but one right-handed) who completed a functional magnetic resonance imaging (fMRI) session. Three participants were excluded from subsequent analyses, due to head motion > 3 mm, a brain anomaly, or limited field-of-view coverage. Thus, data from 58 adolescents (31 girls; *M age*=14.5 years, *SD*=1.2, range=12–16 years) were reported. IQ (*M*=109, *SD*=13, range 80–135) was estimated from the Vocabulary and Block Design subtests of the WISC-III (Wechsler, 1991). The Child Behavior Checklist (CBCL; Achenbach and Rescorla, 2001) was filled out by a parent. No participant scored in the clinical range (T-score ≥70) for internalizing or externalizing problems.

Temporal discounting task

Each participant performed a TD task in the MRI scanner (see Fig. 1). The TD task included two blocks with monetary rewards, and two blocks with snack rewards. The task was potentially real, in that one choice was randomly selected for each reward type and given to participants. If the participant chose an immediate reward, they received the respective outcome (money and snack) immediately. If

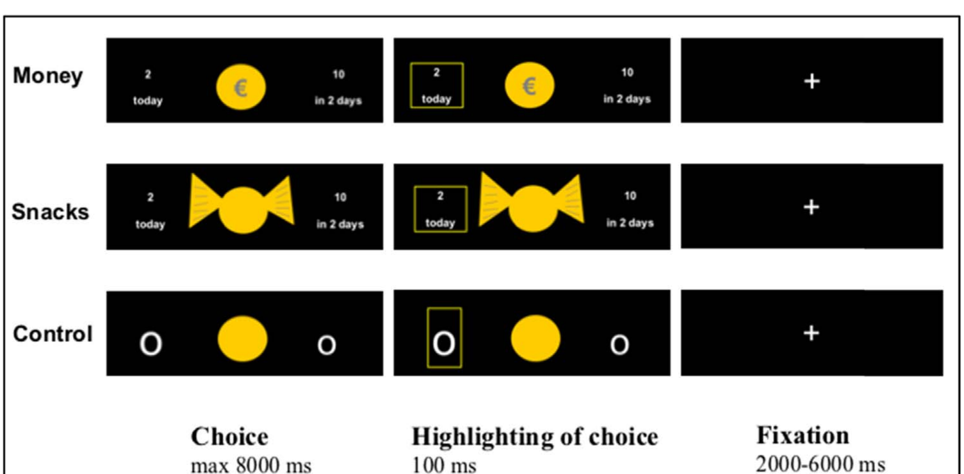

Fig. 1. Trial procedure of the temporal discounting task. *Note.* Participants had to indicate their choice within 8000 ms. After indicating their choice by pressing a button, they immediately continued to the variable fixation period before the next trial.

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