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Modulation of Response Timing in ADHD, Effects of Reinforcement Valence and Magnitude

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Abstract The present study investigated the impact of reinforcement valence and magnitude on response timing in children with ADHD. Children were required to estimate a 1-s interval, and both the median response time (response tendency) and the intrasubject-variability (response stability) were investigated. In addition, heart rate and skin conductance were measured to examine the autonomic responses to reinforcement. Feedback-only trials were compared to low response cost trials (response cost for incorrect responses), low reward trials (reward for correct responses), high response cost and high reward trials. In feedback-only trials, children with ADHD underestimated more severely the interval and responded more variably than controls. Children with ADHD, unlike controls, were unaffected by the reinforcement conditions in terms of time underestimations. The variability of responding, on the other hand, decreased under conditions of reinforcement to a larger extent in children with ADHD than controls. There were no indications that children with ADHD were abnormally affected by the valence or magnitude of reinforcement. Furthermore, skin conductance responses increased when feedback was coupled with reinforcement, an effect which was larger in children with ADHD than controls. This could be interpreted as demonstrating that children with ADHD suffer from a diminished awareness of the significance of feedback in the feedback-only condition. The current study suggests that children with ADHD suffer from motivation problems when reinforcement was not available, at least when variability in responding was measured. Underestimations of time may reflect more stable deficits in ADHD.

Keywords ADHD · Motor timing · Psychophysiology · Reinforcement · Reward · Variability.

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Introduction

Attention problems, motor restlessness and impulsive responding characterize children with Attention Deficit Hyperactivity Disorder (ADHD) (American Psychiatric Association, APA 1994). Recently, motivational abnormalities have been identified as crucial in ADHD (Casey et al. 2007; Castellanos and Tannock 2002; Nigg 2005). Many studies have been designed to investigate whether cognitive performance in ADHD can be modulated by motivation using reinforcement contingencies. Luman et al. (2005) reviewed this literature and demonstrated that performance of children with ADHD and controls improved by using appropriate reinforcement. There is some evidence from that review that the improvement is larger for children with ADHD than for controls, which confirms that cognitive problems in ADHD may be partly explained by motivational dysfunctions. In addition to behavioral reports, there is evidence of an abnormal response to reinforcement in ADHD using brain imaging measures (Plessen et al. 2006; Scheres et al. 2007; Spencer et al. 2005; Van Meel et al. 2005a).

Although there is general consensus that children with ADHD show an abnormal sensitivity to reinforcement, the nature of this abnormality is unclear. For example, it is not clear whether children with ADHD are abnormally sensitive to either reward, response cost or both. Children with ADHD have been found to show an abnormal sensitivity to reward by preferring an immediate small reward over a larger delayed reward (Rapport et al. 1986; Sonuga-Barke et al. 1992). This has been explained by a shortage in dopamine transmission in the fronto-limbic pathway in ADHD that results in a faster decay of reward (Sagvolden et al. 2005). In contrast, there is evidence that children with ADHD were specifically sensitive to response cost rather than reward, by showing a disproportionally greater improvement in accuracy when faced with response cost than controls in a Figure Matching task and an arithmetic task (Carlson et al. 2000; Carlson and Tamm 2000). Electrophysiological studies confirm the suggestion that individuals with ADHD show abnormalities that are specifically related with processing of response cost (Potts et al. 2006; Van Meel et al. 2005a). Other performance studies, however, found no differential impact of reward or response cost on performance of children with ADHD compared to normal controls (Iaboni et al. 1995; Oosterlaan and Sergeant 1998).

Using autonomic measures, studies have revealed smaller responses to *both* reward and response cost in ADHD (Crone et al. 2003; Firestone and Douglas 1975; Iaboni et al. 1997). This would converge with the suggestion that children with ADHD suffer from an elevated threshold for experiencing incentives (Haenlein and Caul 1987), rather than being specifically sensitive to either reward or response cost. Slusarek et al. (2001) studied whether children with ADHD need more reinforcement than controls to improve their performance in a Stop-signal task. Children with ADHD benefited more than controls from large compared to small quantities of response cost (one versus five points loss) by improving the frequency of correct inhibitions, confirming the suggestion that children with ADHD are dependent on intensive external reinforcement to perform well.

The current study was set up to investigate the impact of reward and response cost (investigating the valence of reinforcement) on performance of children with ADHD as well as to test whether children with ADHD suffer from a elevated reinforcement threshold (investigating the magnitude of reinforcement). By investigating these two aspects of reinforcement separately it is possible to disentangle the processes that may underlie reinforcement sensitivity in ADHD in a within subject design (e.g., Haenlein and Caul 1987; Sagvolden et al. 2005). In addition, knowledge regarding the sensitivity of children with ADHD to specific aspects of reinforcement may inform behavioral interventions for ADHD that make use of reinforcement contingencies (DuPaul et al. 1992; McGoey and DuPaul 2000; Rapport et al. 1982).

One of the underlying performance deficiencies in ADHD relates to motor timing (Barkley 1997; Castellanos and Tannock 2002; Toplak et al. 2006). Motor timing is hypothesized to consist of two components: an internal clock component, which reflects central time keeping organizations and a motor delay component, which reflects random variability due to organization of motor output (e.g., Harrington et al. 1998). Both components seem to be affected in children with ADHD: Children with ADHD show a time keeping deficiency as observed by problems with time discrimination, time (re)production, and, compared to controls, children with ADHD systematically underestimate time intervals (see for review, Toplak et al. 2006). In addition, motor output problems in ADHD are observed by a well-known pattern of slow and variable responding (Leth-Steensen et al. 2000; Rubia et al. 2007; Van Meel et al. 2005b). Since reinforcement is found to influence the motor system (Haber 2003; Schultz et al. 1997), it is valuable to investigate whether problems with motor timing in children with ADHD may be secondary to a motivational deficit.

Two studies investigated the impact of reinforcement on motor timing in ADHD. Reward tokens compared to no-reward were found to improve time reproduction performance (3–17 s) to a larger extent in ADHD children compared to controls (McInerny and Kerns 2003). In contrast, using a time production task (1000 ms) no differences in performance improvement were observed between children with ADHD and controls, when either reward or response cost (three eurocents) were added to performance feedback (Van Meel et al. 2005b). Possibly, the discrepancy in the impact of reinforcement on motor timing in ADHD was related to the differences in time intervals. Larger intervals, such as 3–17 s, may have invoked delay aversion in children with ADHD, specifically when performance was not reinforced (Sonuga-Barke et al. 1992; Sonuga-Barke 2002). Otherwise, the magnitude of rewards may have differed between the two studies. Three cents and a promised gift (Van Meel et al. 2005b) may have been perceived as smaller than tokens and a large unwrapped gift that was in sight (McInerny and Kerns 2003). Furthermore, a counterbalanced blocked design (Van Meel et al. 2005b) may have decreased the motivation for some children to perform well (e.g., when the response cost condition *followed* the reward condition, children may have been less motivated to perform well than when the response cost condition was presented first).

To accommodate for these issues, the current study investigated the impact of both reinforcement valence and magnitude on motor timing in a task where children were required to produce a 1-s interval. By using a short time interval, the influence of higher cognitive functions, such as sustained attention or working memory, was minimized and the chance of boredom and frustration due to the delay aversion of children with ADHD reduced (Sonuga-Barke 2002). To study the impact of reinforcement valence and magnitude, five conditions were created: feedback-only (1), feedback and low response cost (2), low reward (3), high response cost (4), and high reward (5). Trials from the five conditions were allocated completely randomized. To investigate whether performance differences would be accompanied by psychophysiological abnormalities in response to reinforcement, heart rate (HR) and skin conductance (SC) were measured during the experiment. These measures are valuable when investigating reinforcement sensitivity, since HR and SC responses have been found to differ in response to positive and negative outcomes such as reward and response cost (e.g., Crone et al. 2003; Fowles 1988). In addition, both measures have been found to differentiate between low and high magnitudes of incentives (Bradley 2000; Fowles 1988).

The following hypotheses were tested. First, children with ADHD were expected to perform worse then controls in estimating the 1-s interval (Toplak et al. 2006). Second, if children with ADHD suffer from an abnormal sensitivity to either reward (e.g., Sonuga-Barke et al. 1992) or response cost (e.g., Carlson et al. 2000), performance should be differentially affected by reward and response cost compared with their normally developing peers (the *valence* hypotheses). Otherwise, if children with ADHD suffer from a higher threshold to experience incentives (Slusarek et al. 2001), their performance would be more optimal when the intensity of reinforcement is large compared to small (the *magnitude* hypothesis), unlike the performance of normal controls. Third, based on earlier findings of attenuated psychophysiological responses to reinforcement in ADHD (e.g., Crone et al. 2003), an abnormal sensitivity to either reward, response cost or both was expected to be associated with smaller HR or SC responses to reinforcement in children with ADHD compared to normal controls.

Materials and Methods

Participants and Selection Procedure

Twenty-five children with ADHD (21 boys) and 30 normal control children (24 boys) aged 7 to 12 participated in this study. Mean age was 121 months (*SD* 17) and 120 months (*SD* 15) for the ADHD and control group, respectively.

Children in the ADHD group were recruited through a university affiliated outpatient clinic for ADHD. They were included, when they met the following criteria: (a) a clinical diagnosis of ADHD, (b) IQ score >80, (c) absence of any psychiatric disorder other than ADHD, oppositional defiant disorder (ODD) or conduct disorder (CD), (d) absence of any neurological disorders as reported by parents, learning disabilities (such as dyslexia or other learning disorder reported by parents as well as severe learning problems noted by the teacher of the child), sensory or motor impairment, (e) no medication other than methylphenidate to control for the impact of psycho-stimulants on the task results. All children that were on methylphenidate discontinued use at least 24 h before testing to achieve complete washout (Pelham et al. 1999).

The assessment procedure consisted of three stages. Firstly, to confirm the ADHD diagnosis and assess comorbid ODD and CD, parents were administered the Dutch version of the disruptive behavior disorder section of the Diagnostic Interview Scale for Children (DISC; Shaffer et al. 2000), which is based on the Diagnostic and Statistical Manual of Mental disorders, fourth edition (DSM-IV; APA 1994). The DISC-IV indicated that ten children met ADHD combined type criteria, 12 children met criteria for ADHD inattentive type, and three children met criteria for ADHD hyperactive/impulsive type. Seven children fulfilled additional criteria for comorbid ODD, none were comorbid for CD. Secondly, to ensure symptom pervasiveness, the Dutch version of both the parent and teacher version of the Disruptive Behavior Disorder rating scale (DBD; Pelham et al. 1992) were administered. The DBD consists of 42 items on a 4-point Likert scale (0 = not at all to 3 = very much). The scores on the scales range from 0–27 (nine items) for the Inattention or Hyperactivity/Impulsivity scales, 0–24 for the ODD scale and 0–48 for the CD scale. Children were required to score within the clinical problem range (95th to 100th percentile) on either the Inattention or Hyperactivity/Impulsivity scale of both parent and teacher rating scales. Finally, the Dutch version of the Child Behavioral Checklist (CBCL) and Teacher Rating Form (TRF) were administered (Achenbach and Edelbrock 1981) as an additional measure of problem behavior, such as attention problems, delinquent and aggressive behavior.

Control children were recruited through local elementary schools. They were included, when the following criteria were met: (a) no diagnosis of either ADHD, ODD or CD, (b) scores in the normal range (<80th percentile) on the ADHD scales of the parent and teacher DBD, (c) IQ score >80, (d) absence of any neurological disorders, learning disabilities, sensory or motor impairment, (e) not taking any medication.

An estimation of the IQ score of each child was obtained by four subtests (Picture Arrangement, Arithmetic, Block Design, and Vocabulary) of the Wechsler Intelligence Scale for Children (WISC-R). These four subtests have been demonstrated to correlate between 0.93 and 0.95 with full scale IQ (Groth-Marnat 1997).

Reinforced Timing Task

A self-paced time production paradigm adapted from Miltner et al. (1997) was employed (see Fig. 1). In this task, children had to produce a time interval of 1000 ms.

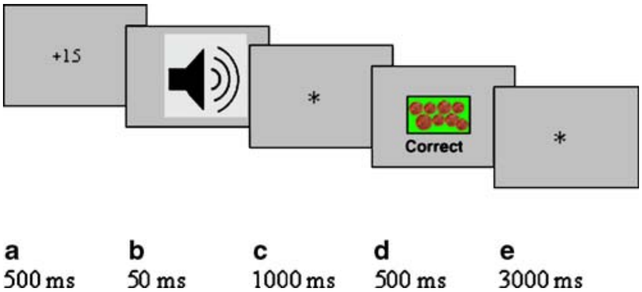

Fig. 1 The time-course of a time-production trial. **a** Background screen turned *blue* (feedback-only), *red* (response cost condition) or *green* (reward condition) for 500 ms. To indicate the magnitude of possible loss/gain, +3, −3, +15 or −15 was presented on the screen. **b** Children heard an auditory beep for 50 ms indicating the start of 1-s interval, after which they were required to press the response button. **c** A 1000 ms screen with *fixation cross* separated the button press from feedback presentation. **d** Feedback appeared on the screen for 500 ms. **e** The screen turned blank for 3000 ms before the next trial started

The trial started with a colored screen for 500 ms that indicated the start of the reinforcement trial. A green screen signaled that the *reward condition* was applicable; a red screen signaled the *response cost condition*; a blue screen the *feedback-only condition*. Information regarding the *magnitude of reinforcement* was presented in the centre of the colored screen (being either +3, −3, +15, −15). While looking at a fixation cross at the centre of the screen, children heard a brief tone (50 ms, 80 db) through headphones. Following the tone, they pressed a response button, when they thought a 1-s interval had elapsed. Thousand ms after the button press, textual accuracy information appeared on the screen for 500 ms that informed the subject whether the estimation was 'too short,' 'too long' (both incorrect) or 'correct.' Accuracy information was provided on every trial. A staircase algorithm determined the time window in which a response was considered correct. The boundaries of the initial window were 500 and 1500 ms and narrowed with 100 ms, when a response was correct, while it widened with 100 ms when a response was incorrect (see Miltner et al. 1997). Consequently, this procedure ensured a similar amount of positive and negative feedback (and reward and response cost) for each participant.

Depending on the reinforcement condition, coins indicating gain or loss appeared on the screen. In the reward condition, feedback was accompanied by either a 3 or 15 cents gain when responses were correct, and children received only feedback in case of an incorrect response. In the response cost condition, feedback was accompanied by a 3 or 15 cents loss when responses were incorrect, and children received only feedback following a correct response. In order to clearly distinguish between low and high magnitude of reinforcement, a 1: 5 ratio was used (Slusarek et al. 2001). During the inter-trial interval (3000 ms) the fixation cross re-appeared on the screen. The trials from the five reinforcement conditions were presented in a random order.

Internal clock functioning (e.g., Harrington et al. 1998) was investigated by the *response tendency* (either over- or underproduction of time, a measure of central time keeping), which was determined by the median time production. The median was used since the data was positively skewed as is common in reaction time distributions (skewness = 3.2, *SE* = 0.03) and the median is less sensitive to time production outliers. In addition, the random variability due to organization of motor output (e.g., Harrington et al. 1998) was investigated by the *stability of responding,* as measured by the intrasubject-variability. A measure of the moment-to-moment fluctuations in performance was used that provides an index of local predictability (trial-to-trial variability) and controls for the mean response (Russell et al. 2006). The intrasubject-variability $= \sqrt{\left(\Sigma\,(\mathrm{RT_i} - \mathrm{RT_i} - 1)^2 \middle/ (n-1)\right)}$, where i = trial number, n = number of trials, and RT = response time. Responses that were more than four standard deviations from a participant's mean were considered as outliers and were excluded to minimize the risk of removing any real data, while still controlling for very extreme observations (Leth-Steensen et al. 2000). In the ADHD group this was 3% of the data points, in the control group 2%.

Procedure

All parents completed a written informed consent prior to the study that was approved by the local ethics committee. Participation was voluntary and travel costs were funded. During the task, children viewed a computer screen, positioned 60 cm in front of them. The response button was utilized with the right hand and could be moved freely on the table. Standardized task instructions were given. In order to familiarize children with a 1-s interval, children saw a cartoon character that appeared ten times on the screen for 1 s. Thereafter, a practice session started in which children practiced the feedback-only trials (six trials), followed by the reward trials (12 trials) and the response cost trials (12 trials). The practice session was repeated until children correctly identified the magnitude and valence of the reinforcer. Finally, children practiced the randomized trials (12 trials). Children received 200 eurocents at the beginning of the task, which was placed in their view. They were instructed to gain as much and lose as little as possible. Participants were informed that their gain or loss would be calculated at the end of the task. At the end of the session, all children were told that their net score was 245 eurocents, which was an (arbitrary) 45 cents gain. Children exchanged their gain for a present worth approximately € 5. The task consisted of 300 trials presented in five blocks of 60 trials lasting approximately 6 min per block. Parents received a report on the outcome of the study.

Psychophysiological Recordings

In order to investigate the psychophysiological responses to reinforcement, the electrocardiogram (ECG) and SC level were registered using the Vrije Universiteit Ambulatory Monitoring System-36 (Klaver et al. 1994). The ECG was registered via two active 10 mm Ag/AgCl electrodes attached (a) between the collarbones over the jugular notch of the sternum and (b) under the left breast, 4 cm under the nipple between the ribs. One ground electrode was attached at the right lateral side between the lower two ribs. The continuous signals were sampled at 500 Hz from which R-peak occurrences were detected. Three inter-beat-intervals (IBIs) were extracted following the feedback moment (Crone et al. 2003). IBI0 represented the interval in which the feedback was presented and IBI+1, IBI+2 followed the feedback. The IBIs were corrected by the IBI at time of the button press to control for possible confounding influences of the HR changes related to preparatory response processes (Jennings and Van der Molen 2002).

SC was measured through two 1 cm^2 AgAg/Cl electrodes, which were attached with Velcro straps to the volar surfaces of the medial phalanges of the index and middle fingers of the left hand. A constant voltage of 0.5 V was used to register SCL and the signals were amplified and sampled at 10 Hz. Electrolyte gel (0.05 molar NaCL) was applied to the two electrodes. Due to artifacts (possibly due to an increase in random movement), only the first three blocks (180 trials) of SC could be analyzed. The reactive SC was calculated as the difference between the baseline SC (previous to the feedback stimulus) and the largest value in the interval 4000 ms following feedback.

Psychophysiological data of two children in the control group was missing due to technical problems.

Statistical Analyses

A repeated measures (RM) ANOVA was conducted for the performance measures, with reinforcement condition as within-subject factor and group as between-subject factor. The impact of reinforcement on performance was investigated using three planned contrasts: (a) feedback-only condition versus the (collapsed) reinforcement conditions (*reinforcement contrast*), (b) reward versus response cost (*valence contrast*), and (c) high versus low intensity of reinforcement (*magnitude contrast*). The planned comparisons were orthogonal to (uncorrelated with) every other contrast. To investigate whether performance of children with ADHD and controls changed over the course of the task, the task was divided into five blocks (60 trials each).

Table 1 Means, standard deviations, and pairwise group comparisons for IQ, age, and rating scale scores

Measure	Group				
	ADHD (*n*=25)		Normal controls (*n*=30)		
	M	*SD*	*M*	*SD*	*F*-value (*df* 1,53)
Age in months	120.5	17.4	119.5	15.0	0.1
IQ score	101.3	11.0	105.2	16.8	1.0
DBD parents					
Inattention	16.8[c]	4.9	3.2	3.2	152.8*
Hyperactivity/Impulsivity	15.0[c]	6.3	2.4	2.3	102.9*
ODD	7.3	4.4	2.0	2.0	34.6*
CD	1.6	2.3	0.3	0.6	8.1*
DBD teacher					
Inattention	16.0[c]	5.0	2.7	2.6	161.3*
Hyperactivity/Impulsivity	13.7[c]	6.8	2.6	3.1	65.7*
ODD	5.7	4.5	0.7	1.8	31.2*
CD	1.1	1.6	0.2	0.5	9.1*
CBCL					
Total problem score	67.4[c]	8.4	–	–	–
Attention problems	70.9[c]	8.9	–	–	–
TRF					
Total problem score	67.4[c]	9.9	–	–	–
Attention problems	66.4[c]	7.8	–	–	–

ADHD Attention Deficit Hyperactivity Disorder; *CD* Conduct Disorder; *DBD* Disruptive Behavior Disorder rating scale; *M* Mean; *ODD* Oppositional Defiant Disorder; *SD* Standard Deviation

[c] scores in the clinical range (>95th percentile) of that (sub)scale

* significant with $p<0.01$

Block was inserted as a within-subject factor in a RM ANOVA with group as between-subject factor.

The impact of the contingencies on HR and SC following feedback were investigated by a RM ANOVA with feedback (positive and negative) and reinforcement condition as within-subject factors and group as between subject factor. Again, the three orthogonal contrasts were employed to test for differences between the reinforcement conditions. For the HR measure, the factor 'sequential IBI' (IBI0, IBI+1, IBI+2) was entered as an additional within-subject factor in the RM analyses.

Greenhousse Geisser adjusted *p*-values are reported for those analyses in which sphericity assumptions were violated. Effect sizes (partial eta squared, η_p^2) are reported to indicate the proportion of total variance explained by the effect, being either small (0.01), medium (0.06), or large (0.14) (Cohen 1988).

Results

As reported in Table 1, children with ADHD did not differ from controls in mean age or estimated full scale IQ. Furthermore, Table 1 indicates that groups differed in the expected direction on all scales of both the parent and teacher DBD with higher symptom levels reported for children with ADHD than for controls. Children with ADHD scored within the clinical problem range on the Total Problem scale and the Attention Problem scale of both the TRF and CBCL (see Table 1), futher demonstrating the validity of our assessment procedure. In addition (not presented in Table 1), children with ADHD scored within the clinical problem range on the Externalizing Problem scale of both the CBCL and TRF, as is frequently observed in an ADHD sample (Angold et al. 1999); all other scores (e.g., Internalizing Problem scale) were below

Table 2 Results from the reinforcement condition contrasts analyses

Effects Measure	Group	Reinforcement contrast (Feedback-only-reinforcement)	Valence contrast (reward-response cost)	Magnitude contrast (low-high)
Median response				
Main effect	$F_{5,49}$=7.7, p=0.003, η_p^2=0.30	p=0.186	$F_{1,53}$=32.9, p <0.001, η_p^2=0.38	p=0.818
Interaction Group	–	$F_{1,53}$=10.5, p=0.002, η_p=0.17	p=0.837	p=0.798
Description of effects	ADHD < NC	FB-only: ADHD = NC RF: ADHD < NC	Reward < Response Cost	
ISV				
Main effect	$F_{5,49}$=5.8, p=0.019, η_p^2=0.09	$F_{1,53}$=10.9, p=0.002, η_p^2=0.17	p=0.106	p=0.096
Interaction Group	–	$F_{1,53}$=4.4, p=0.040, η_p^2=0.08	p=0.390	p=0.446
Description of effects	ADHD > NC	FB-only: ADHD > NC RF[1]: ADHD > NC		
HR				
Main effect	p=0.613	$F_{1,51}$=5.0, p=0.030, η_p^2=0.09	$F_{1,51}$=10.5, p=0.002, η_p^2=0.17	p=0.659
Interaction Group	–	p=0.944	p=0.852	p=0.324
Description of effects		FB-only < Reinforcement	Reward < Response Cost	
SC				
Main effect	p=0.300	p=0.216	p=0.230	p=0.156
Interaction Group	–	$F_{1,51}$=4.8, p=0.033, η_p^2=0.09	p=0.526	p=0.323
Description of effects		ADHD: FB-only < RF NC: FB-only = RF		

ADHD Attention Deficit Hyperactivity Disorder; *FB-only* Feedback-only condition; *RF* (collapsed) reinforcement conditions; *NC* Normal controls
[1] Marginal significant effect

the clinical threshold. Results for the ANOVA's testing the impact of the reinforcement conditions to our dependent variables are reported in Table 2.

Response Tendency Figure 2 illustrates that children with ADHD underestimated the time interval compared to controls as indicated by a lower median response time. The reinforcement contrast comparing the feedback-only condition to the reinforcement conditions was not significant, but there was an interaction between the reinforcement contrast and group. Follow-up analyses demonstrated that groups did not differ in the feedback-only condition ($p=0.28$), in contrast to the reinforcement conditions where children with ADHD more severely underestimated the interval than controls ($p=0.003$). Figure 2 shows that while controls reduced their tendency to respond prematurely when reinforcement was added to feedback ($p=0.003$), children with ADHD responded similarly in the feedback-only and reinforcement conditions ($p=0.25$). The second contrast that tested reinforcement valence was significant: Children responded prematurely in the reward compared to the response cost conditions. Group did not significantly interact with the valence contrast. The magnitude contrast was not significant and no significant interaction between the magnitude contrast and group was observed.

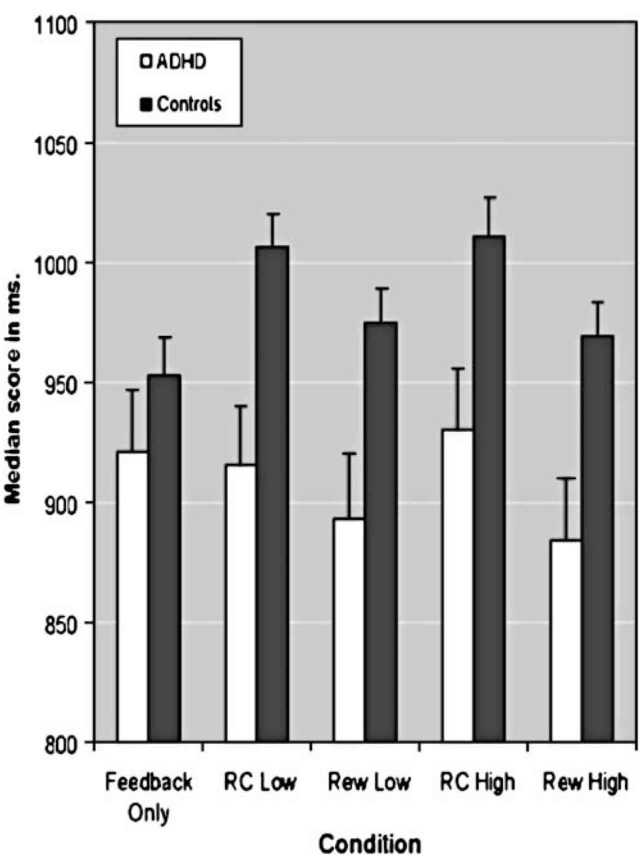

Fig. 2 Response tendency as expressed in terms of median time production (and standard errors) of children with ADHD and normal controls in the reinforced time-production task. Responses < 1000 ms indicated underestimations and responses >1000 ms indicated overestimations. *RC* Response Cost; *Rew* Reward. The figure illustrates the group difference in response tendency and the interaction between group and the reinforcement contrast (feedback-only versus reinforcement conditions)

The tendency to respond prematurely diminished over time (912 versus 960 ms), as indicated by a main effect of block, $F_{4,50}=4.1$, $p=0.012$, $\eta_p^2=0.07$. Groups were not differentiated by the factor block ($p=0.87$).

Timing Stability Figure 3 illustrates that the intrasubject-variability of time production was larger in children with ADHD than in controls, indicating that time production was less stable in children with ADHD. The reinforcement contrast was significant: Response variability decreased in the reinforcement conditions compared to feedback-only and the reinforcement contrast interacted significantly with group. Figure 3 illustrates this interaction: Children with ADHD responded more variably than controls in the feedback-only condition ($p=0.008$), while this group difference was smaller and only marginally significant in the collapsed reinforcement trials ($p=0.058$). The valence contrast was not significant and this contrast did not interact with group. Variability in time production was larger in the low versus high reinforcement trials as indicated by the magnitude contrast, although this effect was only of marginal significance. No significant interaction between the magnitude contrast and group was found.

The variability in time production did not change over time; there was no significant effect of block ($p=0.64$). Groups were not differentiated by the factor block ($p=0.84$).

Psychophysiology

HR Following Feedback HR was faster following positive than negative feedback, $F_{1,52}=25.3$, $p<0.001$, $\eta_p^2=0.33$. The difference between positive and negative feedback did not interact significantly with group ($p=0.87$), nor did feedback significantly interact with group and one of the reinforcement condition contrasts (reinforcement, $p=0.48$; valence $p=0.39$; magnitude $p=0.12$). Therefore, the HR responses to positive and negative feedback were collapsed in the analyses described below.

Table 2 indicates that the HR response (collapsed over positive and negative feedback) did not differ between children with ADHD and controls. However, there was a interaction between sequential IBI (IBI0, IBI+1 and IBI+2) and group (not presented in Table 2), although this just escaped conventional levels of significance, $F_{2,50}=2.5$,

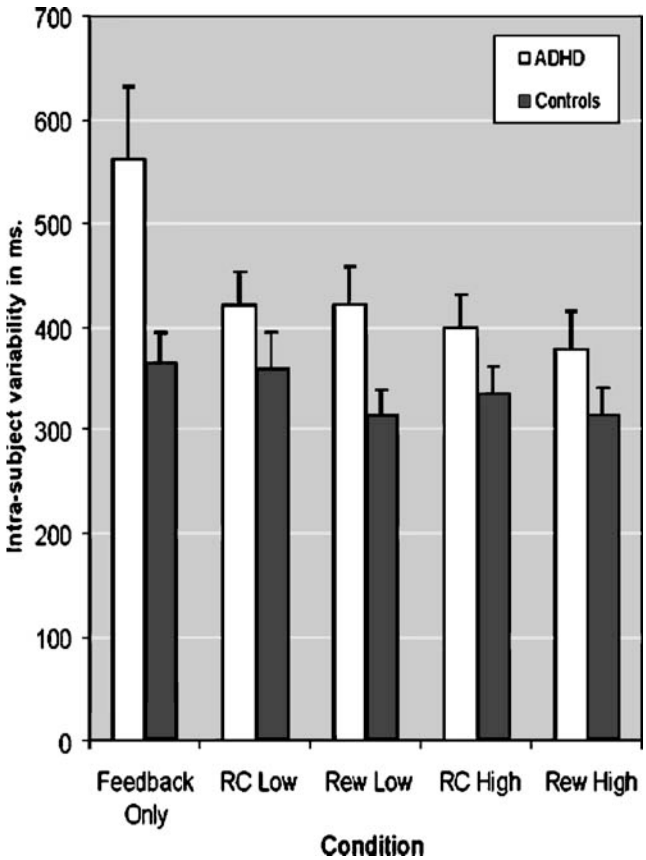

Fig. 3 Timing stability expressed in terms of the intrasubject-variability consecutive variability (and standard errors) of children with ADHD and normal controls in the reinforced time-production task. *RC* Response Cost; *Rew* Reward. The figure illustrates the group difference in timing stability and the interaction between group and the reinforcement contrast (feedback-only versus reinforcement conditions)

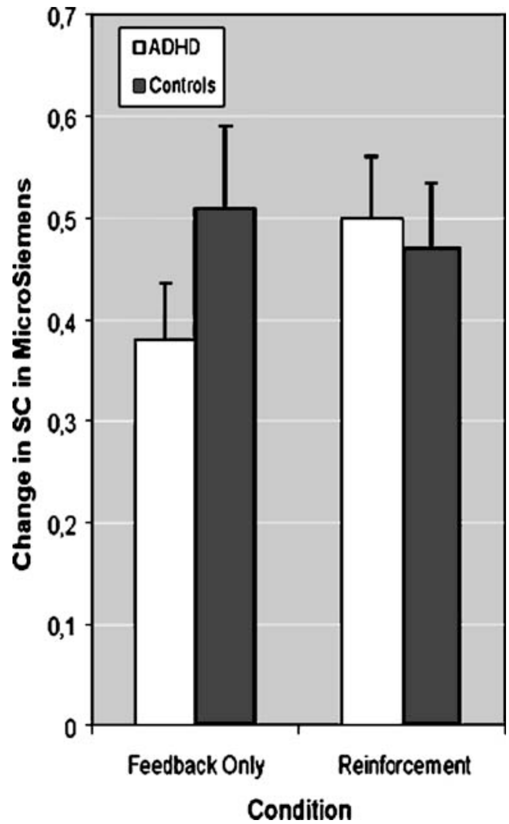

Fig. 4 Amplitude of skin conductance responses to feedback (and standard errors) in the reinforced time-production task for children with ADHD and normal controls for a 4000 ms interval following feedback. Data is baseline corrected by the skin conductance at time of the feedback

$p=0.08$, $\eta_p^2=0.05$. This interaction demonstrates that HR of children with ADHD accelerated immediately following feedback (IBI shortening from IBI0 to IBI+1 and IBI+2), in contrast with controls. HR of controls did not differ between IBI0 and IBI+1 and only accelerated (IBI shortened) between IBI+1 and IBI+2. There were no interactions between sequential IBI, group and the reinforcement condition contrasts (reinforcement, $p=0.73$, valence $p=0.25$, magnitude $p=0.93$).

Table 2 shows that HR accelerated in the (collapsed) reinforcement conditions compared to feedback-only as indicated by a significant effect of the reinforcement contrast. The interaction between group and the reinforcement contrast was not significant. HR in reward trials was faster (lower IBI) than in response cost trials, as indicated by a significant effect of the valence contrast. As shown in Table 2, no other significant effects were found.

SC Following Feedback Children with ADHD exhibited similar SC responses compared to controls. The reinforcement contrast was not significant, however, this contrast interacted significantly with group. Figure 4 illustrates that unlike controls ($p=0.56$), children with ADHD exhibited a smaller SC response in the feedback-only condition compared to the reinforcement conditions ($p<0.01$). As shown in Table 2, no other significant effects were found.

Discussion

This is the first study that separated reinforcement valence and magnitude, when investigating motivational modulation of task performance in children with ADHD. We investigated two aspects of motor timing: response tendency (either over- or underproduction of time as indicated by median response time) and response stability (intrasubject-variability). In line with previous reports, children with ADHD underestimated the time interval more severely than controls and showed more response variability (Leth-Steensen et al. 2000; Rubia et al. 2007; Toplak et al. 2006; Van Meel et al. 2005b). These findings emphasize that children with ADHD suffer from problems that relate to internal clock functioning as well as the organization of response output (e.g., Harrington et al. 1998). In contrast with our expectations, there were no indications that children with ADHD were abnormally affected by the valence or magnitude of reinforcement. Rather, the impact of reinforcement compared to feedback-only differed between children with ADHD and controls. The intrasubject-variability of responding decreased under conditions of reinforcement to a larger extent in children with ADHD than in controls. The tendency to respond prematurely, on the other hand, was unaffected by reinforcement in children with ADHD. In contrast, controls diminished this tendency in the reinforcement conditions compared to the feedback-only condition. Skin conductance responses increased to a larger extent in children with ADHD than in controls when feedback was coupled with reinforcement. No group differences in the HR response to reinforcement were revealed.

The finding that children with ADHD profited from reinforcement to a greater extent than controls when measuring response variability points to an abnormal sensitivity to reinforcement in ADHD. This result corroborates with earlier studies (see for review Luman et al. 2005). The valence hypothesis was not supported: children with ADHD did not show a differential response to reward versus response cost compared to controls. The findings do not converge with the dopamine model of Sagvolden et al. (2005), which suggests that children with ADHD suffer from a faster decay of reward than controls. The preference for a small immediate over a larger delayed reward in children with ADHD (Rapport et al. 1986; Sonuga-Barke et al. 1992) may be more related to delay aversion (APA 1994; Sonuga-Barke 2002) than to an abnormal sensitivity to reward. This is confirmed by Antrop et al. (2006), who reported no group differences in reward preference when children were visually stimulated during the waiting period, suggesting that visual stimulation altered their subjective experience of delay. The findings of a greater sensitivity to response cost in children with ADHD compared to controls (e.g., Carlson et al. 2000) were neither supported by our study, nor by others (e.g., Oosterlaan and Sergeant 1998). Clearly, this issue needs further investigation. In addition, the magnitude hypothesis was not supported. Our findings could not be explained by an elevated reward threshold in children with ADHD (Haenlein and Caul 1987). Instead, in the current study, a small amount of reinforcement already motivated children to perform well in terms of the variability of time productions.

Both ADHD and control children exhibited a tendency to press the response button too early in the feedback-only condition (median response < 1000 ms), suggesting that their internal clock ran too fast. A fast internal clock has been reported in an earlier study in ADHD using the same task (Van Meel et al. 2005b) and such a problem may be related to problems with impulsivity or delay aversion in ADHD (Barkley 1997; Sonuga-Barke 2002). Controls diminished this tendency when faced with reinforcement and we speculate that control children were motivated by reinforcement to perform adequately. Children with ADHD, in contrast, showed a diminished sensitivity to reinforcement by responding prematurely irrespective of the reinforcement condition. Premature responding in ADHD may reflect a deficiency that is not ameliorable by reinforcement. Similarly, premature responses as measured by the inability to withhold responses in an inhibition task have been found insensitive to manipulations of motivation (Crone et al. 2003; Iaboni et al. 1995; Oosterlaan and Sergeant 1998).

When looking at the stability of time production in terms of the intrasubject-variability, children with ADHD responded less variably when faced with reinforcement compared to feedback-only, almost to a level comparable with controls. Highly variable responses seem characteristic for children with ADHD (Leth-Steensen et al. 2000; Rubia et al. 2007; Van Meel et al. 2005b), however, this is the first study to show that this response style is sensitive to motivational manipulations. The absence of a group by magnitude interaction, suggest that the prospect of small gains or losses already motivated children with ADHD to respond less variably. Because the variability of time productions in the ADHD group did not change over time, we speculate that there was no decay in the impact of reinforcement on performance. Van Meel et al. (2005b) did not find an interaction between reinforcement condition and group for response variability when studying the individual standard deviation (*SD*) of responding. In that study children with ADHD more severely underestimated the interval than controls. Possibly, trial-to-trial variability may have been a more accurate measure of intrasubject-variability than *SD*, since it is less sensitive to the mean response (Russell et al. 2006).

The impact of reinforcement on timing variability in the current study converges with evidence of structural and functional brain imaging studies in ADHD. Timing and timing variability problems in ADHD have been associated with the prefrontal cortex, the cerebellum and the basal ganglia (Casey et al. 2007; Rubia et al. 2007; Toplak et al. 2006). A recent paper gathered evidence that reinforcement has a major impact on motor functions, an effect which is mediated by the basal ganglia (e.g., Haber 2003). Future studies, therefore, may focus on the impact of reinforcement on response variability in children with ADHD using brain imaging techniques.

Psychophysiology

No group differences in the HR response to reinforcement were found, except for a marginal significant group by IBI interaction. In line with previous findings (e.g., Crone et al. 2003), children with ADHD exhibited immediate HR acceleration following feedback, while controls showed a delay in acceleration. HR changes following feedback have been suggested to be related to performance monitoring processes that are responsible for the allocation of attention (Jennings and Van der Molen 2002). We speculate that an abnormal HR response in children with ADHD points to a dysfunction in the allocation of attention, that may be necessary to decrease their response variability. In contrast with our expectations, the interaction between group and the reinforcement contrast on performance was not accompanied by a group difference in the HR response to reinforcement. This may relate to the age of our participants: Crone et al. (2004) demonstrated that the monitoring system that is related to HR reactivity (described above) is less active in children as compared to adults.

In terms of SC responses, children with ADHD and controls differed in their reactivity to reinforcement compared to feedback-only. In the ADHD group SC responses increased in the reinforcement conditions, unlike the SC response of controls. SC responses have been associated with affective processing of stimuli, such as discriminating between good and bad outcomes (Damasio 1996). O'Connell et al. (2004) reported smaller SC responses to errors in children with ADHD than in controls. Since children with ADHD demonstrated intact post-error response slowing (an indicator of error detection) in that study, reduced SC responses were interpreted as evidence for a decreased awareness of the significance of errors. In our study, increased SC responses in children with ADHD in the reinforcement conditions may be taken as evidence for an increased awareness of the significance of feedback, which may be associated with the decrease in the variability of responses.

Limitations

An issue in the current study is the presence of comorbid ODD and CD symptoms in the ADHD sample, as specified by scores on the DISC-IV and DBD rating scale. There is substantial overlap between ADHD and anti-social symptoms (Angold et al. 1999), and studies have found an abnormal sensitivity to response cost in ODD/CD measured behaviorally and psychophysiologically (Newman et al. 1997). We examined the contribution of the aggregated parent and teacher reported ODD and CD symptoms as measured by the DBD rating scale to the relationship between reinforcement and all dependent measures. No significant correlations were revealed, except for the SC analyses. The difference in SC between the feedback-only and (collapsed) reinforcement correlated modestly with teacher rated ODD symptoms (r= 0.36). Another limitation is a clear baseline condition in which no feedback was provided. This would have enabled investigation of the impact of feedback (positive, negative) on motivation. Finally, a larger sample size would have increased the power to detect differences between ADHD subtypes, age as well as gender groups.

Conclusions

The current findings indicate that children with ADHD are characterized by a tendency to underestimate time and to show more variability in time production than controls. No evidence was revealed for a differential response to reward and response cost in children with ADHD compared to controls, and no evidence was found for a smaller threshold for experiencing incentives in children with ADHD compared to controls. Rather, the variability in time production decreased to a larger extent in children with ADHD than controls when children were faced with reinforcement compared to feedback-only. This suggests that children with ADHD suffer from motivational problems when performance is not reinforced. The tendency to underestimate time in the ADHD group was less sensitive to our motivational manipulations, which may suggest that these problems cannot be remediated by contingencies. The decreased variability in responding in ADHD in the reinforcement conditions was accompanied by an increase in SC responses to feedback. Possibly, children with ADHD suffered from a diminished awareness of the significance of feedback when reinforcement was not available. There were no group differences in the HR response to reinforcement.

The findings have some important implications. Variability in motor output may translate into diverse domains of motor functioning, such as the planning of simple and more complex motor behavior (Toplak et al. 2006). Children with ADHD have been found to show problems with motor skills, such as tying shoes, printing letters or playing sports (Karatekin et al. 2003) and there is a large overlap between ADHD and motor coordination disorders (Kadesjö and Gillberg 1999). Although the present experimental findings suggest that problems related to response variability in ADHD may be modulated by using appropriate reinforcement, clinical studies need to be undertaken to see how these findings are applicable in the clinical setting. The observed normalization of psychophysiological responses to feedback when reinforcement is at stake may suggest that children with ADHD suffer from problems with feedback processing. Such findings call for interventions that focus on the role of reinforcement in enhancing the impact of environmental feedback in children with ADHD. Furthermore, if both reward and response cost are effective in decreasing the variability of motor responses in children with ADHD, reinforcing positive behavior may be as effective as punishing unwanted behavior.

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