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Temporal and probabilistic discounting of rewards in children and adolescents: Effects of age and ADHD symptoms

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Abstract

This study investigated whether age and ADHD symptoms affected choice preferences in children and adolescents when they chose between (1) small immediate rewards and larger delayed rewards and (2) small certain rewards and larger probabilistic uncertain rewards.

A temporal discounting (TD) task and a probabilistic discounting (PD) task were used to measure the degree to which the subjective value of a large reward decreased as one had to wait longer for it (TD), and as the probability of obtaining it decreased (PD). Rewards used were small amounts of money. In the TD task, the large reward (10 cents) was delayed by between 0 and 30 s, and the immediate reward varied in magnitude (0–10 cents). In the PD task, receipt of the large reward (10 cents) varied in likelihood, with probabilities of 0, 0.25, 0.5, 0.75, and 1.0 used, and the certain reward varied in magnitude (0–10 cents).

Age and diagnostic group did not affect the degree of PD of rewards: All participants made choices so that total gains were maximized. As predicted, young children, aged 6–11 years ($n = 25$) demonstrated steeper TD of rewards than adolescents, aged 12–17 years ($n = 21$). This effect remained significant even when choosing the immediate reward did not shorten overall task duration. This, together with the lack of interaction between TD task version and age, suggests that steeper discounting in young children is driven by reward immediacy and not by delay aversion. Contrary to our predictions, participants with ADHD ($n = 22$) did not demonstrate steeper TD of rewards than controls ($n = 24$).

These results raise the possibility that strong preferences for small immediate rewards in ADHD, as found in previous research, depend on factors such as total maximum gain and the use of fixed versus varied delay durations. The decrease in TD as observed in adolescents compared to children may be related to developmental changes in the (dorsolateral) prefrontal cortex. Future research needs to investigate these possibilities.

Keywords: Attention-deficit/hyperactivity disorder; AD/HD; ADHD; Impulsivity; Reward; Temporal discounting; Probabilistic discounting; Development

1. Introduction

The cognitive, motivational, and neural pathways underlying attention deficit/hyperactivity disorder (ADHD) remain largely unspecified. One promising candidate mechanism consists of the mesocorticolimbic dopamine system (Johansen, Aase, Meyer, & Sagvolden, 2002; Sonuga-Barke, 2002; Viggiano, Vallone, & Sadile, 2004). This neural circuitry originates in the ventral tegmental area and projects to the striatum, nucleus accumbens, limbic areas, and frontal cortex, and underlies the attribution of salience, a key component in reward and motivation (e.g., Schultz, Dayan, & Montague, 1997). Part of this system, the striatum, has been shown to be active during reward anticipation both in studies of animals and healthy adults (Knutson, Fong, Bennett, Adams, & Hommer, 2003; Pagnoni, Zink, Montague, & Berns, 2002), and to play a role in preferences for small immediate rewards over large delayed rewards (McClure, Laibson, Loewenstein, & Cohen, 2004). Hypofunctioning of the mesolimbic reward circuitry has been proposed to contribute to the development of symptoms of ADHD, and to be associated with altered reinforcement mechanisms in ADHD (e.g., Castellanos & Tannock, 2002; Johansen et al., 2002; Sagvolden,

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Aase, Zeiner, & Berger, 1998). Indeed, various researchers have hypothesized that a core problem of children with ADHD is an abnormality relating to reward processes (Blum et al., 2000; Castellanos & Tannock, 2002; Douglas, 1999; Douglas & Parry, 1983; Ernst et al., 2003; Haenlein & Caul, 1987; Iaboni, Douglas, & Ditto, 1997; Sagvolden et al., 1998; Sonuga-Barke, 2002, 2003; Tripp & Alsop, 1999, 2001; Wender, 1972).

The nature of a supposed deficiency in reward processing in ADHD remains largely unclear for three main reasons. First, there are many different aspects to reward such as magnitude, immediacy, and probability (Williams & Taylor, 2004), and the contribution of each of these aspects to reward sensitivity in ADHD has not been comprehensively studied. Second, little research has focused on the neural basis of reward processing in ADHD (for a recent contribution in this area, see van Meel, Oosterlaan, Heslenfeld, & Sergeant, 2005). Finally, studies of reward in ADHD have used a range of tasks and task manipulations, and findings have been inconsistent (see, for a review, Luman, Oosterlaan, & Sergeant, 2005). The overarching goals of this study were to systematically examine the effects of variations in reward magnitude, immediacy, probability and participant age on preferences for reward in ADHD and matched comparison subjects, beginning with the task that has yielded the most consistent results. Although research on the neural basis of these reward aspects is also needed, the goal of this initial study was purely to look at choice preferences, without measuring brain activation.

Investigators have repeatedly demonstrated that children with ADHD have a greater preference for small immediate compared to larger delayed rewards (Barkley, Edwards, Laneri, Fletcher, & Metevia, 2001; Kuntsi, Oosterlaan, & Stevenson, 2001; Schweitzer & Sulzer-Azaroff, 1995; Solanto et al., 2001; Sonuga-Barke, Taylor, Sembi, & Smith, 1992; Tripp & Alsop, 2001; for a review, see Luman et al., 2005). It should be noted that the specific paradigm and task parameters used in these studies varied. In two studies (Solanto et al., 2001; Sonuga-Barke et al., 1992), the paradigm that was used was identical. Participants were presented with a choice-delay task (CDT) between a small immediate reward (e.g., 5 cents now) and a larger delayed reward (e.g., 10 cents after 30 s) on repeated trials. One limitation of such a fixed-choice design is that it does not give insight into how trade-offs are made between reward magnitude and delay duration, because these variables are not systematically varied. Hence, it is unclear how reward preferences in ADHD may vary as a function of delay durations and reward magnitudes.

By contrast, studies of impulsivity in adults have employed more sophisticated paradigms in which reward magnitude and delay duration are varied in order to obtain a *temporal discounting function* (e.g., Coffey, Gudleski, Saladin, & Brady, 2003; Crean, de Wit, & Richards, 2000; Green, Meyerson, Lichtman, Rosen, & Fry, 1996; Kirby, Petry, & Bickel, 1999; Kollins, 2003; Petry, 2001, 2002; Petry & Casarella, 1999; Reynolds, Richards, Horn, & Karraker, 2004; Richards, Zhang, Mitchell, & de Wit, 1999). Temporal discounting (TD) refers to the decrease of subjective reward value as a function of increasing delay (Critchfield & Kollins, 2001; Monterosso & Ainslie, 1999). In one study on adolescents with ADHD and controls (mean age for each group was 15 years), a TD paradigm that allowed for discounting functions was used, with hypothetical choices, i.e., participants were asked to predict their choices over intervals as long as a year and with sums of money that were not really being offered (such as US$ 100 or 1000) (Barkley et al., 2001). This study showed that adolescents with ADHD chose the smaller immediate reward more often than controls when the large delayed reward was US$ 100, but not when the large delayed reward was US$ 1000. While the results of such a hypothetical exercise were informative, they also raise questions of applicability to decisions of daily life.

Thus we decided to employ a TD paradigm in which delay durations and reward magnitudes were systematically varied so that the subjective value of the large delayed reward could be plotted as a function of delay. These TD functions capture the trade-off between reward magnitude and delay, and can be expressed as a single parameter (area under the discounting curve) per individual (Myerson, Green, & Warusawitharana, 2001). Real choices were used in which participants experienced the pre-reward delay on trials on which they chose the delayed reward which consisted of small sums of money that were paid at the end of the task. We predicted that subjects with ADHD would exhibit steeper discounting of delayed rewards than comparison subjects.

There is debate as to whether relatively strong preferences for small immediate rewards reflect hypersensitivity to the immediacy of the reward (Tripp & Alsop, 2001), or, alternatively, a preference for shorter delays (Sonuga-Barke et al., 1992). In order to distinguish between these two explanations for the expected steeper discounting in ADHD, two task versions were used: one in which preferences for immediate rewards led to a reduction in trial duration, and therefore, task duration; one in which choosing the immediate reward did not result in shorter trial durations (see Section 2). We expected that, if reward preferences in ADHD were driven by the reward immediacy, then subjects with ADHD would demonstrate steeper discounting than controls in both versions. If, however, their preferences were driven by aversion to delay, we expected them to show steeper discounting than controls on the version that would lead to shorter task durations, but not on the version in which post-reward delays were inevitable.

We also examined reward preferences in ADHD in a probabilistic discounting paradigm. Probabilistic discounting (PD) refers to the decrease of the subjective value of a reward due to decreasing probability. In PD paradigms, participants are typically presented with choices between a small certain reward and a large probabilistic uncertain reward. While magnitude of the certain reward usually varies, the magnitude of the probabilistic reward is kept constant while its probability level varies. We included a PD paradigm for two reasons: (1) ADHD, and impulsivity in particular, have been associated with a tendency toward greater risk-taking (APA, 1994; Barkley, Murphy, DuPaul, & Bush, 2002; Richards et al., 1999). Therefore, we expected to see less discounting of probabilistic rewards in ADHD; (2) comparisons of temporal and probabilistic discounting have suggested that TD and PD are positively correlated (Myerson, Green, Hanson, Holt, & Estle, 2003; Reynolds, Karraker, Horn,

& Richards, 2003; Richards et al., 1999). This means that individuals who demonstrate steeper TD (stronger preferences for small immediate rewards) also demonstrate steeper PD (stronger preferences for small certain rewards). However, the relationship between TD and PD has not been examined in ADHD. Based on the literature that individuals with ADHD demonstrate strong preferences for small immediate rewards and the clinical correlate of predilection towards risk-taking behavior, it can be hypothesized that ADHD should be characterized by steeper TD and weaker PD, i.e., by a negative correlation (Myerson et al., 2003).

A final goal of this study was to investigate age effects on TD and PD of rewards. The ability to wait for a large/preferred delayed reward in preschoolers predicts cognitive and social competence in the teenage years (Mischel, Shoda, & Rodriguez, 1989). However, the development of TD of rewards has not been studied. Similarly, with respect to PD, although the ability to judge probabilities appears to be established by age 6 years (Schlottmann, 2000), little is known about whether younger children are more or less tempted than adolescents to make riskier choices. We sought to address the question of whether younger children would exhibit riskier or more risk-averse choice strategies than adolescents, both of which would result in a lower total gain.

In summary, the four goals of this study were: (1) to investigate whether children and adolescents with ADHD demonstrate steeper TD of rewards than controls; (2) to investigate whether children and adolescents with ADHD differ from controls in the extent to which they would discount less certain rewards; (3) to investigate whether TD and PD correlate positively in controls and negatively in ADHD; (4) to study the effects of age on TD and PD of small monetary rewards.

2. Methods

2.1. Participants

2.1.1. Recruitment

Participants were recruited from the New York University Child Study Center ADHD Clinical Service, and through notices on our website, University newsletters, and through community resources including local independent schools and not-for-profit organizations. Participants with ADHD and healthy controls were separately recruited, i.e., we specifically looked for participants with symptoms of ADHD and participants who were symptom-free. This was explicit in the ads.

2.1.2. Inclusion criteria

To be assigned to the ADHD group, participants had to have a *T*-score above 65 on at least one of the following Conners' Parent Rating Scale-Revised-Long version (CPRS-R-L) scales: Inattention–Cognitive problems, Hyperactive–Impulsive, ADHD Index, DSM-IV Inattentive, DSM-IV Hyperactive, Global Index Restless–Impulsive. Moreover, they had to meet DSM-IV criteria for any ADHD subtype based on the K-SADS parent version. To be assigned to the control group, participants had to have *T*-scores below 65 on all ADHD-related scales of the CPRS-R-L. Additionally, all subjects had to have a WASI IQ above 75. Although additional rating scale scores were collected (see below), these were used as descriptive instruments rather than selection instruments. Teacher ratings were not used as a selection instrument because of the large number of missing data in the control group. Importantly, pervasiveness of the ADHD symptoms could be determined for the majority of participants in the ADHD group, because teacher-rating scales were available for most participants with ADHD (see below).

2.1.3. Screening procedure

A stepwise selection procedure was used for both groups. In the first stage, parents completed the Child Behavior Checklist (CBCL), the CPRS-R-L, the Strengths and Weakness of ADHD-symptoms and Normal Behavior Parent Scale (SWAN-P), and a demographics questionnaire. Teachers completed the Teacher Report Form (TRF), the Conners' Teacher Rating Scale-Revised-Long version (CTRS-R-L), and the SWAN Teacher Scale (SWAN-T). Prospective participants with a *T*-score above 65 on at least one of the CPRS-R-L ADHD scales were provisionally classified in the ADHD group. Children with *T*-scores below 65 on all the ADHD scales of the CPRS-R-L were provisionally included in the control group.

At the assessment meeting, we interviewed a parent of participants with probable ADHD using the K-SADS-PL while the participant was administered the Wechsler Abbreviated Scale of Intelligence (WASI) and the Wechsler Individual Achievement Test (WIAT). For children who were provisionally included in the control group, this meeting only included administration of the WASI and WIAT, but not the K-SADS-PL. Participants who did not meet current DSM-IV criteria for any of the ADHD subtypes based on the K-SADS-PL, and/or participants with WASI IQ below 75, were excluded from the study.

The ADHD and control group were not matched at the participant level, but at the group level. In other words, we made sure that if age categories were not naturally similar in size across diagnostic groups towards the end of enrollment, we recruited some children in a specific age range. We did not specifically match for intelligence level, but groups turned out not to differ in terms of IQ (see Table 1).

2.2. Group characteristics

Although a total of 69 children and adolescents ages 6–17 years enrolled, prior to analyses, data were excluded from two siblings of participants (in accordance with the assumption of independence of observations); 3 participants with comorbid psychotic symptoms or symptoms of Pervasive Developmental Disorder; 1 with an estimated IQ below 75; 4 in whom the diagnostic interview did not confirm current diagnosis of ADHD; 10 who used medication on the day of testing; 3 who demonstrated a lack of understanding of the tasks when debriefed at session end (e.g., one alternated between left and right button presses independent of the nature of the choices; another reported she chose so as to always keep her total gain a round number). Therefore, statistical analyses were conducted with a sample of 46 participants (22 with ADHD and 24 controls).

Table 1 shows the demographic and behavioral characteristics of the groups broken down by age and diagnosis. Diagnostic groups did not differ significantly in age, and diagnostic and age groups did not differ significantly in WASI IQ, or achievement levels. Within the ADHD group, 13 met criteria for ADHD-combined type, two for hyperactive/impulsive type, and 7 for predominantly inattentive type. Seven participants with ADHD met DSM-IV criteria for oppositional defiant disorder, two for nocturnal enuresis, one had symptoms of anxiety, and one symptoms of depression. Eight participants in the ADHD group discontinued medication one day prior to testing (five on OROS type methylphenidate, two on mixed amphetamine salts, and one on atomoxetine who paused for two days with physician supervision).

As shown in Table 1, ADHD related scores were significantly elevated (indicated with a *) for the ADHD group, as expected. Elevated scores were also observed in the ADHD group for some other scales related to oppositional behavior, anxiety, and social problems. This was the case not only for the selection instrument (the CPRS-R-L) but also for the CBCL and the SWAN-P. Although our inclusion criteria of *T*-scores > 65 for the ADHD group and <65 for the control group allowed for little or no significant difference between the two groups, the mean scale scores show that they do differ (see Table 1). Inspection of the individual scale scores showed that most participants with ADHD had *T*-scores > 70 ($n = 19$) and even >75 ($n = 14$). In the control group, the majority had *T*-scores < 60 on the ADHD scales ($n = 21$) and even <55 ($n = 13$).

Although we did not obtain teacher questionnaires for about half of control participants, we did receive teacher ratings for 20 of the 22 participants with ADHD. For 17 of these, there was at least one elevated CTRS ADHD-related scale score (*T*-score > 65). Therefore, the vast majority of this ADHD group had symptoms of ADHD not only at home, but also in school.

Table 1
Demographics for the ADHD and NC groups, broken down by age

	ADHD 6–11 years, $n = 12$; 10 M		NC 6–11 years, $n = 13$; 9 M		ADHD 12–17 years, $n = 10$; 7 M		NC 12–17 years, $n = 11$; 8 M	
	M	S.D.	*M*	S.D.	*M*	S.D.	*M*	S.D.
Age	8.8	1.6	9.1	1.7	14.4	1.6	14.3	1.5
WASI								
Estimated TIQ	108.4	18.6	105.2[b]	12.2[b]	102.9	13.1	98.0[c]	14.0[c]
Estimated VIQ	107.7	18.0	103.6[b]	13.5[b]	102.5	13.4	99.0[c]	15.2[c]
Estimated PIQ	107.5	17.8	106.1[b]	14.5[b]	102.2	11.7	97.2[c]	11.6[c]
WIAT								
Reading	107.4	14.9	108.7[b]	9.6[b]	106.6	9.4	105.1[c]	12.3[c]
Spelling	101.3	17.8	102.5[b]	9.1[b]	102.1	12.8	108.3[c]	14.2[c]
Numerical operations	99.2	19.0	104.8[b]	11.4[b]	99.2	18.0	90.0[c]	19.4[c]
Total	103.0	17.9	105.3[b]	9.3[b]	102.6	15.3	101.0[c]	16.6[c]
CBCL *T*-scores								
Attention*	68.9	7.8	53.2	5.1	66.6	10.0	53.6	3.8
Aggressive*	60.7	10.0	54.7	6.3	62.0	9.8	52.6	4.4
Rule breaking*	59.8	7.4	55.3	6.7	61.9	7.8	53.6	4.3
Withdrawn	55.8	7.2	54.6	7.1	58.7	8.2	54.4	3.7
Somatic	54.9	5.8	57.1	7.3	63.0	8.4	56.6	5.8
Social problems	58.8	8.5	55.7	5.2	57.9	10.2	55.1	6.1
Thought problems*	60.2	9.3	52.9	6.3	61.4	10.2	54.2	5.4
Anxious*	58.3	5.4	53.9	5.6	61.0	12.0	53.4	5.5
CPRS-R-L *T*-scores								
Oppositional*	61.3	13.7	49.1	6.5	69.1	11.2	51.6	12.7
Inattention*	72.3	7.6	48.1	4.6	72.2	8.0	49.6	7.9
Hyperactive*	68.4	14.9	48.6	5.9	68.6	20.2	48.9	4.6
Anxious	53.5	8.7	48.7	6.9	55.4	13.7	50.0	5.6
Perfectionism	51.6	11.1	48.3	9.5	52.1	8.8	45.3	5.0
Social problems*	58.0	12.0	49.8	7.3	56.2	14.6	47.3	3.6
Psychosomatic*	55.1	10.9	51.3	13.6	66.3	13.4	46.8	7.9
ADHD*	75.3	6.9	47.1	4.8	72.3	12.6	48.7	8.3
GI restless–impulsive*	70.1	10.0	47.5	5.7	70.1	11.8	48.6	7.2
GI emotional*	56.2	14.8	48.0	5.3	60.1	11.4	49.5	10.4
GI total*	67.1	10.9	47.6	5.6	68.4	10.7	48.6	8.4
DSM-IV inattentive*	74.3	7.3	46.1	3.4	72.6	20.3	49.4	7.3
DSM-IV hyperactive*	71.0	13.3	49.0	5.3	63.2	11.6	52.6	7.2
DSM-IV total*	74.7	8.5	47.4	4.0	71.2	9.5	50.6	7.4
SWAN-P								
Inattention*	−1.5	.63	.59	.68	−1.1	.49	.57	1.2
Hyperactive/impulsive*	−1.0	.71	.77	1.1	−.48	.82	.67	1.0
Combined*	−1.3	.47	.72	.80	−.75	.63	.62	1.0

M, number of males; WASI, Wechsler Abbreviated Scale of Intelligence; WASI, Wechsler Abbreviated Scale of Intelligence; TIQ, total intelligence quotient; VIQ, verbal intelligence quotient; PIQ, performance intelligence quotient; WIAT, Wechsler Individual Achievement Test; scores are standard scores; CBCL, Child Behavior Checklist; CPRS-R-L, Conners' Parent Rating Scale-Revised-Long version; GI, Global Index; SWAN-P, Strengths and Weakness of ADHD-symptoms and Normal Behavior Scale Parent version.

[b] $n = 12$.

[c] $n = 10$.

* Significant difference between the ADHD and control groups.

Two age groups were created: 6–11 years (primary school) and 12–17 years (middle or secondary school), to cover an equal number of ages in both the young and the old group (see Table 1).

2.3. Tasks

2.3.1. Temporal discounting task

Participants played a computerized task in which they were instructed to make repeated choices between a small variable reward (0, 2, 4, 6, 8, or 10 cents) that would be delivered immediately (i.e., after 0 s) and a large constant (10 cents) reward that would be delivered after a variable delay of 0, 5, 10, 20, or 30 s. Each small immediate reward was paired twice with every delay for the large reward, resulting in a total of 60 choice trials. For example, participants had to choose between 8 cents now or 10 cents after waiting 10 s. Trials were administered in the same pseudo-random order to all participants. Choices were visually represented by two airplanes on a computer screen (one on each side), each carrying their corresponding quantity of money. Delays were represented by the "height" at which the planes were flying: the higher the plane, the longer the delay duration (see Fig. 1). Left or right position of the delayed reward plane was balanced over trials. Participants chose by pressing the button corresponding to the preferred plane, which resulted in the plane dropping its money cargo into the participant's money basket on the computer screen, immediately or after the appropriate delay. Before the next trial, a reward counter updated the total

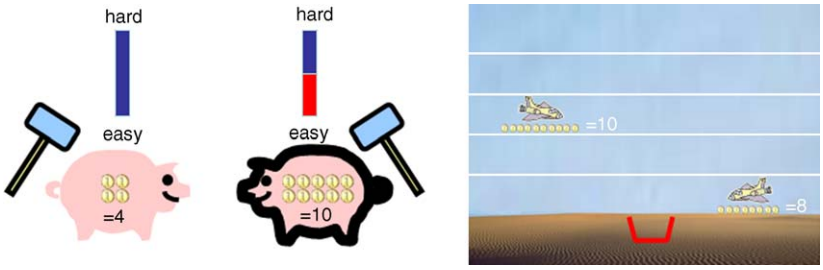

Fig. 1. Example of a trial in the temporal discounting (TD) task (right) and probabilistic discounting (PD) task (left). The TD trial represents a choice between 8 cents immediately or 10 cents after 10 s. The PD trial represents a choice between a certainty of receiving 4 cents or 10 cents with a probability of .5.

number of cents won. After completion of the task, participants received the total amount of money won.

The experimenter read standardized instructions to participants. Participants were not told the durations of the delays, but they experienced each of the delays. Participants were then asked to reproduce each delay by pressing the button when they thought the reward should arrive in their money basket. This procedure ensured that participants understood that the higher the plane was flying, the longer the delay duration. Participants were informed that the task would consist of 60 trials, that there were no correct or incorrect answers, and that they should choose their preference. It was emphasized that there were no correct or incorrect answers, and that they should choose whatever they preferred. Five practice choice trials were administered. After practice, participants received the money they won during the instructions and practice trials (which never exceeded 80 cents). Before proceeding, participants had to be able to demonstrate understanding of the task by explaining it to the experimenter. Once the experimental task began, all participants started with 0 cents in their money basket. Two versions of this task were administered to each participant: one version in which participants did not have to wait for the next trial after receiving the immediate reward, and another in which post-reward delays of the same duration as the pre-reward delay period to the large reward were introduced. In this latter condition, overall trial lengths were the same, regardless of the option selected. For example, if a participant chose 6 cents now over 10 cents after 20 s, 6 cents would be dropped in his/her money basket immediately, but then (s)he had to wait 20 s for the next choice trial. Therefore, in the task without post-reward delays, preferences for immediate rewards led to a reduction in trial duration, and therefore, task duration. In the task with post-reward delays, choosing the immediate reward did not result in shorter task duration.

2.3.2. Probabilistic discounting task

Participants played a computerized task in which they were instructed to make repeated choices between a small reward that would be delivered with 100% certainty and a larger reward that would be delivered with a probability between 0 and 1. The size of the probabilistic reward was constant (10 cents) while the probability of receiving it varied across trials. Five probabilities were used: 0, .25, .50, .75, and 1. The size of the certain reward varied across trials and was 0, 2, 4, 6, 8, or 10 cents. Each small certain reward was paired four times with every large probabilistic reward, resulting in a total of 120 choice trials. For example, participants were presented with the choice between a certain 4 cents or 10 cents with a delivery probability of 50%. Trials were administered in the same randomly generated order for all participants. Choices were represented by two piggy banks drawn on a computer screen (one on each side of the screen), each containing a quantity of money. Probabilities were represented by the thickness of the piggy bank's shell, and by a colored bar, in which red indicated thickness of the shell (see Fig. 1). The position (left or right) of the probabilistic reward was balanced over trials. Pressing the button corresponding to the preferred piggy bank activated a hammer that hit the chosen piggy bank. If the piggy bank broke, the money dropped into the participant's money basket on the computer screen and a reward counter updated the total amount of cents won. After completion of the task, participants received the total amount of money won.

The experimenter read standardized instructions to participants. Participants were not explicitly told what the probability levels were, but they experienced each probability level four times and were asked to hit the piggy bank with the hammer each time. This procedure ensured that participants understood that piggy banks with thinner shells broke more often than piggy banks with thicker shells. Participants were informed that the task would consist of 120 trials. It was emphasized that there were no correct or incorrect answers, and that they should choose whatever they preferred. Five practice choice trials were administered. After practice, participants received the small amount of money that they won during the practice trials, which never exceeded 80 cents. Before proceeding, participants had to demonstrate they understood the task by explaining it to the experimenter. During the experimental task, all participants started with 0 cents in their money basket.

2.4. Procedure

The study was approved by the Institutional Review Board of New York University School of Medicine, and all participants provided prior written informed assent/consent. After signing consent and assent forms, parents returned the completed rating scales. Parents of children who were on medication rated their child's behavior on medication. Therefore, obtained rating scale scores may have underestimated the severity of ADHD symptoms for those being treated with medication.

Participants being treated with psychostimulants were asked to discontinue medication the morning prior to TD and PD testing.

The experimenter remained with the participant at all times during task performance. Participants were instructed to keep their fingers on the response buttons, to look at the screen, and to refrain from talking during task performance. If participants attempted to break these rules, the experimenter used standard phrases such as "keep looking at the screen," "keep your fingers on the buttons," and "we cannot talk during the game."

All three tasks (the two versions of the TD task and the PD task) were run on the same day. The order of the two versions of the TD task was counterbalanced across subjects for each age and diagnostic group. The PD task was always administered last, after the two versions of the TD task. A short break was scheduled between each task. At the end of the session, participants were debriefed. Specifically, they were asked how they chose on each of the tasks.

2.5. Data preprocessing

As a first step, subjective values were calculated for the delayed reward (10 cents) for each delay, and for the probabilistic reward (10 cents) at every probability level. The subjective value of the delayed reward was defined as the magnitude of the small immediate reward for which the participant showed indifference in a choice against the large delayed reward. Likewise, the subjective value of the probabilistic reward was defined as the magnitude of the small certain reward for which the participant showed indifference in a choice against the large probabilistic reward (Critchfield & Kollins, 2001). In Table 2, the determination of the subjective value is illustrated by an example of temporal discounting. The large delayed reward is preferred when the immediate reward has a low value (indicated by a "D" in Table 2). However, as the value of the immediate reward increases, preference shifts towards the immediate reward (indicated by an "I" in Table 2). In this example (Table 2), the subjective value of 10 cents after 0 s is 10 cents, and drops to 3 cents after 20 s, and 2 cents if delivered after 30 s. In order to determine the subjective value for the temporal and probabilistic discounting tasks, choice preferences for each participant were ordered based on delay duration/probability level and magnitude of the immediate/certain reward.

Table 2
Representative trials and hypothetical data of the temporal discounting task

Immediate reward in cents	Delay to large reward (10 cents) in seconds									
	0		5		10		20		30	
	t1	t2	t1	t2	t1	t2	t1	t2	t1	t2
0	D	D	D	D	D	D	D	D	D	D
2	D	D	D	D	D	D	D	D	D	I
4	D	D	D	D	D	D	I	I	I	I
6	D	D	D	D	D	I	I	I	I	I
8	D	D	D	I	I	I	I	I	I	I
10	D	D	I	I	I	I	I	I	I	I
Subjective value of delayed reward	10		8		6		3		2	

t1, trial 1; t2, trial 2. Preferences for the delayed reward are indicated with a "D", and preferences for the immediate reward are indicated with an "I". For each delay, the subjective value of the delayed reward is located where the choice preference switches from "D" to "I".

Then, subjective values were determined for each delay and for each probability level. Two raters independently determined the subjective values based on the procedure described above. Agreement between the raters was high (mean kappa .91, range .72–1.0), partly reflecting that participants responded in quite a stable way. Hence, for most participants, it was not very difficult to determine the subjective value. In rare cases of disagreement, a consensus on subjective value was reached by discussion.

The second step was to calculate the area under the curve (AUC) for the temporal and probabilistic discounting functions following the procedure described by Myerson et al. (2001). First, subjective values, delays and probability levels were normalized. That is, subjective values were expressed as proportions of the amount of the maximum delayed/probabilistic reward (10 cents). Delay and probability level were expressed as proportions of the maximum delay (30 s) and maximum odds against (1), respectively. The normalized values were used as x and y coordinates (x, delay/odds against; y, subjective value). The data points on the y axis were connected and formed the discounting function. From each standardized subjective value, vertical lines were drawn to determine four separate trapezoids. The area of each trapezoid equals $(x_2 - x_1) \times [(y_1 + y_2)/2]$, where x_1 and x_2 are successive delays/odds against, and y_1 and y_2 are the subjective values associated with these delays/odds against. The standardized values for the delays are 0, .17, .33, .67, and 1, and the standardized subjective values for the large reward range between 0 and 1. Using this formula, the area of each trapezoid was calculated and subsequently the areas were summed, which resulted in the dependent variable of interest: total AUC. In general, a smaller AUC reflects a steeper discounting function.

2.6. Missing data

Due to technical problems, we lost data for two participants with ADHD during the TD task with post-reward delays. Therefore, analyses for this task were conducted with 20 participants (10 children; 10 adolescents) in the ADHD group instead of 22. WASI data were unavailable for two participants in the control group. WASI averages for the control group are therefore based on 22 participants (12 children; 10 adolescents) instead of 24.

2.7. Analyses

Separate ANOVA's were performed for each task (TD task with post-reward delays, TD task without post-reward delays, and PD task), with diagnostic group (ADHD and controls) and age group (6–11 years and 12–17 years) as independent variables, and total area under the discounting curve (AUC) as dependent variable. In order to study the effect of TD condition, we performed another ANOVA with task version as within-subject factor, diagnostic group and age group as between-subject factor, and AUC as the dependent variable.

We also conducted an analysis treating age as a dimension rather than using two artificially created age groups. We performed correlational analysis looking at the association between age and AUC on the discounting tasks.

In order to study the association between TD and PD measures, correlations were calculated between the total AUCs for all three discounting functions.

3. Results

3.1. ANOVA

3.1.1. Temporal discounting

The ADHD group did not differ in rate of discounting from the control group for either of the TD tasks ($F(1,42) = .69$, n.s.; $\eta^2 = .02$ without post-reward delays; $F(1,40) = .07$, n.s.; $\eta^2 = .00$ with post-reward delays) (see Figs. 2 and 3). Younger participants discounted delayed rewards significantly more strongly than adolescents on both versions of the TD task ($F(1,42) = 4.3$; $p < .05$; $\eta^2 = .09$ without post-reward delays; $F(1,40) = 6.9$, $p < .01$; $\eta^2 = .15$ with post-reward delays). Diagnostic and age groups did not interact significantly for either task version ($F(1,40) = .04$, n.s.; $\eta^2 = .00$ with post-reward delays; $F(1,42) = .02$, n.s.; $\eta^2 = .00$ without post-reward delays). A significant main effect of task version was observed. Participants discounted delayed rewards more strongly when this strategy shortened overall task duration, than when it did not ($F(1,40) = 20.7$, $p < .001$; $\eta^2 = .34$). Task version, age group, and diagnostic group did not interact significantly (see Figs. 2 and 3).

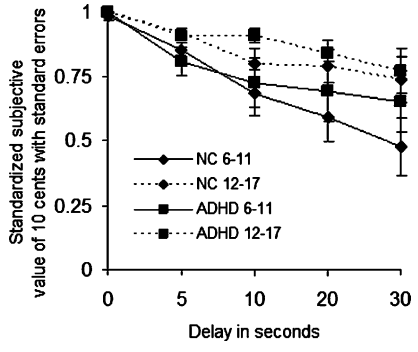

Fig. 2. Temporal discounting functions without post-reward delays for diagnostic and age groups.

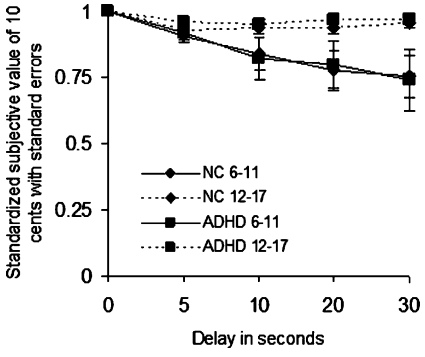

Fig. 3. Temporal discounting functions with post-reward delays for diagnostic and age groups.

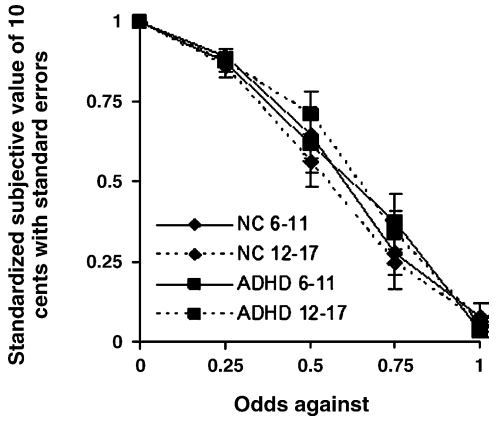

Fig. 4. Probabilistic discounting functions for diagnostic and age groups.

3.1.2. Probabilistic discounting

There was no significant effect of diagnostic group ($F(1,42) = .81$, n.s.; $\eta^2 = .02$) or age group ($F(1,42) = .05$, n.s.; $\eta^2 = .00$) on rate of PD, nor was there an interaction between diagnostic and age groups ($F(1,42) = .51$, n.s.; $\eta^2 = .01$) (see Fig. 4).

3.2. Correlational analyses

3.2.1. Age effects

Significant positive associations were found between age and AUC for both versions of the TD task: $r = .39$, $p < .008$ for the version without post-reward delays and $r = .42$, $p < .004$ for the version with post-reward delays. Visual inspection of the data showed that there was a gradual increase in the ability/willingness to wait for the large rewards with increasing age for the TD task without post-reward delays. For the TD task with post-reward delays, however, only five children (all below the age of 10 years) had relatively small AUCs, whereas all the others maximized their gains (with AUCs > .80). In line with the ANOVA, no significant association was found between AUC for PD and age: $r = .05$, n.s.

3.2.2. Task effects

Correlations were calculated between the total AUCs for all three discounting functions for each diagnostic group. TD without post reward delays was significantly correlated with TD with post reward delays in the ADHD group ($r = .78$, $p < .01$) as well as in the control group ($r = .53$, $p < .05$). PD correlated significantly and positively with TD without post reward delays in the ADHD ($r = .51$, $p < .05$) group but not in the control group ($r = .22$, n.s.).

4. Discussion

Contrary to expectations, we did not find differences between children and adolescents with ADHD and controls in TD of real monetary rewards. We observed a significantly positive correlation between TD and PD in the ADHD group but not in controls. Children (ages 6–11 years) discounted delayed rewards more steeply than adolescents (ages 12–17 years) regardless of diagnosis. There were no age or diagnostic effects on PD.

The lack of steeper TD in ADHD compared to controls raises a number of questions. Previous work in the field of ADHD with single-choice delay tasks has generally shown that children with ADHD have stronger preferences for small immediate rewards than controls (Barkley et al., 2001; Schweitzer & Sulzer-Azaroff, 1995; Sonuga-Barke et al., 1992; Solanto et al., 2001; Tripp & Alsop, 2001; see, for a review, Luman et al., 2005). Sonuga-Barke and co-workers (1992) found that hyperactive children preferred to receive 2 points (each point being worth 5 cents) after 30 s over 1 point immediately on only 18% of trials, versus 48% in controls. Of note is that this group difference emerged only in a condition without post-reward delays, when choosing the small immediate reward resulted in a shorter session. When it did not, children with ADHD chose the large delayed reward as often as controls. Using the same task and condition that had differentiated between hyperactive children and controls in Sonuga-Barke's study, Solanto and colleagues (2001) found that children with ADHD preferred the large delayed reward on 42% of all trials, compared to 64% for controls. In our study, we did not find a group difference, even when preference for the small immediate reward resulted in shorter overall task duration.

First, these findings need to be considered in light of relatively limited power available for this study: 22 versus 24 participants for the ADHD–control comparison and 25 versus 21 participants for the child–adolescent comparison were available. Although we recognize that these findings would need to be replicated with larger samples before we can draw any firm conclusions, it is important to note that the effect sizes for the ADHD–control comparison were very small. Therefore, it is unlikely that increasing the sample sizes will result in a significant group difference with such small effects. Moreover, when inspecting the group averages, the ADHD–control difference, if at all detectable, goes in the opposite direction from what we had predicted. Inspection of the individual discounting plots shows that there was a *higher* percentage of participants in the ADHD group who waited for the large reward consistently on all trials (73%) than in the control group (58%) (data available from the first author). The effect sizes for the child–adolescent comparison, on the contrary, were large and resulted in significant effects even with these modest sample sizes.

Another issue related to power has to do with the task design: we only used two repetitions for each trial type. Ideally, we would have used more repetitions. However, for this study, we aimed at including a substantial range in reward magnitudes (immediate reward) and delays. Moreover, we felt it was important to include a TD task with post-reward delays in order to distinguish between reward immediacy and delay aversion. As a result, including more repetitions would have increased the total task duration beyond participants' capabilities. For future research, however, in which less trial types may be used, it is recommended to include more repetitions per trial.

The second question that needs to be examined in light of our findings relates to the validity of our tasks, which were newly developed. The designs, i.e., varying magnitudes of the immediate/certain reward and varying delays/probability levels of the

large reward, are based on existing paradigms that have been used extensively with adults (e.g., Coffey et al., 2003; Crean et al., 2000; Green et al., 1996; Kirby et al., 1999; Kollins, 2003; Petry, 2001, 2002; Petry & Casarella, 1999; Reynolds et al., 2004; Richards et al., 1999). Unlike those adult studies, however, we used real rewards and real delays instead of hypothetical ones. In order to determine what range of reward magnitudes and delays to use in our tasks, we conducted a pilot study in a small number of children and adults from which we selected the current task parameters. It could be argued that our tasks were simply too insensitive. However, we detected robust age effects on TD, and we observed discounting of delayed rewards on average, which indicates that the balance between reward magnitudes and delay durations/probability levels allowed for a decrease in the subjective values of the delayed/probabilistic rewards. Furthermore, introducing post-reward delays in the TD task significantly raised the TD functions, demonstrating that at least some of the TD effect was associated with aversion to delay. What is different in our results is that delay aversion was equally distributed in both ADHD and control groups.

Understanding the relevant differences between our task and the choice delay task (CDT) used in previous studies could fruitfully highlight relevant dimensions of these tasks for future study and perhaps shed light on aspects of delay aversion that have not yet been fully explored. The tasks used here and typical CDT differed in number of trials, amount of money that could be won, extent of practice and experience of being paid, and the range of options that were available. Any or all of these may have accounted for our discrepant findings and should be examined in turn.

First, in the current study, we used 60 TD trials and participants were informed of the number of trials before starting the task. Accordingly, participants knew that consistent preferences for the delayed reward could result in a total gain of US$ 6 by the end of the task. In the work by Sonuga-Barke et al. (1992) and Solanto et al. (2001), children were given a total of 40 trials split into two blocks. Before starting the first block they were told that they were going to choose 20 times. Then, after finishing the first 20 trials, they were told that they would choose another 20 times. Therefore, children were under the impression (during the first half of the task) that they could win a maximum of US$ 2 if they chose the delayed reward on every trial. The prospect of winning US$ 6 in our study, versus US$ 2 in previous studies, may have increased the motivation to wait for the large rewards in participants with ADHD. Thus it is possible that if we had used a smaller number of trials, or a large delayed reward that was smaller in magnitude (for example, 5 cents), we might have observed steeper TD in ADHD. Although earlier work with reward choice paradigms did not yield evidence that children with ADHD are sensitive to reward magnitude per se (Douglas & Parry, 1994; Pelham, Milich, & Walker, 1986; Solanto, 1990; Solanto et al., 2001), the only study in ADHD employing a TD paradigm (Barkley et al., 2001) found that magnitude of the delayed (hypothetical) reward on individual trials differentially affected reward preferences in adolescents with ADHD. In the Barkley study, adolescents with ADHD discounted delayed rewards more steeply than normal controls only when the delayed hypothetical reward was US$ 100, but not when it was US$ 1000. This suggests that steeper discounting in ADHD is more easily detected when the delayed rewards are relatively small. Future work with a TD paradigm with real rewards will need to vary the magnitude of the delayed reward systematically in order to test this hypothesis.

Second, participants were well practiced and then paid a small amount of money after the practice trials. In previous studies with the CDT, participants did not receive reinforcers before starting the task. Receiving real money before starting the task may have differentially increased the salience of the reward in participants with ADHD, perhaps leading to increased motivation to wait for the larger rewards during the actual task. Interestingly, in the Solanto et al. (2001) study, preferences for the large delayed reward increased significantly between the first and second task blocks, after reinforcers had been dispensed to participants at the end of the first task block. Solanto et al. suggested that this may have increased the subjective incentive value of the points administered. An increased sensitivity to cash dispensed before starting the task may have led to increased motivation to wait for the large reward in our study, which may be partly responsible for the lack of steeper TD in ADHD.

Third, and we believe most likely, is that in previous studies with the CDT, every choice trial was the same, with constant delays of 30 s, and constant magnitudes of the immediate rewards of 5 cents. In our study, delays varied across trials between 0 and 30 s, and magnitudes of the immediate reward varied between 0 and 10 cents. These variations across trials may have decreased monotony and they also decreased the effective delay time to an average of only 13 s if participants chose to always maximize their reward. Thus by introducing parametric variations in delay time, we decreased the intensity of the delay effect. This possibility could be easily tested by adding longer delays such as 60 s. To summarize, future parametric analyses of TD in ADHD should take into account the effective average delay, include longer delay intervals, vary the magnitude of the delayed reward as well as manipulate the effects of rewarded practice trials.

No evidence of increased risk-taking behavior in ADHD or in young children was found, and indeed all groups made choices that maximized their total gains. The PD task was designed such that the probabilities were quite explicit, and therefore, participants could rely on a relatively simple rule to compute which option would pay more in the long run. While the task was quite predictable in terms of the pay-off probabilities, we chose to make these probabilities quite explicit in order to investigate the trade-off between reward magnitude and probability, while controlling for processes such as probability estimation and learning. These results do not rule out the possibility that diagnostic category and age group may affect either probability estimation or choice preferences on a task in which probabilities are less explicit. For example, risky behavior as observed in ADHD in daily life (APA, 1994), such as risky driving (e.g., Barkley, 2004; Barkley, Guevremont, Anastopoulos, Dupaul, & Shelton, 1993; Nada-Raja et al., 1997; Richards, Deffenbacher, & Rosen, 2002; Woodward, Fergusson, & Horwood, 2000), gambling (Rugle

& Melamed, 1993; Specker, Carlson, Christenson, & Marcotte, 1995), and substance abuse (Gordon, Tulak, & Troncale, 2004; Wilens, 2004), may be attributed to distorted *estimations of risk*. Previous experimental research with reward choice paradigms provides little evidence for risk-taking behavior in ADHD. Wiers, Gunning, and Sergeant (1998) used a door-opening task in which the probability to win 10 cents gradually decreased over trials from 90% to 0%, and participants could quit the task at any moment. Like in our study, ADHD was not associated with risky choices (stopping too late). Ernst and colleagues (2003) used a gambling task in which probabilities had to be learned during task performance and administered it to adolescents with behavioral disorders (mainly ADHD) and healthy controls. They found that the group with behavioral disorders performed worse than controls but only on the second session. Similarly, Toplak, Jain, and Tannock (2005) showed that adolescents with ADHD, compared to healthy controls, failed to learn over time to select more cards from advantageous than disadvantageous decks in the IOWA Gambling Task. These findings suggest that risk-taking behavior in ADHD may be related to poor learning of risks. The same may apply to young children. Although Schlottmann (2000) showed that children as young as 6 years have a basic understanding of probabilities, when probabilities had to be learned during performance of an equivalent of the IOWA gambling task (Crone & van der Molen, 2004), young children performed slightly more poorly than adolescents, and children and adolescents performed more poorly than adults. This suggests that choosing less risky options when probabilities are not explicit increases with age. Research by Kahneman and Tversky (1979) has shown that healthy adults use risk-averse choice styles when choosing between rewards. Therefore, it may be suggested that the optimal-to-risky choice styles observed in children and adolescents in this study may develop into risk-averse styles in adulthood. This is a hypothesis that should be tested in future research by including an adult sample.

Consistent with previous studies (e.g., Green, Myerson, & Ostaszewski, 1999; Myerson et al., 2003; Reynolds et al., 2003; Richards et al., 1999; but see Reynolds et al., 2004 for an exception), we found positive correlations between TD and PD. Interestingly, this correlation was larger for the ADHD group than for the control group, and only statistically significant in the ADHD group. This positive correlation in the ADHD group is not consistent with the intuitive hypothesis that TD and PD should be negatively correlated in ADHD, because ADHD has been associated with poor delay of gratification (steep TD) and increased risk-taking behavior (shallow PD). However, this finding suggests that willingness to wait for the large reward was associated with willingness to take risks to win the large reward on the PD task in the ADHD group. It suggests that participants with ADHD when drawn by the large reward, were willing to wait for it, and to take risks for it. It suggests a potentially important role of sensitivity to reward magnitude in ADHD that deserves further investigation. Previous researchers (Rachlin, 1986; see also Reynolds et al., 2003) have suggested that positive correlations between TD and PD may be due to the possibility that participants equate certainty with immediacy. Choosing the certain reward in a PD paradigm results in immediate reward receipt, whereas choosing the probabilistic uncertain reward may, if not delivered due to its probabilistic nature, result in a delay until the next reward is delivered.

Children aged 6–11 years discounted delayed rewards more steeply than adolescents, even when choosing the immediate reward did not shorten overall task duration. This, together with the lack of interaction between TD task version and age, suggests that steeper discounting in young children is driven by reward immediacy and not by delay aversion. By contrast, for adolescents, choices were influenced less by reward immediacy and more by reward magnitude. The increasing preference for delayed rewards with increasing age may be associated with maturation of the dorsolateral prefrontal cortex. Developmental studies have shown that the dorsolateral prefrontal cortex (DLPFC) develops throughout childhood and adolescence (e.g., Casey, Tottenham, Liston, & Durston, 2005; Giedd, 2004), and a recent fMRI study on temporal discounting in adults suggested that activation in areas such as DLPFC was predictive of preferences for the large delayed reward (McClure et al., 2004). Future fMRI research with child and adolescent populations needs to address the neural basis of the development of temporal discounting of rewards.

Although 6–11 years olds differed from 12 to 17 years olds, we did not have a specific hypothesis that there would be a sudden jump in the ability/willingness to wait for the large reward once a child turns 12 years. When treating age as a continuum, results were in line with findings based on ANOVAs. The observation that there was a gradual increase in AUC with increasing age for the TD task without post-reward delays, while for the TD task with post-reward delays only five children (all below the age of 10 years) had relatively small AUCs, suggests that choosing the small immediate reward because of its immediacy only occurs in children younger than 10 years, whereas choosing the small immediate reward in an attempt to escape delays develops across the full age range of 6–17 years.

A number of limitations need to be discussed. First, since we did not conduct a direct comparison between the TD task and a CDT as used in previous research, our potential explanations of our divergent results are merely speculative. Because of the possibility that contextual factors affect choice preferences in ADHD, such a direct comparison between these tasks would be desirable, but it also raises questions of potential "carry-over" effects that would need to be carefully examined. Secondly, this study included both boys and girls. Although groups did not differ in the number of males and females, it may be the case that performance on these tasks differs across genders. Future research needs to address this possibility. Third, the ADHD group included children of all three DSM-IV subtypes. It may be argued that steep temporal reward discounting is only to be expected for children who have symptoms of impulsivity, but not for children who have symptoms of inattention only (for example, see Barkley, 1997). Inspection of the AUCs for all tasks across ADHD subtypes did not reveal any meaningful differences. Similarly, due to power restrictions, we did not control for a number of other potentially relevant variables such as levels of ODD/CD and anxiety/depression. Future research

with larger sample sizes needs to address the potential association between ADHD subtype and comorbidity on the one hand, and reward discounting on the other. Fourth, eight children in the ADHD group were treated with medication. Although they were off medication on the day of task performance, there is still a possibility that they differed in task performance from medication-naïve children. Inspecting the AUCs demonstrated that medication-naïve children with ADHD had very similar AUCs as medication-discontinued children for PD (.60 and .61, respectively) and TD without post-reward delays (.78 and .83, respectively). For TD with post-reward delays, however, although non-significant, the AUC was .87 for medication-naïve children with ADHD and .96 for medication-discontinued children with ADHD (effect size $\eta^2 = .06$). Therefore, it may be possible that the use of medication, even though it was discontinued, increased the ability/willingness to wait for the large reward, even beyond the ability of the control group (AUC = .88). It should be noted that the AUC for the medication-naïve group, although lower than the medication-discontinued group, was identical to that of the control group. Finally, it needs to be noted that, although the ADHD group did not differ from the control group in terms of discounting, it could still be the case that within the ADHD group, symptom severity was associated with level of reward discounting. We explored this possibility, and, although no correlations were significant, hyperactive symptoms as measured with the CPRS-R-L were negatively associated with AUC for the TD task with post-reward delay within the ADHD group (−.37).

In summary, contrary to our expectations, we did not observe steeper TD of small, real monetary rewards in ADHD relative to an age- sex-, and intelligence-matched control group. A number of differences between the tasks we used and the more standard choice-delay task may have accounted for our divergent results, but such a possibility will need to be examined in future studies. We did find, as predicted, steeper TD in children as compared to adolescents, an effect that appeared to be driven by reward immediacy and not by delay aversion. Future research needs to address the neural basis of the development of temporal discounting of rewards.

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