Disrupted waiting behavior in ADHD: exploring the impact of reward availability and predictive cues

Emi Furukawa, Brent Alsop, Heloisa Alves, Valerie Vorderstrasse, Kelly D. Carrasco, Chi-Ching Chuang & Gail Tripp

CHILD NEUROPSYCHOLOGY
https://doi.org/10.1080/09297049.2022.2068518

Disrupted waiting behavior in ADHD: exploring the impact of reward availability and predictive cues

Emi Furukawa[a*], Brent Alsop[b*], Heloisa Alves[c], Valerie Vorderstrasse[a], Kelly D. Carrasco[d], Chi-Ching Chuang[e] and Gail Tripp[a]

[a]Human Developmental Neurobiology Unit, Okinawa Institute of Science and Technology Graduate University, Okinawa, Japan; [b]Department of Psychology, University of Otago, Dunedin, New Zealand; [c]Department of Psychology, University of Massachusetts Dartmouth, Massachusetts, USA; [d]Wellington Faculty of Education, Victoria University of Wellington, Wellington, New Zealand; [e]Department of Psychology and Counseling, University of Taipei, Taipei, Taiwan

ABSTRACT

Altered motivational processing is purported to contribute to ADHD symptoms. A stronger preference for immediate over delayed reward is well documented in ADHD. However, little attention has been paid to children's capacity to withhold responding until a "better" reward becomes available, and their actions while waiting. Using a novel computer task, we examine the ability of children with and without ADHD to wait to collect a large reward in the presence of a small available reward. The effects of a reward-predicting cue on response times and response choices are also explored. Data from 136 children (6–12 years), 90 with ADHD and 46 typically developing (TD) children, are included. The children could collect a small immediately available reward or wait to access a larger reward after a variable delay, its imminent availability sometimes signaled by a cue. Subsequent probe trials explored the effects of longer waiting times and disruption of the cue-reward association. As expected, children with ADHD collected the small immediately available reward more often than TD children. Importantly, they were more likely to terminate waiting once commenced, collecting the small reward or attempting to collect the large reward early. The cue decreased their response time but disrupted their waiting when it no longer consistently predicted reward. Children with ADHD were more likely to abandon efforts to wait, especially when wait times were extended and when expected rewards failed to appear. Behavioral interventions for ADHD should take into account reduced waiting capacity that extends beyond children's preference for immediate reward.

ARTICLE HISTORY
Received 9 August 2021
Accepted 13 April 2022

KEYWORDS
ADHD; waiting behavior; reward cue; reward delay

Introduction

Attention deficit hyperactivity disorder (ADHD) is a common neurodevelopmental disorder marked by symptoms of inattention, hyperactivity, and impulsivity that impair daily functioning. The etiology of the disorder remains uncertain (Nigg et al., 2020).

CONTACT Emi Furukawa furukawa@oist.jp Human Developmental Neurobiology Unit, Okinawa Institute of Science and Technology Graduate University, 1919-1 Tancha, Onna, Okinawa, 904-0495, Japan

*These authors contributed equally to this work.

Supplemental data for this article can be accessed at https://doi.org/10.1080/09297049.2022.2068518.

Altered motivational processing is considered as one of the pathways to ADHD symptoms with accumulating empirical support (Luman et al., 2010; Sonuga-Barke et al., 2010). The most consistent finding is that children with ADHD have a stronger preference for immediate reward and discount delayed rewards, even when doing so results in smaller earnings (Patros et al., 2016; Scheres et al., 2010; Sonuga-Barke et al., 2008). However, limited attention has been paid to the *behavior* of children with ADHD, while they wait for reward, and factors that affect their waiting behavior.

Most of the evidence that children with ADHD show a stronger preference for immediate reward comes from studies using two-alternative forced choice paradigms, with the options presented concurrently and a decision required before reward is delivered or waiting is initiated. In these tasks, children repeatedly choose between two known options that differ in the size of reward and the time to reward delivery (e.g., the choice delay task (Sonuga-Barke et al., 1992), the Maudsley Index of Delay Aversion (Kuntsi et al., 2001) or temporal discounting tasks (Scheres et al., 2010)). Steeper (faster/stronger) discounting of delayed rewards (Scheres et al., 2010), an aversion to delay (Sonuga-Barke, 2003), and impulsive decision-making (Patros et al., 2016, see Figure 1) have been offered as reasons for the increased tendency of children with ADHD to choose smaller sooner over larger later rewards. More generally, researchers have proposed children with ADHD evidence an increased likelihood to respond to any available rewards in the environment (Schweitzer & Sulzer-Azaroff, 1995), a lack of behavioral inhibition (Barkley, 1997), including difficulty suppressing responses to collect available rewards (Killeen et al., 2013), and an increased need for immediate reward (Parry & Douglas, 1983) or stimulation (Antrop et al., 2006; Zentall, 1975) (see Figure 1).

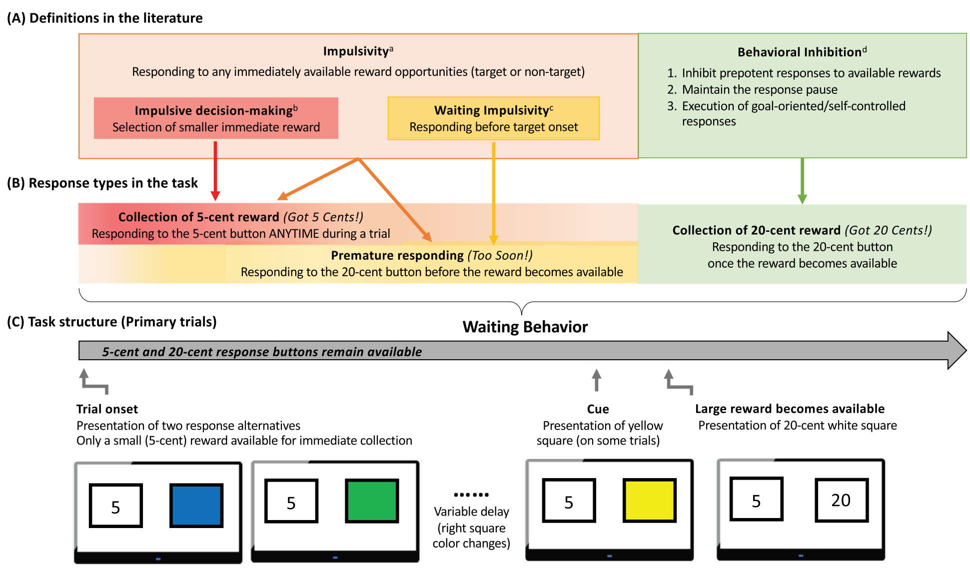

Figure 1. Relationships between (A) the terms used to describe impulsivity and behavioral inhibition in the literature, (B) the three response alternatives in the current task, and (C) the structure of the current task.

Altered dopamine signaling is hypothesized to underlie this stronger preference for immediate reward/steeper discounting of delayed reward in those with ADHD (Sagvolden et al., 2005; Tripp & Wickens, 2008). Tripp and Wickens (2008) suggest the transfer of dopamine cell firing from unexpected rewards to reward predicting cues, thought to bridge the delay between an action and a reward at the biological level, is impaired in those with ADHD, leading to the stronger preference for immediate rewards. Imaging studies have demonstrated reduced striatal responses to reward predicting cues (Baroni & Castellanos, 2015; Plichta & Scheres, 2014) and increased responses to reward delivery (Baroni & Castellanos, 2015; Furukawa et al., 2014) in those with ADHD.

In everyday life, children seldom face explicit choices between such clearly defined behavioral options, with the consequences fixed at the time the decision is made. While often aware that waiting (for their turn, an opportunity to respond, or a positive outcome) is expected and/or advantageous (social approval, better grades, etc.), alternative reward opportunities (playing, going first, etc.) remain available, while children wait to respond or to receive reward. Under these circumstances, they may initiate waiting, later abandoning the wait to engage in activities that result in more immediate feedback/reward. Outside of the laboratory, children are also exposed to stimuli that signal the availability of different reward opportunities. The effect of reward predicting cues on children's waiting is not known. Patros and colleagues argue strongly for the need to examine decision-making using a range of different paradigms in response to their findings that context impacts the preference of children with ADHD for smaller immediate rewards (Patros et al., 2017).

The above highlights the importance of assessing children's responses to immediate and delayed reward under conditions that more closely mirror their daily experiences. Current behavioral interventions recognize the importance of immediate reward for shaping and maintaining desired behavior (van der Oord & Tripp, 2020). They do not address children's ability to wait for delayed outcomes when more immediate reward opportunities are available or the effects of reward predicting cues on waiting and responding.

Here we address these gaps in the research literature, examining the behavior of children with and without ADHD when waiting offers the opportunity to collect a larger, delayed reward, while the option to choose a smaller immediate reward remains available. We also assess the children's sensitivity to a cue that signals the availability of the larger reward, and how their behavior is impacted when the cue is presented, but is not followed by the opportunity to collect the larger reward. We use a novel task in which the children are able to collect a small reward at any time during a trial or wait for a larger reward to become available after a variable delay. Thus, the children could collect the small reward immediately, wait to collect the larger reward, or end the wait by collecting the small reward. Attempts to collect the large reward early (prematurely) ended the trial without reward. We refer to this set of possible actions after trial onset as "waiting behavior" (Figure 1). A cue signaled imminent availability of the larger reward on some trials. During subsequent exploratory probe trials, the wait for the larger reward was extended and the cue appeared multiple times. In these trials only the last appearance of the cue was followed by reward availability, thus it no longer consistently predicted access to the larger reward.

We predict children with ADHD will be more likely to collect the small reward immediately, as in choice delay studies, or during the waiting period for the larger reward. We also expect children with ADHD will be more likely to attempt to collect the larger reward prematurely, given the well-documented problems with behavioral inhibition in this population (Barkley, 1997), and more recent reports that those with ADHD demonstrate greater "waiting impulsivity", i.e., a tendency to respond before target onset in a 4-choice serial reaction time task (Van Dessel et al., 2019; Voon, 2014, see Figure 1).

We are unaware of previous research examining the effect of reward-predicting cues on waiting among children with ADHD. As the cues initially signal the imminent availability of the large reward, it is expected that they will invigorate behavior, reducing response times for reward collection on the cued versus uncued trials. Their impact on responding during the probe trials is more difficult to predict. If the cues come to serve as conditioned reinforcers they could provide immediate reinforcement at the cellular level, bridging the reward delay and maintaining children's waiting (Cardinal et al., 2004). The cues could also increase reward salience, activating reward-seeking behavior, i.e., attempts to collect reward immediately, especially as the timing of the large reward is uncertain (Robinson et al., 2016). It is unclear if cue effects will differ in children with and without ADHD.

Methods

Ethical approval for the study was obtained from the OIST Graduate University Human Subjects Research Review Committee (Japan) and the University of Massachusetts Dartmouth Institutional Review Board (US). Participating parents, teachers and children were volunteers and provided written consent.

Participants

The current study includes data from 136 6–12-year-old children, 90 meeting DSM-5 diagnostic criteria for ADHD (67.8% boys) and 46 typically developing (TD) children (30.4% boys). Within the ADHD group, 44 children met the criteria for inattentive presentation and 46 for combined presentation ADHD; 22 (24%) children had at least one comorbid disorder and 36 (40%) were prescribed medication for ADHD symptom management. Those prescribed stimulant medication ($n = 34$) discontinued its use for at least 48 hours prior to participation. The two participants prescribed atomoxetine were not asked to withhold their medication.[1]

Study inclusion criteria for all children were English as a first language[2], an estimated IQ ≥ 70, normal or corrected vision, and no past or current: head injury, neurological disorder, or psychosis. Children in the ADHD group were required to display six or more symptoms of inattention and/or hyperactivity/impulsivity in at least one setting, clear evidence of symptoms in a second setting (e.g., school or clinic), and functional

[1]Acute discontinuation of atomoxetine is not recommended. Results are unchanged if data from these two participants are excluded.

[2]All participating children are US residents attending US or international schools.

impairment from symptoms. Data from a single child with hyperactive/impulsive presentation ADHD were excluded from the current study as we were unable to test if this child's performance differed significantly from that of children with inattentive or combined presentation ADHD. Children in the TD group were required to have fewer than four parent-reported symptoms of ADHD and no evidence of comorbidity.

Children in the ADHD group were recruited through the OIST Children's Research Center. Families received study information from American (US) school personnel, health-care professionals, and community support organizations, and volunteered directly. Typically developing (TD) children were recruited through the OIST Children's Research Center (outreach to parents of children attending US and International schools) and the University of Massachusetts Dartmouth (invitation letters sent home to parents through school and afterschool programs).

The children in the ADHD group participated in multi-method multi-informant research diagnostic assessments. Data from the semi-structured Kiddie Schedule for Affective Disorders and Schizophrenia for School-Aged Children (K-SADS-PL DSM-5, ADHD, ODD, and CD sections) (Kaufman et al., 2016), parent and teacher ratings of ADHD symptoms from the Conners Behavioral Rating Scale (CBRS) (Conners, 2008b) and observations of the child, during testing and interviews, were used to determine if they met the DSM-5 criteria for ADHD (i.e., best estimate clinical diagnosis using all available data, n.b. symptoms were not summed across informants). Parent responses to the CBRS, the developmental, medical, and academic history questionnaires, and clinical interviews were used to screen for other behavioral and emotional problems and neurological and medical conditions. Cognitive functioning (WISC-V core subtests/full scale IQ) (Wechsler, 2014), language (CELF-5) (Wiig et al., 2013), academic skills (WIAT-III) (Wechsler, 2009), and visual working memory (CANTAB Spatial Span Forward and Reverse) (Cognition, 2019) were evaluated for all children, with other measures administered as needed for differential diagnosis. Assessments were carried out over two or three morning sessions by a licensed psychologist or supervised research staff. All diagnostic decisions were reviewed by at least two doctoral-level clinical psychologists.

Typically developing children completed an abbreviated IQ assessment (WISC-V, Vocabulary and Matrix Reasoning subtests). One parent in each family completed the Conners-3 (Conners, 2008a) and a developmental/medical/demographic history questionnaire to assess for symptoms of ADHD, comorbid disorders, and other inclusion criteria. Data from 15 children was excluded from the study due to elevated ADHD symptoms.

Table 1 presents the demographic and diagnostic characteristics of the ADHD and TD groups together with between-group comparisons. Supplemental Table S1 presents the demographic data of the TD group participants at the two data collection sites separately. Supplemental Table S2 presents these data separately for children with inattentive and combined presentation ADHD.

Experimental task

The children sat at a table with a two-button response panel and computer monitor in front of them. The left and right-hand panel buttons were labeled with the numbers 5 and 20, respectively. During each trial, the children were presented with two colored squares on the computer monitor, one on the left and one on the right. A window at the top of the

Table 1. ADHD and TD group demographic and diagnostic characteristics: descriptive statistics, group comparisons, and effect sizes.

	TD			ADHD					
	(n=46)			(n=90)					
	M	SD	Range	M	SD	Range	*t/χ2a*	*p*	η^2
Age (years)	9.59	2.11	6-13	9.54	1.81	6-13	*.122*	*.903*	*.001*
Estimated IQ	106.39	14.89	71-150	102.52	11.54	71-132	*1.673*	*.097*	*.020*
Boys n (%)		14 (30.4)			61 (67.8)		*17.162*	*<.001*	*.126*
Medication n		–			36				
ODD/Mood/Anxiety n		–			0/2/8				
ASD/LD/Other n[b]		–			3/9/3				
Annual Household Income % <30K/30K-60K/>60K ($)		2.5/35.0/62.5			0.0/39.5/60.5		*2.316*	*.314*	*.017*
Race %[c] White/Black/Asian/Other[d]		76.9/.0/5.1/17.9			64.4/7.8/3.3/24.5		*7.888*	*.162*	*.058*

a. t-tests for age and estimated IQ, and chi-square tests for others, examining the group differences.
b. Other included tic, speech, and adjustment disorders.
c. Children in TD and ADHD groups are US residents attending US or international schools.
d. Other included those reporting as 'mixed' and 'Hispanic'.

screen indicated the child's accumulated earnings. The left square was always white with the number 5 at its center. The right square changed color multiple times (green, red, and blue, in a quasi-random order) at the rate of one color per second, stopping with the presentation of a white square with the number 20 at its center. This white square was programmed to appear between 4 and 24 seconds (4 to 24 color changes) after a trial began. Each trial was separated by a one-second inter-trial-interval followed by an on-screen countdown, i.e., 3, 2, 1, before the two squares appeared. Overall task length varied depending on children's performance on the task.

Primary trials

On some trials, the right-side square turned yellow for one second, immediately prior to the appearance of the white square. As the yellow square was always followed by the white square it was expected to serve as a cue to the imminent presentation of the white square and the availability of reward (for collection). Although the other colored squares sometimes preceded the white square, they did not do so consistently, and were not expected to become cues. Trial order was the same for all participants.

Children were told that they could press the left button on the response panel to earn 5 OIST/UMass cents any time, but that if they waited for the right square to turn white, they could press the right-hand button and earn 20 cents. They were advised that at the end of the task they could use their accumulated cents to buy something from the prize box. The task instructions appeared on the monitor and were read aloud to the child to ensure all participants received the same instructions (see Supplemental Methods). The children then completed two practice trials before the experimental trials began. No information was given about the number of trials, the length of waiting periods, overall task duration, or the number of cents needed to "buy" something from the prize box (containing a range of toys/art supplies/games etc., included for their appeal to children).

When a child pressed the 5-cent button after the squares appeared, or the 20-cent button after the right-side square turned white, they received on screen confirmation of collecting the money, "5/20 cents of OIST/UMass money", and their total earnings were updated. If a child pressed the 20-cent button before the right-side square turned white, the message 'Too soon. NO Money' appeared in the center of the monitor. If they waited for the square to turn white but did not respond within two seconds, the message 'Too late. NO money' appeared.[3] No reward was delivered in either case. The trials continued until a child was exposed to the yellow square (cue) followed by the white square 18 times or for a maximum of 90 trials if the former condition was not met. This criterion was set to ensure children going on to the probe trials had equal exposure to the cue/reward opportunity pairing.

Exploratory probe trials

Children who reached the criteria of 18 cue/white square pairings were presented with an additional 15 trials (Supplemental Table S3). These began immediately with no further instructions. There were nine short trials during which the right square turned white between the 6th and 10th color change. On these trials, the white square was always preceded by the yellow square/cue. The remaining six trials were longer probe trials, designed to explore the effect of the cue on the children's waiting behavior. On all six trials, the right-side square turned white at the 41st color change. During three of these trials, the right-side square was programmed to turn yellow at the 10th, 20th, 30th, and 40th color changes, with only the last presentation followed by the white square. The yellow square was never presented during the remaining three long trials. The nine short trials were interspersed among the long trials to maintain the children's task engagement.

Data analysis

The following dependent variables were extracted from the data for each participant. Performance on these variables was compared across groups using ANOVA, unless specified otherwise. Critical alpha was maintained at $p = .05$ for all analyses. Exact p values and effect sizes are reported in tables to indicate the strength of the findings, including for those with $p > .05$.

Primary trials (completed by all participants)

Overall performance. The total number of trials completed and earnings adjusted for (divided by) the number of trials completed were examined. The number of trials presented depended on the child's response strategy, i.e., waiting for the 20-cent square could reduce the total trials presented.

[3]Slow responses occurred rarely, thus no analyses were conducted for these responses. 65.4% of participants never made a 'too slow' response, 20.6% of participants responded too slowly once, 8.1% of participants 2–3 times, and 5.9% of participants 4–8 times.

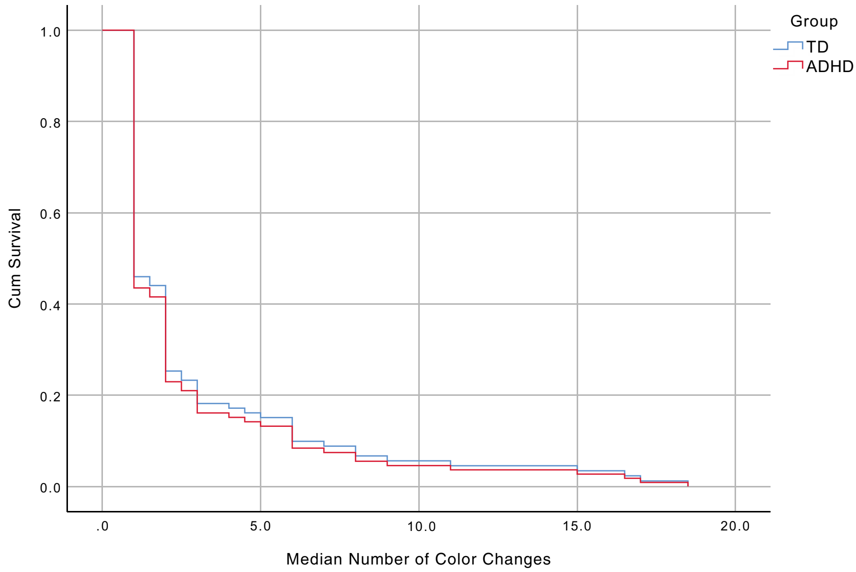

Figure 2. Survival plot showing the time (number of color changes, i.e., one per second) the children waited for the larger reward before collecting the 5-cent reward. The y-axis shows the proportion of children in each group continuing to wait against the median number of color changes (×-axis). Regardless of group membership, when children made the decision to collect 5 cents, more than half of them did so by the first color change, i.e., one second after the trial began.

Response choices. Three response types were examined: 1) the proportion of trials on which the child collected 5 cents (either immediately or after a delay)[4]; 2) the proportion of trials on which the child waited for and collected 20 cents; and 3) the proportion of trials on which the child responded to the 20-cent button prematurely, i.e., before the white square appeared and reward became available (premature responding, see Figure 1). This included analysis of the effect of the cue (yellow square) on responding. Proportions were used to control for differences in the number of completed trials across participants. These were log10-transformed for use in parametric statistics (Sokal & Rohlf, 2012)[5]

Time to collect 5 cent reward: The median time (in whole seconds/number of right-square color changes) from the onset of the trial until the small reward was collected. This was calculated for all participants who responded to the 5-cent button at least twice during the task. These data were subject to a survival analysis to examine the effect of group membership on response times, i.e., children's tendency to opt for the small reward immediately versus later in the trial. A plot was created to show the length of time (number of color changes, i.e., one per second) the children waited (for the larger reward) before collecting the 5-cent reward (Figure 2).

[4]Trials on which participants responded to the 5-cent button after waiting for the 20-cent reward were not included in this proportion. As they waited for the large reward, this would not be considered as a preference for immediate reward. 70.6% of participants did so once, and 24.2% of participants made such a response 2–3 times.

[5]For participants who never made a certain response type, .01 was added to the calculated proportion, and for participants who always made the same response, .01 was subtracted from the calculated proportion, before the log10 transformation.

Time to collect 20 cent reward: The median time from the appearance of the 20-cent white square to collection of the large reward, i.e., response to the 20-cent button. This was calculated and analyzed separately for trials in which the white square was preceded by the yellow (cue) versus other colored squares. The medians, instead of means, were used due to the skewed distributions of the response time data (Rousselet & Wilcox, 2020).

Exploratory probe trials (completed by those exposed to 18 cue/white square pairings)

The data from the long probe trials explored if the children waited for and collected 20 cents at the 41st color change, and if not, when and how the trial ended (i.e., by collecting 5 cents or making a premature 20 cent response). Survival analyses of the waiting time before trial termination were undertaken for each cued and uncued probe trial. Plots were created to show the length of time (number of color changes, i.e., one per second) children waited (for the larger reward) during the uncued and cued long probe trials (Figure 3).

Group differences in the number of each response type (collecting 5 cents, premature 20 cent response, and collection of 20 cents) were also examined across all six long probe trials, using Quade ANOVAs. Data from the short trials interspersed among the long probe trials were not analyzed.

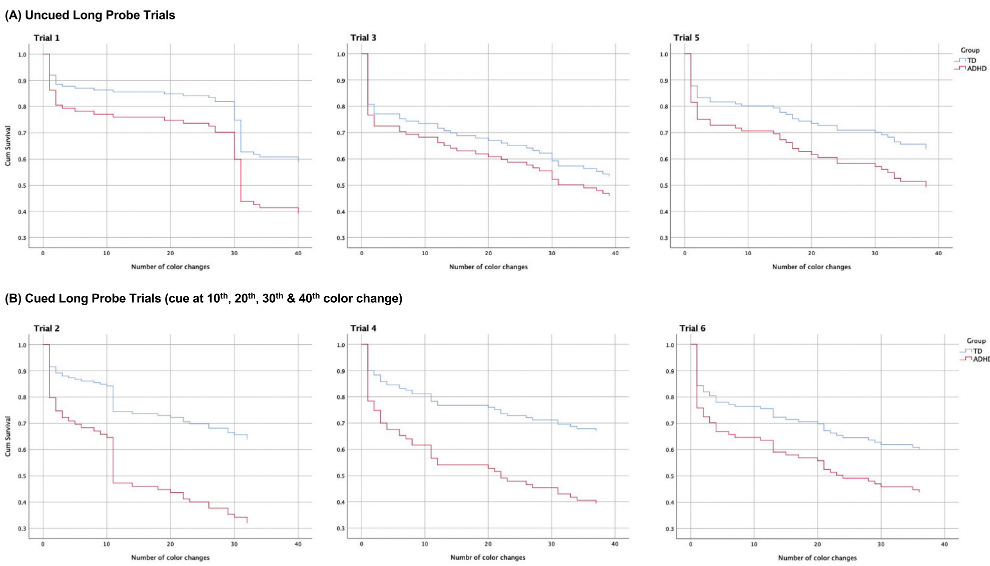

Figure 3. Survival plots showing the time (number of color changes, i.e., one per second) the children in the ADHD and TD groups waited for the larger reward during the (A) uncued and (B) cued long probe trials. the y-axis shows the proportion of children continuing to wait against the number of color changes (×-axis). Compared with the TD children, a larger proportion of children with ADHD dropped out, i.e., collected 5 cents or pressed the 20-cent button prematurely, during the first and second cued probe trials. While similar response patterns were observed, no significant group differences were found for the third cued trial or for any of the uncued trials.

Preliminary analyses

The performance of the TD group participants at the two data collection sites is presented in Supplemental Table S4. The performance of children with inattentive and combined presentation ADHD was compared on overall performance, response choices, time to collect 5 cents, and time to collect 20 cents (Supplemental Table S5). To determine which variables needed to be controlled in evaluating ADHD vs. TD group performance, the following analyses were conducted. Age, estimated IQ, sex, reported household income and race were compared between the ADHD and TD group (Table 1). The relationships between the outcome variables and age and IQ were also examined (Supplemental Table S6). As reduced working memory has been suggested as a cause of impulsivity in ADHD (e.g., Patros et al., 2015; Raiker et al., 2012), we also assessed the relationship between visual working memory and the outcome variables in the ADHD group (Supplemental Table S7).

Results

Given small sample size of TD participants at each data collection site (Supplemental Table S4), the data were combined into a single TD group. As the performance of children with inattentive and combined presentation ADHD did not differ on the outcome variables assessed, the data were combined into a single ADHD group (Supplemental Table S5). No significant differences were identified for age, estimated IQ, reported household income or race between the ADHD and TD groups (Table 1). There was a higher proportion of boys in the ADHD group; however, the performance of male and female participants did not differ significantly (Supplemental Table S8). Sex was therefore not considered further in the analyses, although its effect on performance is presented in Table 2. Significant correlations were identified between age and several outcome variables (Supplemental Table S6), as a result, age is included as a covariate in all analyses. Estimated IQ and visual working memory were not generally associated with performance and are not considered further in the analyses (Supplemental Table S6 & S7). We present the ADHD and TD group comparisons, together with the effect sizes, for the primary and exploratory probe trials in Table 2.

Primary trials

Overall task performance

ANOVAs examined the effect of group (ADHD vs. TD) on the number of trials completed and trial adjusted earnings. There was a significant group effect for the number of trials completed, $F\,(1, 133) = 8.288$, $p = .005$. Children with ADHD completed significantly more trials than the TD group before the primary trials ended (i.e., required more trials to reach, or failed to reach, the cutoff of 18 exposures to the yellow square/white square pairing), indicating they waited less often for the white 20-cent square to appear. Total earnings, adjusted for the number of trials completed, were significantly higher for the TD group, $F\,(1, 133) = 11.032$, $p = .001$, indicating a more efficient response style.

Table 2. ADHD and TD group task performance: descriptive statistics, group comparisons, and effect sizes.

	TD				ADHD							Controlling for sex[h]		
	M[a]	SE	95% CI	Range	M	SE	95% CI	Range	*F*[b]	*p*[f]	η_p^2[g]	*F*	*p*	η_p^2
Primary trials			(n = 46)				(n = 90)							
# of trials completed	55.67	2.90	49.94–61.39	35-90	65.92	2.07	61.82–70.01	35-90	*8.288*	*.005*	*.059*	*9.064*	*.003*	*.064*
Earnings adjusted for (divided by) # of trials	15.25	0.55	14.15–16.34	5.28-20	12.99	0.40	12.20–13.77	4.56-20	*11.032*	*.001*	*.077*	*10.943*	*.001*	*.077*
Median response time after yellow (cue)[c,d]	502.94	23.50	456.45–549.44	297-878	454.79	16.99	421.16–488.41	234-1794						
Median response time after other colors[c]	578.28	18.58	541.52–615.04	407-1328	571.81	13.44	545.22–598.39	390-1482						
*Color*group interaction*									*4.246*	*.041*	*.032*	*2.866*	*.093*	*.022*
Color main effect									*5.100*	*.026*	*.038*	*5.090*	*.026*	*.039*
Group main effect									*1.284*	*.259*	*.010*	*2.089*	*.151*	*.016*
% of 5 cents responses	26.81	3.88	19.13–34.48	0–88.89	36.01	2.77	30.53–41.50	0–94.44	*7.098*	*.009*	*.051*	*7.403*	*.007*	*.053*
% of premature 20 cents responses[d]	2.97	0.67	1.65–4.30	0–10.87	6.20	0.48	5.25–7.14	0–26.25	*18.832*	*<.001*	*.124*	*14.145*	*<.001*	*.097*
% of successful 20 cents responses	69.35	3.69	62.07–76.64	3.33-100	55.60	2.63	50.39–60.81	0-100	*10.968*	*.001*	*.076*	*9.881*	*.002*	*.070*
Exploratory probe trials (six long trials)[e]			(n = 37)		(n = 62)									
# of trials terminated by choosing 5 cents	1.79	0.33	1.13–2.45	0-6	2.24	0.26	1.73–2.75	0-6	*1.110*	*.295*	*.011*	*4.001*	*.008*	*.072*
# of trials terminated by premature response to 20-cent button	0.49	0.18	0.14–.84	0-2	1.29	0.14	1.02–1.56	0-5	*11.248*	*.001*	*.104*	*6.527*	*.012*	*.064*
# of trials earning 20 cents at 41st trial	3.72	0.33	3.07–4.38	0-6	2.47	0.26	1.97–2.98	0-6	*8.147*	*.005*	*.077*	*12.167*	*.001*	*.112*

a. Means adjusted for age. b. All analyses conducted controlling for age. c. The analyses for these two variables are presented below in italics, i.e., *the color*group interaction effect, color main effect, and group main effect on the response time*. d. This variable correlated with EIQ; the effect remained significant even when EIQ was entered as a covariate. e. Group differences were examined using Quade ANOVAs. f. If a conservative correction was made for the number of analyses undertaken of the primary trials data, then critical alpha would reduce to $p = .005$. g. Partial Eta Squared (.06 is considered as a medium and .14 a large effect size). h. Group comparisons when controlling for sex. Survival analyses not depicted here were unchanged when controlling for sex.

Response choices

ANOVAs examined the effect of group (ADHD vs. TD) on the three response types. A significant group difference was observed for the proportion of trials where children successfully waited for and earned 20 cents, F (1, 133) = 10.968, p = .001. Typically developing children waited for, and collected, 20 cents on a higher proportion of trials than those with ADHD. Conversely, the children with ADHD collected the 5 cent reward on a higher proportion of trials than TD children, F (1, 133) = 7.098, p = .009.

The groups also differed significantly on the proportion of premature responses to the 20-cent button, F (1, 133) = 18.832, p < .001. The ADHD group made a significantly higher proportion of premature responses compared to TD children. Post-hoc comparisons examined premature responses following non-yellow squares (i.e., responses at any time during a trial before the 20-cent square appeared) and presentation of the yellow square separately. Group comparisons were significant for premature responses following non-yellow squares, F (1, 133) = 16.681, p < .001, but not for responses following presentation of the yellow square F (1, 133) = 3.351, p = .069. Together, these findings suggest that higher proportions of premature 20 cent responses in the ADHD group are not being triggered by presentation of the cue.

Time to collect 5 cent reward

Among those who collected 5 cents at least twice (TD group n = 27 [58.7%], ADHD group n = 75 [83.3%], χ^2 (1) = 9.855, p = .002, η^2 = .072), the time from the start of a trial to collecting 5 cents was examined. Cox regression examined survival with group and age entered as predictors simultaneously. Neither group membership nor age was predictive of survival.[6] When children made the decision to collect 5 cents, they did so quickly; the median response time was one second (one right-square color change) for more than half of the children included in the analysis (TD group n = 14 [51.9%], ADHD group n = 43 [57.3%], χ^2 (1) = .242, p = .623, η^2 = .004) (Figure 2).

Time to collect 20 cent reward

A mixed ANOVA evaluated the within-subject effect of preceding square color (yellow vs. other colors), between-subject effect of group (ADHD vs. TD), and the color*group interaction for the median time from the appearance of the 20-cent white square to collection of the large reward. There was a significant interaction effect, F (1, 128) = 4.246, p = .041 and a main effect of color, F (1, 128) = 5.100, p = .026, but no main effect of the group.[7] Both groups of children responded more quickly when the right-side square turned white following a yellow square (cue) (ADHD M = 454.79, TD M = 502.94) compared with another colored square (ADHD M = 571.81, TD M = 578.28). This effect was more marked in the ADHD group.

[6]The results are unchanged when using the mean response times. See Supplemental Table 9 for the median and mean response time data.

[7]These effects are no longer significant when using the mean response time data, although the direction of the results is unchanged. See Supplemental Table 9.

Exploratory probe trials

Only children exposed to 18 yellow square (cue) events were presented with the probe trials. The proportion of TD (80.4%) and ADHD (68.9%) group children presented with these trials was not significantly different, χ^2 (1) = 2.049, *p* = .152, η^2 = .021. Among these children, the number of primary trials completed was greater for the ADHD group (M = 55.07) than the TD group (M = 47.27), *F* (1, 96) = 5.395, *p* = .022, η^2 = .053 (Supplemental Table S10). Subsequently, the mean duration of primary trials was 1.21 minutes longer for the ADHD group (M = 785.40 seconds) than the control group (M = 712.84 seconds), *F* (1, 96) = 5.706, *p* = .019, η^2 = .056. While the time spent on primary trials could affect children's performance during the probe trials (e.g., fatigue), we did not control for this in the subsequent analyses, because the number of primary trials was dependent on children's waiting performance. Controlling for the time spent on primary trials would mean taking out the variance that we are interested in examining.

There were three cued and three uncued long probe trials. During the cued probe trials (second, fourth, and sixth long trials), the yellow square was presented multiple times. The white square followed the last presentation of the yellow square for these cued trials. The yellow square never appeared during the uncued trials (first, third, and fifth long trials).

Survival analysis

Cox regression examined survival, i.e., continuing to wait for the opportunity to collect 20 cents, during each long probe trial, with group and age entered as predictors simultaneously (Figure 3). For the first and second cued probe trials, the model fit was adequate with χ^2 (2) = 12.286, *p* = .002, η^2 = .124 (Long Trial 2) and χ^2 (2) = 12.833, *p* = .002, η^2 = .130 (Long Trial 4). For both trials, the contribution of group was significant (*B* = .935, *p* = .003; *B* = .844, *p* = .011). Compared with the TD children, a larger proportion of children with ADHD dropped out, i.e., collected 5 cents or pressed the 20-cent button prematurely, during these trials. On the second of these trials (Long Trial 4) age also made a significant contribution (*B* = −.014, *p* = .016), with older children waiting longer. On the third cued trial (Long Trial 6), neither group nor age predicted survival.

For the first and third uncued trials, the model fit was adequate, χ^2 (2) = 9.574, *p* = .008 (Long Trial 1), χ^2 (2) = 8.191, *p* = .017, η^2 = .083 (Long Trial 5). Group membership did not predict survival on either trial, while the contribution of age was significant for both (*B* = −.015, *p* = .014, *B* = −.015, *p* = .017). Older children were slower to drop out. Neither group membership nor age was a significant predictor for the second uncued trial (Long Trial 3).

Response choices

Non-parametric tests (Quade ANOVAs) were conducted to examine the effect of group on the likelihood of making different types of responses during the six probe trials[8] We counted the number of trials on which children collected 20 cents, 5 cents, or responded prematurely. A significant group difference was observed for the number of trials on which the children collected 20 cents, *F* (1, 97) = 8.147, *p* = .005, with the TD children

[8]The reported results remained the same when the cued and uncued trials were considered separately..

collecting 20 cents on more trials than those with ADHD. Conversely, the ADHD group was more likely to respond prematurely to the 20-cent button, $F\,(1, 97) = 11.248$, $p = .001$. The groups did not differ on the number of trials on which they collected 5 cents.

Discussion

The current study extends our understanding of the effects of delays in reward availability and reward-predicting cues on the waiting behavior of children with ADHD. Using a novel computer task, we examined children's capacity to wait to collect a larger reward when a smaller reward remained available. Children with ADHD demonstrated less successful waiting than their TD counterparts, in that they were more likely to end the wait by collecting the smaller available reward or attempting to collect the larger reward early. The reward predicting cue differentially affected the performance of the ADHD and TD groups.

Unlike other experimental choice delay tasks, children were not informed of the length of the waiting period, which varied across trials. In addition, the immediate reward response option remained available, while children waited for the larger reward. Under these conditions, children with ADHD continued to demonstrate a well-documented preference for immediate reward (e.g., Patros et al., 2016; Scheres et al., 2010; Sonuga-Barke et al., 2008) and were more likely than TD children to collect the small reward than wait for the larger reward to become available. The children's performance on this new task may also reflect their tolerance for uncertainty over the wait time to collect the large reward. For both groups, the decision to collect the small reward was often made quickly, shortly after a trial began. Overall, the response pattern of the children with ADHD was less efficient than that of the TD children, with their trial corrected earnings significantly lower.

When children with ADHD attempted to wait to collect the larger reward, their behavior differed from the TD children. Children with ADHD were more likely to try to collect the larger reward early, i.e., before it became available, resulting in no reward. These premature responses were not anticipatory (i.e., only in response to the cue signaling imminent reward availability) and occurred throughout the task, including during the probe trials. This was not a failure to understand task requirements, instructions were clear and the consequences of premature responding evident. Similar premature responding, at the cost of reward, was reported in children with ADHD in a task that required them to wait for the appearance of a target before responding (Van Dessel et al., 2019). Such increased premature responding leads to fewer opportunities for waiting to be rewarded. Together, these studies provide experimental evidence for the frequently reported problems children with ADHD experience with waiting.

The reward predicting cues showed stronger effects on the behavior of children with ADHD. During the primary trials, when presentation of the yellow square consistently signaled the arrival of the white square, both groups responded more quickly following the cue, indicating awareness of its significance. This invigorating effect was larger in the ADHD group, suggesting increased sensitivity to the cue, or possibly to the reward availability it signaled. Such increased response readiness was also evident in the proportion of the ADHD group (24%) who made cue-triggered responses during the first long cued probe trial. These effects are not a result of overall faster responding in the ADHD group; there was no significant main effect of group on response time.

The cues also disrupted the waiting of the ADHD group during the exploratory probe trials when they no longer predicted imminent reward availability. In the first two cued trials, children with ADHD were more likely to abandon their efforts to wait, opting for the small available reward or responding prematurely in attempts to collect the large reward. The intermittent appearance of the cue may have increased the children's motivation to obtain reward, activated their reward collection response, or "distracted" their waiting efforts. Alternatively, the "missing" reward opportunities may have led to frustration and more erratic responding or abandoning the wait (Amsel, 1990; Douglas & Parry, 1994). During these probe trials, the appearance of the cues did not help maintain waiting in either group, suggesting they were not serving as conditioned reinforcers and bridging the reward delay. Interestingly, the waiting behavior of the two groups was not significantly different during the uncued probe trials. This may reflect the participation of only the "better" waiters (i.e., individuals who waited for the large 20-cent reward on sufficient primary trials to reach the criteria of cue/white square pairings) in probe trials. Nonetheless, the absence of group differences in responding during these uncued trials, together with the differences observed during cued trials, highlight the disruptive effect of the cues on the behavior of those with ADHD while waiting.

Despite these interesting findings, the study has some limitations. TD samples were collected across two sites and while the same inclusion and exclusion criteria applied in both settings, possible site effects should be considered in interpreting the findings. The children in the ADHD group, while all meeting strict criteria for ADHD, were recruited through a research clinic and possibly represent a less impaired sample than might be seen in clinical practice. On the other hand, the absence of marked comorbidity in the ADHD group increases our confidence that the observed group differences are due to the children's ADHD symptoms (Table 1). Interestingly, performance did not differ between children with inattentive and combined presentation ADHD, suggesting that disrupted waiting behavior is not unique to symptom reports of impulsivity/hyperactivity. The TD group included a higher proportion of girls than the ADHD group. We do not believe this impacted the findings given the evidence that TD boys and girls perform similarly on choice delay tasks (Doidge et al., 2021). Only parent data were collected for the TD children. The exclusion of 15 potential control participants (24.6%) suggests their parents over, rather than under, reported ADHD symptoms. The study introduced a novel task. The increased preference of the ADHD group for the small immediate reward argues for its validity as a choice delay task with an observed effect size similar to those reported in the literature (Marx et al., 2021). Critical alpha was maintained at $p = .05$, and a number of analyses were undertaken with the primary trial data. Statistically significant findings should therefore be interpreted cautiously with reference to the effect sizes reported in the tables. Well-powered replication studies are recommended. We propose a number of explanations for differences in the responses of children with and without ADHD. However, the children were not asked to explain their actions. Children's explicit awareness of the cue and their response strategies should be assessed in future studies. Administering established neuropsychological measures, such as reaction time and response inhibition tasks, together with this novel task, could help tease apart whether impulsive responding, altered timing, cue-triggered reactions, and/or poor decision-making contribute to the waiting difficulties of children with ADHD.

The probe trials in this study were exploratory and limited in number. Going forward, we recommend including more probe trials and having all participants complete these trials. The current task did not allow examination of possible effects of primary trial experiences on probe trial performance. A task design with a fixed number of primary trials may be better suited to evaluate children's waiting on longer trials with intermittent appearance of reward-related stimuli. In the current study, the disruptive effects of the cue during the exploratory probe trials appeared to diminish with increased exposure. By the third cued probe trial, the dropout rates for the two groups were no longer significantly different. The ADHD group seemed to show improved persistence, while more TD children abandoned the wait. The children with ADHD may have developed "frustration tolerance" to the missing reward opportunities (Amsel, 1992) or simply learned to inhibit their reward collecting responses (Killeen et al., 2013). Alternatively, it may have taken them longer to adjust to the new response contingencies (Alsop et al., 2016), or their performance on the earlier probe trials was influenced more by the number of primary trials completed. The TD group children, having experienced the length of the probe trials, may have become less willing to wait for the large reward to become available. A future study with a larger number of probe trials is required to test these hypotheses.

Clinical implications

In implementing this novel task, we demonstrate less successful waiting behavior in children with ADHD. They experience more difficulty waiting for a "better" outcome in the presence of an immediate reward opportunity. Reward predicting cues increased their response readiness but appeared to interfere with their ability to wait when the expected cue-reward association was disrupted. While replication studies and tests of ecological validity are needed, the current findings highlight the complexity of waiting difficulties in children with ADHD. We offer the following recommendations with caution, given the ecological validity of the task is yet to be established.

In everyday life, increased vulnerability to immediate reward opportunities likely results in suboptimal outcomes for children with ADHD. While they may begin to wait for their turn or to complete a task, for desired rewards, they experience difficulty resisting immediately available reward opportunities. Effective accommodations require acknowledging children's desire to wait and helping them develop the necessary self-control skills. This will be especially important in situations where feedback and reward are delayed or not consistently delivered, and when alternative, immediate and easily accessed, rewards are available. This should include creating opportunities in which children can wait successfully so that their waiting is rewarded. For example, ensuring the wait time is within children's capacity, acknowledging/rewarding their efforts to wait through small gestures or attention, and ensuring non-immediate rewards remain salient. The current data also highlight the importance of being aware of cues in the child's environment and their potential impact on children's reward seeking and waiting behavior. Increasing parent and teacher understanding of children's vulnerability to available reward opportunities, and their waiting difficulties, may improve the implementation of antecedent- and consequent-based behavior management strategies.

Acknowledgements

The authors thank the children, families and teachers who participated and the members of the research teams in Japan and the U.S. This study was supported by internal subsidy funding from the Okinawa Institute of Science and Technology Graduate University.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

The author(s) reported that there is no funding associated with the work featured in this article.

Consent for publication

Participating parents, teachers and children were volunteers and provided written consent for anonymous data to be used for publication.

Consent to participate

Participating parents, teachers and children were volunteers and provided written consent to participate.

Data availability statement

The data supporting the conclusions of this study are available upon reasonable request to the corresponding author.

Ethics approval

Ethical approval for the study was obtained from the OIST Graduate University Human Subjects Research Review Committee (Japan) and the University of Massachusetts Dartmouth Institutional Review Board (US).

References

Alsop, B., Furukawa, E., Sowerby, P., Jensen, S., Moffat, C., & Tripp, G. (2016). Behavioral sensitivity to changing reinforcement contingencies in attention-deficit hyperactivity disorder. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *57*(8), 947–956. https://doi.org/10.1111/jcpp.12561

Amsel, A. (1990). Arousal, suppression, and persistence: Frustration theory, attention, and its disorders. *Cognition & Emotion*, *4*(3), 239–268. https://doi.org/10.1080/02699939008410798

Amsel, A. (1992). *Frustration theory: An analysis of dispositional learning and memory*. Cambridge University Press.

Antrop, I., Stock, P., Verté, S., Wiersema, J. R., Baeyens, D., & Roeyers, H. (2006). ADHD and delay aversion: The influence of non-temporal stimulation on choice for delayed rewards. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *47*(11), 1152–1158. https://doi.org/10.1111/j.1469-7610.2006.01619.x

Barkley, R. A. (1997). Behavioral inhibition, sustained attention, and executive functions: Constructing a unifying theory of ADHD. *Psychological Bulletin*, *121*(1), 65–94. https://doi.org/10.1037/0033-2909.121.1.65

Baroni, A., & Castellanos, F. X. (2015). Neuroanatomic and cognitive abnormalities in attention-deficit/hyperactivity disorder in the era of “high definition” neuroimaging. *Current Opinion in Neurobiology*, *30*, 1–8. https://doi.org/10.1016/j.conb.2014.08.005

Cardinal, R. N., Winstanley, C. A., Robbins, T. W., & Everitt, B. J. (2004). Limbic corticostriatal systems and delayed reinforcement. *Annals of the New York Academy of Sciences*, *1021*(1), 33–50. https://doi.org/10.1196/annals.1308.004

Cognition, C. (2019). *CANTAB® [Cognitive assessment software]*. www.cantab.com

Conners, C. K. (2008a). Conners 3rd edition: Manual. In *Multi-Health systems*.

Conners, C. K. (2008b). Conners comprehensive behavior rating scales: Manual. In *Multi-Health systems*.

Doidge, J. L., Flora, D. B., & Toplak, M. E. (2021). A meta-analytic review of sex differences on delay of gratification and temporal discounting tasks in ADHD and typically developing samples. *Journal of Attention Disorders*, *25*(4), 540–561. https://doi.org/10.1177/1087054718815588

Douglas, V. I., & Parry, P. A. (1994). Effects of reward and nonreward on frustration and attention in attention deficit disorder. *Journal of Abnormal Child Psychology*, *22*(3), 281–302. https://doi.org/10.1007/BF02168075

Furukawa, E., Bado, P., Tripp, G., Mattos, P., Wickens, J. R., Bramati, I. E., Alsop, B., Ferreira, F. M., Lima, D., Tovar-Moll, F., Sergeant, J. A., & Moll, J. (2014). Abnormal striatal BOLD responses to reward anticipation and reward delivery in ADHD. *PloS One*, *9*(2), e89129. https://doi.org/10.1371/journal.pone.0089129

Kaufman, J., Birmaher, B., Axelson, D., Pereplitchikova, F., Brent, D., & Ryan, N. (2016). *The KSADS- PL DSM-5*. Kennedy Krieger Institute.

Killeen, P. R., Russell, V. A., & Sergeant, J. A. (2013). A behavioral neuroenergetics theory of ADHD. *Neuroscience and Biobehavioral Reviews*, *37*(4), 625–657. https://doi.org/10.1016/j.neubiorev.2013.02.011

Kuntsi, J., Oosterlaan, J., & Stevenson, J. (2001). Psychological mechanisms in hyperactivity: I. Response inhibition deficit, working memory impairment, delay aversion, or something else? *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *42*(2), 199–210. https://doi.org/10.1111/1469-7610.00711

Luman, M., Tripp, G., & Scheres, A. (2010). Identifying the neurobiology of altered reinforcement sensitivity in ADHD: A review and research agenda. *Neuroscience and Biobehavioral Reviews*, *34*(5), 744–754. https://doi.org/10.1016/j.neubiorev.2009.11.021

Marx, I., Hacker, T., Yu, X., Cortese, S., & Sonuga-Barke, E. (2021). ADHD and the choice of small immediate over larger delayed rewards: A comparative meta-analysis of performance on simple choice-delay and temporal discounting paradigms. *Journal of Attention Disorders*, *25*(2), 171–187. https://doi.org/10.1177/1087054718772138

Nigg, J. T., Karalunas, S. L., Feczko, E., & Fair, D. A. (2020). Toward a revised nosology for attention-deficit/Hyperactivity disorder heterogeneity. *Biological Psychiatry, Cognitive Neuroscience and Neuroimaging*, *5*(8), 726–737. https://doi.org/10.1016/j.bpsc.2020.02.005

Parry, P. A., & Douglas, V. I. (1983). Effects of reinforcement on concept identification in hyperactive children. *Journal of Abnormal Child Psychology*, *11*(2), 327–340. https://doi.org/10.1007/BF00912095

Patros, C. H. G., Alderson, R. M., Lea, S. E., & Tarle, S. J. (2017). Context influences decision-making in boys with attention-deficit/hyperactivity disorder: A comparison of traditional and novel choice-impulsivity paradigms. *Child Neuropsychology: A Journal on Normal and Abnormal Development in Childhood and Adolescence*, *23*(2), 242–254. https://doi.org/10.1080/09297049.2015.1119261

Patros, C. H. G., Matt Alderson, R., Kasper, L. J., Tarle, S. J., Lea, S. E., & Hudec, K. L. (2016). Choice-Impulsivity in children and adolescents with attention-deficit/hyperactivity disorder (ADHD): A meta-analytic review. *Clinical Psychology Review*, *43*, 162–174. https://doi.org/10.1016/j.cpr.2015.11.001

Patros, C. H. G., Matt Alderson, R., Lea, S. E., Tarle, S. J., Kasper, L. J., & Hudec, K. L. (2015). Visuospatial working memory underlies choice-impulsivity in boys with attention-deficit/hyperactivity disorder. *Research in Developmental Disabilities*, *38*, 134–144. https://doi.org/10.1016/j.ridd.2014.12.016

Plichta, M. M., & Scheres, A. (2014). Ventral-Striatal responsiveness during reward anticipation in ADHD and its relation to trait impulsivity in the healthy population: A meta-analytic review of the fMRI literature. *Neuroscience and Biobehavioral Reviews*, *38*, 125–134. https://doi.org/10.1016/j.neubiorev.2013.07.012

Raiker, J. S., Rapport, M. D., Kofler, M. J., & Sarver, D. E. (2012). Objectively measured impulsivity and attention-deficit/Hyperactivity disorder (ADHD): Testing competing predictions from the working memory and behavioral inhibition models of ADHD. *Journal of Abnormal Child Psychology*, *40*(5), 699–713. https://doi.org/10.1007/s10802-011-9607-2

Robinson, M. J. F., Fischer, A. M., Ahuja, A., Lesser, E. N., & Maniates, H. (2016). Roles of "wanting" and "liking" in motivating behavior: Gambling, food, and drug addictions. *Current Topics in Behavioral Neurosciences*, *27*, 105–136. doi:10.1007/7854_2015_387.

Rousselet, G. A., & Wilcox, R. R. (2020). Reaction times and other skewed distributions: Problems with the mean and the median. *Meta-Psychology*, *4*. https://doi.org/10.15626/MP.2019.1630

Sagvolden, T., Johansen, E. B., Aase, H., & Russell, V. A. (2005). A dynamic developmental theory of attention-deficit/hyperactivity disorder (ADHD) predominantly hyperactive/impulsive and combined subtypes. *The Behavioral and Brain Sciences*, *28*(3), 397–419. https://doi.org/10.1017/S0140525X05000075

Scheres, A., Tontsch, C., Thoeny, A. L., & Kaczkurkin, A. (2010). Temporal reward discounting in attention-deficit/hyperactivity disorder: The contribution of symptom domains, reward magnitude, and session length. *Biological Psychiatry*, *67*(7), 641–648. https://doi.org/10.1016/j.biopsych.2009.10.033

Schweitzer, J. B., & Sulzer-Azaroff, B. (1995). Self-Control in boys with attention deficit hyperactivity disorder: Effects of added stimulation and time. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *36*(4), 671–686. https://doi.org/10.1111/j.1469-7610.1995.tb02321.x

Sokal, R. R., & Rohlf, F. J. (2012). *Biometry: the principles and practice of statistics in biological research*. W. H. Freeman and Company.

Sonuga-Barke, E. J. (2003). The dual pathway model of AD/HD: An elaboration of neuro-developmental characteristics. *Neuroscience and Biobehavioral Reviews*, *27*(7), 593–604. https://doi.org/10.1016/j.neubiorev.2003.08.005

Sonuga-Barke, E. J., Bitsakou, P., & Thompson, M. (2010). Beyond the dual pathway model: Evidence for the dissociation of timing, inhibitory, and delay-related impairments in attention-deficit/Hyperactivity disorder. *Journal of the American Academy of Child and Adolescent Psychiatry*, *49*(4), 345–355. https://doi.org/10.1016/j.jaac.2009.12.018

Sonuga-Barke, E. J., Sergeant, J. A., Nigg, J., & Willcutt, E. (2008). Executive dysfunction and delay aversion in attention deficit hyperactivity disorder: Nosologic and diagnostic implications. *Child and Adolescent Psychiatric Clinics of North America*, *17*(2), 367–384. https://doi.org/10.1016/j.chc.2007.11.008

Sonuga-Barke, E. J., Taylor, E., Sembi, S., & Smith, J. (1992). Hyperactivity and delay aversion? I. the effect of delay on choice. *Journal of Child Psychology and Psychiatry*, *33*(2), 387–398. https://doi.org/10.1111/j.1469-7610.1992.tb00874.x

Tripp, G., & Wickens, J. R. (2008). Research review: Dopamine transfer deficit: A neurobiological theory of altered reinforcement mechanisms in ADHD. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *49*(7), 691–704. https://doi.org/10.1111/j.1469-7610.2007.01851.x

van der Oord, S., & Tripp, G. (2020). How to improve behavioral parent and teacher training for children with ADHD: Integrating empirical research on learning and motivation into treatment. *Clinical Child and Family Psychology Review*, *23*(4), 577–604. https://doi.org/10.1007/s10567-020-00327-z

Van Dessel, J., Morsink, S., Van der Oord, S., Lemiere, J., Moerkerke, M., Grandelis, M., Sonuga-Barke, E., & Danckaerts, M. (2019). Waiting impulsivity: A distinctive feature of ADHD neuropsychology? *Child Neuropsychology: A Journal on Normal and Abnormal Development in Childhood and Adolescence*, *25*(1), 122–129. https://doi.org/10.1080/09297049.2018.1441819

Voon, V. (2014). Models of impulsivity with a focus on waiting impulsivity: Translational potential for neuropsychiatric disorders. *Current Addiction Reports*, *1*(4), 281–288. https://doi.org/10.1007/s40429-014-0036-5

Wechsler, D. (2009). Wechsler individual achievement test—third edition (WIAT-III) administration and scoring manual. In *San Antonio*. The Psychological Association.

Wechsler, D. (2014). Wechsler intelligence scale for children—Fifth edition (WISC-V) administration and scoring manual. In *San Antonio*. The Psychological Association.

Wiig, E. H., Secord, W. A., & Semel, E. (2013). *Clinical evaluation of language fundamentals: CELF-5*. San Antonio, TX: The Psychological Association.

Zentall, S. (1975). Optimal stimulation as theoretical basis of hyperactivity. *The American Journal of Orthopsychiatry*, *45*(4), 549–563. https://doi.org/10.1111/j.1939-0025.1975.tb01185.x