

Decision-making in ADHD: sensitive to frequency but blind to the magnitude of penalty?

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Background: Decision-making and reinforcement sensitivity were investigated in 23 children with ADHD and 20 healthy controls using a gambling paradigm. **Methods:** Children were required to choose between three alternatives that carried (A) small rewards and small penalties (advantageous), (B) large rewards and increasing penalties and (C) small rewards and increasing penalties (both disadvantageous). Penalties increased either in frequency or magnitude in two independent conditions. Heart rate (HR) and skin conductance (SC) were measured to examine whether impaired decision-making was accompanied by autonomic abnormalities. **Results:** Children with ADHD showed a maladaptive response style compared to controls by demonstrating a smaller preference for the advantageous alternative, when penalties increased in magnitude. When penalties increased in frequency, children with ADHD performed like controls. Group differences in decision-making attenuated after the task was administered twice. Compared to controls, performance of children with ADHD in the magnitude condition was accompanied by increased HR acceleration following reward. In this condition, the post-selection SC of children with ADHD was larger for advantageous than for disadvantageous alternatives, in contrast to controls who showed an opposite SC pattern. **Conclusions:** The current findings suggest that during decision-making, children with ADHD may be sensitive to the frequency but blind to the magnitude of penalty. **Keywords:** ADHD, decision-making, feedback, penalty, reward.

Attention-deficit/hyperactivity disorder (ADHD) is a severe developmental behaviour disorder, which is accompanied by attention difficulties, disinhibition and impaired motor-control (APA, 1994). One of the key issues in ADHD is an abnormal sensitivity to reinforcement (Luman, Oosterlaan, & Sergeant, 2005; Nigg, 2005; Sonuga-Barke, 2002). Children with ADHD have been found to show an increased sensitivity to instances of (immediate) gratification (see Luman et al., 2005 for review). Otherwise, children with ADHD have been found to require more response cost than controls in order to perform accurately (Slusarek, Velling, Bunk, & Eggers, 2001), suggesting that children with ADHD suffer from a diminished sensitivity to negative outcomes. A diminished sensitivity to the negative outcome of behaviour and a craving for immediate reward in children with ADHD become apparent in the increased risk for substance abuse (e.g., alcohol, drugs) and pathological gambling (Biederman et al., 2006).

Several theoretical models of ADHD have incorporated an abnormal sensitivity to reinforcement (see Luman et al., 2005), although the models differ greatly in detail. According to the dual-pathway model (Sonuga-Barke, 2002), children with ADHD show both cognitive and motivational problems.

According to this model, as a result of a distortions in the cortico-ventral-striatal pathway, children with ADHD are reward-delay averse and are therefore less sensitive to rewards that are not delivered immediately. Several other theoretical paradigms (e.g., Patterson & Newman, 1993; Quay, 1997) suggest that children with ADHD suffer from a smaller sensitivity to punishment (or non-reward) and are therefore focused on instances of reward. This would be the result of a dysregulation of sympathetic nervous system activity, which has been demonstrated in studies where children with ADHD display smaller skin conductance (SC) responses to penalty than controls (Firestone & Douglas, 1975; Iaboni, Douglas, & Ditto, 1997).

An abnormal sensitivity to reinforcement may influence cognitive processes such as decision-making through unconscious 'somatic marker signals' that arise from bioregulatory processes (Damasio, 1996). Somatic markers develop through the coupling of positive or negative affective experiences with a stimulus, which may gradually result in the acquisition of somatic responses when the stimulus is presented. These responses can automatically be re-activated upon the presentation of a stimulus that resembles the original stimuli and therefore, the somatic markers differentiate between 'right' and 'wrong' before consciously *knowing* this. Evidence for this hypothesis comes from the Iowa

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Gambling Task (IGT), which simulates real-life decision-making (Bechara et al., 1994). In this task, players are instructed to choose between four decks of cards. Turning a card results in immediate reward, which is either high (deck A or B) or low (deck C or D). In addition to reward, there is an unpredictable penalty, which is larger in decks A and B compared to decks C and D. In the long run, playing from decks A and B is disadvantageous, while playing from decks C and D is advantageous. Healthy subjects were found to develop SC responses during the course of the task before selecting a card from the disadvantageous decks and choose more cards from the advantageous decks, while not aware (Bechara et al., 1994).

If ADHD is associated with a smaller sensitivity to negative outcomes and larger sensitivity to reward, they would show a smaller preference for the advantageous alternatives as compared to healthy controls. Ernst et al. (2003) reported on intact performance on the IGT in adults with ADHD, while Toplak, Jain, and Tannock (2005) demonstrated that adolescents with ADHD showed more disadvantageous choices than controls, especially when the frequency of penalty was low compared to high. There is some evidence of impaired performance in children with ADHD using the IGT; however, this may be true for a sub-group of children with ADHD without internalizing symptoms (Garon, Moore, & Waschbusch, 2006; Geurts, van der Oord, & Crone, 2006).

The current study investigates decision-making in ADHD as well as the autonomic response to reinforcement. Measures such as heart rate (HR) and SC responses to reinforcement are used to detect whether impaired decision-making may be explained by dysfunction activity of the autonomic system. An adapted version of the IGT was developed that contained an advantageous alternative carrying small rewards and small penalties, and two disadvantageous alternatives that carried either large rewards and large penalties or small rewards and large penalties. This alternative version was developed for three reasons. Firstly, the original four-choice IGT may have been too difficult for children (Geurts et al., 2006), while the two-choice IGT (Kerr & Zelazo, 2004), in our opinion, did not reflect real-life decision-making since rejecting one alternative automatically led to choosing the other. Secondly, since humans may be more sensitive to detecting changes in the frequency than changes in the magnitude of penalty (Lin, Chiu, Lee, & Hsieh, 2007), it is important to separate these two aspects when investigating sensitivity to penalty. In the original IGT, reinforcement magnitude and frequency were manipulated in a single design, which did not allow these two aspects to be assessed in isolation. In our task, penalty increased either in frequency or in magnitude in the disadvantageous alternatives in two *separate* conditions. Thirdly, in the original task,

the amount and frequency of the contingencies remained stable over the course of the task. In our adapted version, penalty increased over the course of the task to investigate whether (maladaptive) choice behaviour in children with ADHD will 'normalize' when the contingencies are larger or allocated more frequently.

If children with ADHD exhibit a diminished sensitivity to aversive outcomes and an enhanced preference for immediate gratification, they should show a smaller preference for the advantageous rather than disadvantageous alternatives compared to controls, and prefer the alternative carrying large rewards. Group differences should be smallest in the condition where the frequency (compared to the magnitude) of penalty increased, similar to adolescents with ADHD (Toplak et al., 2005). In line with previous findings, abnormal choice behaviour in the ADHD group was expected to be associated with *smaller* psychophysiological responses to penalty and reward (e.g., Iaboni et al., 1997), indicating dysfunctional somatic markers (Damasio, 1996).

Methods

Participants and selection procedure

Twenty-three children with ADHD (M 9.6 years; 5 girls) and 20 normal control children (M 9.1 years; 5 girls), all aged 7 to 12, participated in this study. Background information on the participants is presented in Table 1. Children were included when they met the following criteria: (a) for the control group absence of any psychiatric disorder and for the ADHD group no diagnosis other

Table 1 Means, standard deviations, and pair-wise group comparisons for age, IQ and rating scale scores

| Measure | Group | | | | <i>F</i> (<i>df</i> 1,41) |
|-------------------------------|--------------------------|-----------|-------------------------------------|-----------|-------------------------------|
| | ADHD (<i>n</i> = 23) | | Normal controls (<i>n</i> = 20) | | |
| | <i>M</i> | <i>SD</i> | <i>M</i> | <i>SD</i> | |
| Age in months | 115.9 | 17.0 | 113.2 | 16.5 | .3 |
| IQ | 98.9 | 11.3 | 114.7 | 14.3 | 15.3** |
| DBD parent | | | | | |
| Inattention | 16.4 ^a | 4.2 | 2.6 | 2.1 | 175.9** |
| Hyperactivity/ Impulsivity | 18.1 ^a | 4.2 | 2.4 | 2.3 | 227.1** |
| ODD | 9.3 | 4.8 | .2 | .4 | 71.8** |
| CD | 2.7 | 2.7 | 1.3 | 1.5 | 4.3* |
| DBD teacher | | | | | |
| Inattention | 13.0 ^a | 5.4 | 3.6 | 4.5 | 37.4** |
| Hyperactivity/ Impulsivity | 14.6 ^a | 6.1 | 2.1 | 3.2 | 68.2** |
| ODD | 6.9 | 4.7 | 1.4 | 2.6 | 21.5** |
| CD | 2.0 | 2.2 | .4 | 1.1 | 8.1** |

Note: ADHD = attention deficit hyperactivity disorder; CD = conduct disorder; DBD = Disruptive Behavior Disorder rating scale; ODD = oppositional defiant disorder.

^aClinical score (>95th percentile of this subscale score).

* $p < .05$; ** $p < .01$.

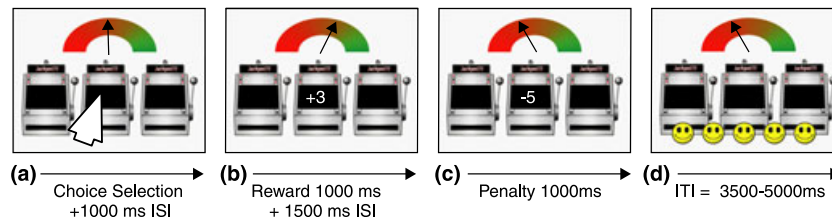


Figure 1 Time course of a jackpot trial. (a) Children had to press the mouse button to select an alternative. A thousand ms later, (b) reward feedback appeared on the screen for 1000 ms in green ink. Another 1500 ms later, (c) when applicable, penalty feedback appeared on the screen for 1000 ms in red ink. (d) During the inter-trial interval of 3500–5000 ms, five ‘smileys’ disappeared one by one from the screen to indicate when the next trial started

than ADHD, oppositional defiant disorder (ODD) or conduct disorder (CD); (b) IQ score >80; (c) absence of any neurological disorders, learning disabilities, sensory or motor impairment; (d) not taking medication except for methylphenidate. All children who were on methylphenidate discontinued use at least 24 hours before testing.

Children in the ADHD group had a clinical ADHD diagnosis and were recruited through the parents’ association for children with developmental disorders. The assessment procedure consisted of two stages. First, parents were administered the Dutch version of the disruptive behaviour disorder section of the DSM-IV Diagnostic Interview Scale for Children (DISC-IV; Schaffer et al., 2000), to confirm the diagnosis of ADHD. Fifteen children met the ADHD combined type criteria, 5 children met criteria for ADHD inattentive type and 3 children met criteria for ADHD hyperactive/impulsive type. Ten children fulfilled criteria for an additional diagnosis of ODD; one other child was comorbid for CD. Second, to ensure symptom pervasiveness, the Disruptive Behavior Disorder rating scale (DBD; Pelham, Evans, Gnagy, & Greenslade, 1992) was administered to both the parent(s) and teacher of the child. Children had to score above the clinical cut-off (>95th percentile) on either the Inattention or Hyperactivity/Impulsivity scale of both parent and teacher rating scales. Control children were recruited through local elementary schools and were included when they scored in the normal range (<90th percentile) on all scales of the parent and teacher DBD.

The IQ score of each child was estimated by four subtests (Picture Arrangement, Arithmetic, Block Design, and Vocabulary) of the Wechsler Intelligence Scale for Children (WISC-III). These four subtests have been demonstrated to correlate between .93 and .95 with Full Scale IQ (Groth-Marnat, 1997). IQ scores of children with ADHD who participated in this study were significantly lower than those of controls (see Table 1). Correlation analysis revealed no significant relation between IQ and performance on the gambling task (preference for alternative A), either for period 1 ($\rho = .22$, $p = .15$) or period 2 ($\rho = .18$, $p = .25$).

Materials

Gambling task. Children were shown three alternatives presented as jackpots. The advantageous alternative A carried small rewards (1, 2 or 3 cents) on every trial and small penalties (–2 cents) in one-third of the trials (see Appendix A). The disadvantageous alternative

B carried large rewards (3, 4 or 5 cents) on every trial and large penalties (–8 cents in one-third of the trials), and the disadvantageous alternative C carried small rewards (1, 2, or 3 cents) on every trial and large penalties (–8 cents in one-third of the trials). Children performed the task twice: in a *magnitude* and a *frequency* condition, where the penalty in the disadvantageous alternatives increased either in magnitude (6 cents every 9 trials) or in frequency (6 cents every 9 trials). Half of the children of each group were presented with the magnitude condition first and the other half were presented with the frequency condition first.

Children had to choose a jackpot (10 by 5 cm) by clicking on it (see Figure 1). The position of the three alternatives on the screen (left, middle, right) was counterbalanced between subjects. A digital scale (range –100 to +100) monitored the amount of money obtained. After 1000 ms, the reward appeared for 1000 ms on the display of the chosen jackpot, printed in green. Fifteen hundred ms after the reward was removed, if applicable, the penalty appeared for 1000 ms printed in red (otherwise, the display remained black). The inter-trial interval varied between 3500 and 5000 ms. During this interval, pressing the mouse was ineffective and five ‘smileys’ disappeared one by one from the screen to indicate when the next choice could be made. Both conditions contained 180 trials.

Procedure

All parents completed^a written informed consent prior to the study, which was approved by the local ethical committee. Children were told that they were in a theme park in which they played ‘Jackpot’. They had to win as much as possible by choosing between the alternatives. In both conditions, winning over 50 cents was required to receive a gift. After trial 90, the task ended automatically when children chose the same alternative 20 times in a row (so each child played a minimum of 110 trials) to prevent the task from becoming too boring. The remaining trials (to trial 180) were scored as if the child kept choosing this alternative. A break was scheduled between the conditions in which children were administered the WISC-III. At the end of the task, all children received a small present worth €3 irrespective of their performance.

Autonomic measures. 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, 1.6 inches 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. On every trial three inter-beat intervals (IBIs) were extracted contingent on the occurrence of reward; when applicable, a second identical window was extracted contingent on the occurrence of penalty. IBIs following reward and penalty were analysed separately. IBI-1 represented the interval preceding the reward and/or penalty; IBI0 represented the interval in which the reward and/or penalty was presented; IBI+1 just followed the reward and/or penalty. Since IBI-1 preceding rewards differed between the conditions ($p < .001$) and interacted significantly between group and condition ($p = .035$), the dependent measure was calculated as the difference between IBI+1 and IBI0. For IBI0, no group, condition, or group by condition effects were revealed that could invalidate the difference score (p -values $> .24$).

SC was measured with two 1cm^2 AgAg/Cl electrodes that 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 .5 volt was used to register SC and the signals were amplified and sampled at 10 Hz. Electrolyte gel (.05 molar NaCl) was applied to the two electrodes. Pre-selection SC was calculated as the largest difference between the minimum and maximum in SC level within the interval 2500 ms prior to the (advantageous and disadvantageous) choices, while post-selection SC was calculated as the difference between the minimum and the maximum within SC level in the interval 2500 ms following the (advantageous and disadvantageous) choices. Only positive reflections of the difference score (the maximum follows the minimum) were incorporated.

Statistical analyses

To explore choice behaviour over time (nominal data) in this task with three alternatives, an ANOVA such as used in most IGT studies could not be utilized, since the number of data points in each cell (number of choices for each alternative) greatly differed between the alternatives. Using multilevel nominal logistic regression, time functions of choice behaviour (probabilities of alternatives A, B and C) for ADHD children and controls could be created across the 180 trials of the two conditions (magnitude, frequency). The logistic functions $\log(\pi_{ib}/\pi_{ia})$ of alternative B (high reward and increasing penalty) and $\log(\pi_{ic}/\pi_{ia})$ of alternative C (low reward and increasing penalty) were expressed in a multiple logistic model using alternative A (advantageous alternative) as a baseline category (Agresti, 1996, pp. 205–211). The probability functions of the three alternatives (π_{ia} , π_{ib} and π_{ic}) summed to 1 for each of the 180 time points. Dummy variables were created for group and condition.

Multilevel models consist of two parts, a fixed part which describes the average time curve, and a random part which describes the between-subject and within-subject variance (Goldstein, 1995). Here, the intercept, group, condition, and time were used to describe the fixed part. The intercept refers to the initial level of the dependent variable. Time was modelled in either a

linear or quadratic parameter. The linear parameter describes the slope of the model at each time point. The quadratic factor describes the acceleration (or deceleration) of the slope. The model was estimated using MLwiN 2.02 (Rasbash, Browne, Healy, Cameron, & Charlton, 2005).

There were carry-over effects from the first to the second administration (period) of the task as indicated by a significant difference in the intercept (initial choice preference) of $\log(\pi_{ib}/\pi_{ia})$ in periods 1 and 2, $X^2_2 = 7.5$, $p < .05$. Initially, children were expected to choose randomly (probability of .33 for each alternative), which was observed in period 1. In period 2, however, the choice probability of the intercept for alternative B was .45, possibly due to a learning history of choice behaviour in period 1. Since group differences were detected in period 1 in the magnitude condition (see Results), the effect of group could not be disentangled from the crossover effect in the analysis of the frequency condition in period 2. Therefore, the frequency condition was excluded from the analyses in period 2. The two periods were analysed *separately* with the aim of answering two different questions. In period 1, decision-making problems in children with ADHD were investigated, while in period 2 the persistency of such problems was studied. In period 1, the parameters of four different groups were inserted into the model (ADHD magnitude, ADHD frequency, controls magnitude, control frequency); in period 2, the parameters of two groups were inserted (ADHD magnitude, controls magnitude).

HR responses to reward and HR responses to penalty were both submitted to a repeated measures (RM) ANOVA with group as within-subject factor and condition as between-subject factor. The responses were collapsed over the two periods: when period (instead of condition) was inserted as a within-subject factor in the RM ANOVAs no significant group by period interactions on the HR measures were revealed (all $p > .24$). Pre- and post-selection SCs were both submitted to a repeated measures ANOVA with condition and choice (advantageous, disadvantageous) as within-subject factors and group as between-subject factor. The responses were collapsed over the two periods: No group by period interactions were revealed (all $p > .46$), except for an almost marginal significant group by period interaction for post-selection SC ($p = .11$; no differences for the control group, while larger post-selection SC in period 1 than 2 for children with ADHD). Psychophysiological data of two children were missing owing to technical problems (one ADHD child and one control child). One other child in the ADHD group completed the frequency condition only and was left out of the psychophysiological analyses.

Results

Performance

First, the model is presented for both periods. Three parameters were tested: the intercept (initial choice preference), linear (linear change in choice preference at each time point) and quadratic parameter (acceleration of the change in choice preference), the

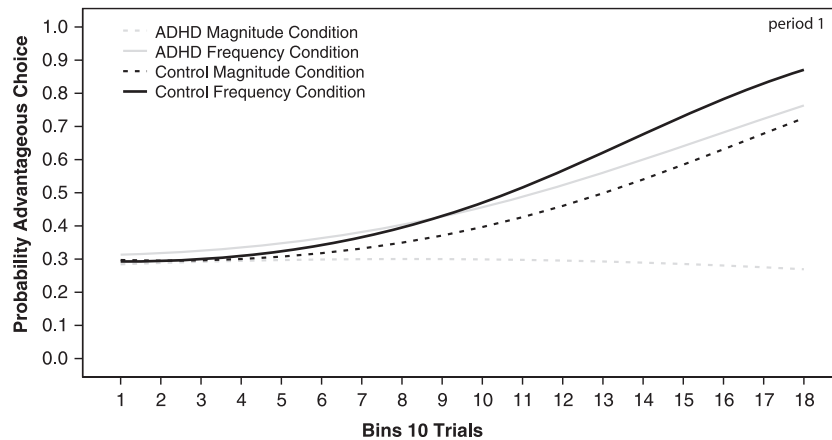


Figure 2 Choice probabilities over time (trials 1–180) for the advantageous alternative A (low reward, low penalty) for children with attention-deficit/hyperactivity disorder (ADHD) and normal controls (NC) in period 1. The slopes are described by quadratic trends of a multilevel nominal logistic regression model with random error terms set at 0

highest trend being the most informative. Second, the group comparisons of the joint effects of these three parameters (referred to as slope) are presented. To guard against type-1 errors, post-hoc analyses of individual parameters were only performed when significant differences between the slopes were revealed.

Decision-making in period 1. Choice behaviour was best described by the quadratic trend, joint $X^2_8 = 110.1$, $p < .001$, demonstrating that children increased their preference for the advantageous alternative (A) (see Figure 2; see Appendix C for the real data), while decreasing their preference for the disadvantageous alternatives (B and C). This negative quadratic trend (see Appendix B) indicated that the decrease in preference for the disadvantageous alternatives became larger over time. There was no difference in the decrease in preference for alternative B and C, as indicated by a non-significant difference between $\log(\pi_{ib}/\pi_{ia})$ and $\log(\pi_{ic}/\pi_{ia})$, joint $X^2_{12} < 21.0$, $p > .05$.

Figure 2 illustrates that children with ADHD and controls differed in their preference for alternative A, when the penalty (carried by the disadvantageous alternatives) increased in magnitude, but not when the penalty increased in frequency. The slopes of the ADHD group in the magnitude condition differed significantly from the three other groups, joint $X^2_{18} = 75.5$, $p < .001$. Post-hoc tests indicated that the quadratic trend, describing the behaviour of children with ADHD in the magnitude condition, differed from the quadratic trend of the control group in the magnitude condition ($\log(\pi_{ib}/\pi_{ia})$, $X^2_1 = 8.1$, $p < .01$; $\log(\pi_{ic}/\pi_{ia})$, $X^2_1 = 9.7$, $p < .01$), the control group in the frequency condition ($\log(\pi_{ib}/\pi_{ia})$, $X^2_1 = 11.1$, $p < .001$; $\log(\pi_{ic}/\pi_{ia})$, $X^2_1 = 12.5$, $p < .001$), and the ADHD group in the frequency condition ($\log(\pi_{ib}/\pi_{ia})$, $X^2_1 = 9.7$, $p < .01$; $\log(\pi_{ic}/\pi_{ia})$, $X^2_1 = 3.5$, $p < .10$). Figure 2 illustrates that children with ADHD in the magnitude condition did not

develop *any* preference for the advantageous alternative (A). In terms of decision-making as measured by the gambling task, children with ADHD seem sensitive to increases in frequency while being blind to increases in magnitude of the penalty.

Decision-making in period 2. Choice behaviour was best described by the quadratic trend, joint $X^2_4 = 15.3$, $p < .01$, which indicated that children increased their preference for the advantageous alternative (A) (see Figure 3; see Appendix C for the real data), and decreased their preference for the disadvantageous alternatives (B and C). The positive quadratic trend (see Appendix A) indicated that the decrease in preference for alternatives B and C became smaller over time.

There were significant differences between the slopes of the ADHD and control group, joint $X^2_1 = 19.9$, $p < .01$. Post-hoc analyses showed that this was due to a smaller linear trend for $\log(\pi_{ib}/\pi_{ia})$ in the ADHD compared to the control group, $X^2_1 = 3.8$, $p = .05$ (see Appendix B). Figure 3 illustrates that over the course of the task, the linear increase in the preference for alternative A was smaller for children with ADHD and controls. This group difference could be explained by the initial preference of controls for the disadvantageous alternative B, in contrast to children with ADHD who favoured the advantageous alternative (see Figure 3). The findings suggest that when the task was administered twice, children with ADHD were able to make adaptive decisions when penalty increased in magnitude.

HR response to reinforcement. A significant group effect was found for the HR responses to reward, $F_{1,38} = 5.9$, $p = .021$, $\eta_p^2 = .15$. Figure 4a illustrates that HR in response to reward accelerated in children with ADHD (lower IBI), while controls did not show any evidence for heart rate acceleration. There was an effect of condition, $F_{1,38} = 5.7$,

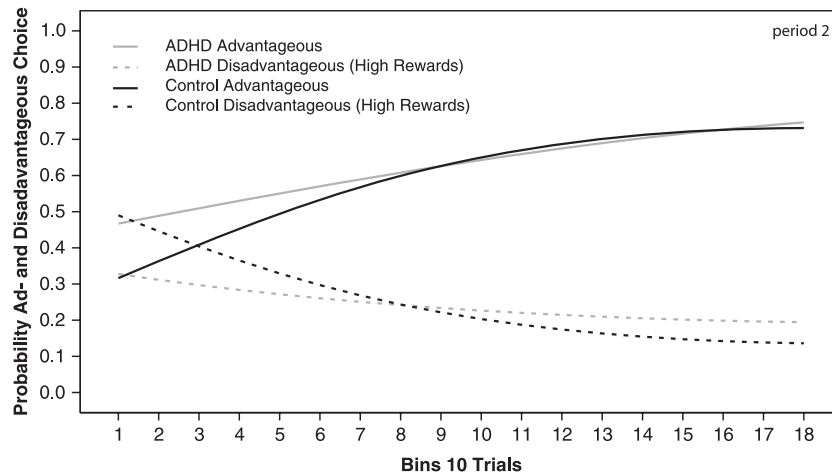


Figure 3 Choice probabilities over time (trials 1–180) for the advantageous alternative A (low reward, low penalty) and the disadvantageous alternative B (high reward, high penalty) for children with attention-deficit/hyperactivity disorder (ADHD) and normal controls (NC) in the magnitude condition of period 2. No group differences were revealed for the disadvantageous alternative C (low reward, high penalty). The slopes are described by quadratic trends of a multilevel nominal logistic regression model with random error terms set at 0

$p = .023$, $\eta_p^2 = .14$. The increase in HR following reward was more pronounced in the frequency compared to the magnitude condition. There was no significant interaction between group and condition ($p = .27$). No significant group effect was revealed for HR responses to penalty ($p = .50$). Again, there was an effect of condition: the increase in HR following penalty was more pronounced in the frequency compared to the magnitude condition, $F_{1,38} = 2.2$, $p = .083$, $\eta_p^2 = .09$, although the effect was of marginal significance. Group did not interact significantly with condition ($p = .65$).

SC anticipation and SC responses. Pre-selection SC revealed no significant effects of group, condition, period or choice and no significant interactions were obtained (all $p > .50$).

For post-selection SC, there was no effect of group ($p = .39$), choice ($p = .52$) or condition ($p = .63$). However, group interacted with condition, $F_{1,38} = 15.0$, $p < .001$, $\eta_p^2 = .31$. Follow-up analyses showed that in the magnitude condition the post-selection SC was larger for controls than children with ADHD, $p = .003$ (see Figure 5). In contrast, groups did not differ on post-selection SC in the frequency condition ($p = .51$). There was a 3-way interaction between group, condition and choice, $F_{1,38} = 6.5$, $p = .015$, $\eta_p^2 = .16$. Figure 5 illustrates this interaction: in the magnitude condition, SC responses of children with ADHD were smaller following disadvantageous compared to advantageous alternatives, while the SC responses of control children showed the opposite pattern (group by choice interaction, $p = .10$). This (marginal) significant group and choice interaction was not observed in the frequency condition ($p = .20$). No other significant interactions were revealed (all $p > .70$).

Discussion

Using a decision-making task, we investigated whether children with ADHD exhibited a diminished sensitivity to aversive outcomes and an enhanced preference for immediate gratification. The task contained an advantageous alternative (small rewards, small penalties) and two disadvantageous alternatives (large rewards, large penalties or small rewards, large penalties). In contrast to the original IGT, penalties carried by the disadvantageous alternatives slowly increased in frequency or magnitude in two separate conditions. This allowed tracking of whether (maladaptive) choice behaviour in children with ADHD changed as a result of an increase in penalty. All children increased their preference for the advantageous alternative over time, except for ADHD children in the magnitude condition, indicating that the task could discriminate between groups in terms of decision-making. In addition, autonomic responses to reinforcement were recorded, which has not been done earlier when studying decision-making in ADHD.

When the penalty increased in magnitude, children with ADHD exhibited a smaller sensitivity to aversive outcomes than controls, as indicated by the absence of a preference for the advantageous alternative. When the penalty increased in frequency, children with ADHD performed like controls. Contrary to prediction, children with ADHD did not display a specific preference for the disadvantageous alternative that carried large rewards. In the second period children with ADHD were able to make advantageous decisions, when the penalty increased in magnitude, hence indicating that they learned from past experience. Furthermore, children with ADHD showed abnormal autonomic responses to reinforcement. HR responses following reward

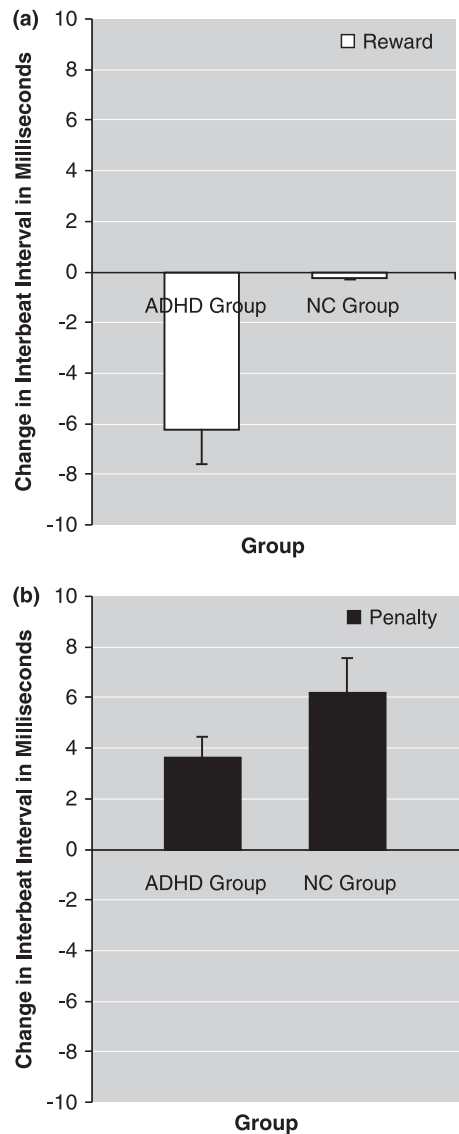


Figure 4 Heart rate (HR) response (difference between IBI+1 and IBI0) following reward (4a) and penalty (4b) for children with attention-deficit/hyperactivity disorder (ADHD) and normal controls (NC). Responses are averaged over trials, alternatives and conditions. Positive values indicate HR deceleration; negative values indicate HR acceleration

accelerated more strongly in children with ADHD than in controls. No evidence was obtained for group differences in skin conductance prior or following advantageous compared to disadvantageous alternatives, except for a three-way interaction between choice, condition and group as described below.

Although several studies (Luman et al., 2005) show evidence of an increased sensitivity to instances of immediate gratification in ADHD (Sonuga-Barke, 2002), this reward-driven choice behaviour was not observed in the current study. Rather, when making decisions, children with ADHD were blind to increases in penalty, specifically when the magnitude (and not the frequency) of the penalty carried by the disadvantageous alternatives in-

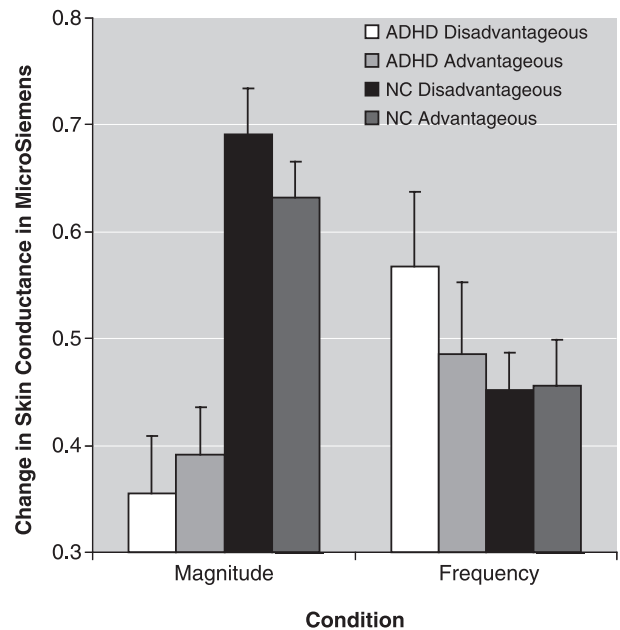


Figure 5 Post-selection skin conductance (SC) to disadvantageous choices (alternatives B and C) and advantageous choices (alternative A) for children with attention-deficit/hyperactivity disorder (ADHD) and normal controls (NC). Responses are averaged over trials

creased. These findings point at a smaller sensitivity to penalty in ADHD (e.g., Patterson & Newman, 1993). A greater sensitivity to frequency than magnitude concurs with findings in ADHD adolescents using the original IGT (Toplak et al., 2005) and findings in healthy adults (Lin et al., 2007). Since ADHD children were sensitive to penalty, like controls, when it was administered in a frequent manner, we speculate that the decay of penalty may have been faster in children with ADHD than in controls. A faster decay of reinforcement in ADHD has been suggested earlier with respect to reward processing, resulting from a dysfunction in dopamine transmission in the limbic system (Johansen, Aase, Meyer, & Sagvolden, 2002). Tripp and Alsop (1999) showed that children with ADHD, compared to controls, were extremely sensitive to the last reward received and less sensitive to the overall history of reward. Future studies should verify whether such findings could be replicated when studying the impact of penalty in ADHD.

In line with previous studies (see Luman et al., 2005), HR findings in the present study suggest abnormal autonomic responses to reward in children with ADHD. Children with ADHD displayed larger HR acceleration following reward than controls, while groups did not differ in HR response to penalty. Reward influences the sympathetic nervous system and increases HR (Fowles, 1988), suggesting that children with ADHD were more aroused than controls when receiving a reward in our study. The HR findings of children with ADHD contrasted with their choice behaviour: whereas HR responses to reward

were increased in children with ADHD compared to controls, they did not display an increased preference for immediate high rewards (Alternative B). Similarly, no group differences were observed in the HR response to penalty, while children with ADHD showed a larger preference for the disadvantageous alternatives than controls (in the magnitude condition). These findings contrast with the somatic marker theory (Damasio, 1996), which suggests that optimal bodily responses are a prerequisite for decision-making.

The findings in the present study indicate that children with ADHD are blind to future consequences of their decisions, despite the increasing penalties. This 'myopia' for future consequences was accompanied by an abnormal SC pattern. In the magnitude condition, children with ADHD displayed smaller SC responses than controls, indicating impaired sympathetic activity following their choices, which could have activated an alternative response strategy. In addition, SC responses of children with ADHD showed a trend towards being smaller following favourable as opposed to unfavourable outcomes, while SC responses of controls showed the opposite pattern, similarly to that of healthy adults (Bechara et al., 1994). The findings in this condition suggest an abnormality in ADHD in discriminating between 'good' and 'bad' in ADHD (Bechara et al., 1994). In line with these findings, Van Meel, Oosterlaan, Heslenfeld, and Sergeant (2005) demonstrated that, compared to controls, children with ADHD demonstrated poor discrimination between positive and negative outcomes on event-related potentials that have been associated with affective evaluation. In the frequency condition of the current study, the group and condition interaction was not significant: the SC responses of controls did not differ between the alternatives, which indicated that this condition may have been too easy (see Figure 2), resulting in a lack in arousal response to the disadvantageous alternatives.

This study has some limitations that are worth noting. The study is limited by statistical power, which was exaggerated by the crossover effects of period 1 onto period 2. Another issue is that groups differed in estimated IQ, although it is unlikely that this difference may have affected the present findings, since IQ did not relate to performance on the gambling task (see Method section). Finally, larger inter-stimulus intervals might have allowed inspection of SC responses in a larger interval than 2500 ms.

Conclusion

The findings point to difficulties for children with ADHD in behaviour regulation in the face of reinforcement. When making decisions, children with ADHD seem sensitive to the frequency of penalty, while being blind to increased magnitude of penalty.

This insensitivity to the aversive future outcomes of decisions in ADHD children when the frequency of penalty was small was accompanied by abnormal psychophysiological responses to reinforcement and following choice selection.

If replicated, the findings have important clinical implications, since feedback and reinforcement play a major role in behavioural interventions. If children with ADHD are unable to identify the significance of (large) losses as readily or as reliably as controls, warning children with ADHD regarding the negative consequences of their (undesirable) behaviour should be repeated often, since raising the intensity of these consequences may be ineffective.

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Appendix A

Gain and penalty carried by the alternatives in the frequency and magnitude condition

| Trial | Gain | | | Penalty | | |
|-------|-------------|---|---|---------------------|---------------------|---------|
| | Alternative | | | Magnitude Condition | Frequency Condition | |
| | A | B | C | A | B and C | B and C |
| 1 | 1 | 3 | 1 | | | |
| 2 | 3 | 5 | 3 | -2 | | -8 |
| 3 | 2 | 4 | 2 | | -8 | |
| 4 | 1 | 3 | 1 | | | -8 |
| 5 | 2 | 4 | 2 | -2 | -8 | |
| 6 | 3 | 5 | 3 | | | |
| 7 | 2 | 4 | 2 | -2 | | -8 |
| 8 | 3 | 3 | 3 | | -8 | |
| 9 | 1 | 5 | 1 | | | |
| 10 | 2 | 4 | 2 | | | |
| 11 | 1 | 5 | 1 | -2 | -14 | -8 |
| 12 | 3 | 3 | 3 | | | |
| 13 | 3 | 5 | 3 | | | -6 |
| 14 | 2 | 3 | 2 | | | |
| 15 | 1 | 4 | 1 | -2 | -8 | -8 |

| Trial | Gain | | | Penalty | | |
|-------|-------------|---|---|---------------------|---------|---------------------|
| | Alternative | | | Magnitude Condition | | Frequency Condition |
| | A | B | C | A | B and C | B and C |
| 16 | 3 | 5 | 3 | | | |
| 17 | 1 | 4 | 1 | | | -8 |
| 18 | 2 | 3 | 2 | -2 | -8 | -8 |
| 19 | 1 | 3 | 1 | -2 | | |
| 20 | 3 | 5 | 3 | | | |
| 21 | 2 | 4 | 2 | -2 | -14 | -6 |
| 22 | 1 | 3 | 1 | | | |
| 23 | 2 | 4 | 2 | | | -8 |
| 24 | 3 | 5 | 3 | | -8 | -8 |
| 25 | 2 | 4 | 2 | | | |
| 26 | 3 | 3 | 3 | | | -6 |
| 27 | 1 | 5 | 1 | -2 | -14 | -6 |
| 28 | 2 | 4 | 2 | -2 | | |
| 29 | 1 | 5 | 1 | | | -6 |
| 30 | 3 | 3 | 3 | -2 | -14 | -8 |
| 31 | 3 | 5 | 3 | | | |
| 32 | 2 | 3 | 2 | | | -8 |
| 33 | 1 | 4 | 1 | -2 | -14 | -6 |
| 34 | 3 | 5 | 3 | | | -8 |
| 35 | 1 | 4 | 1 | | -14 | |
| 36 | 2 | 3 | 2 | | | |

Note: Gains of all three alternatives, as well as penalty of alternative A are similar in the magnitude and frequency condition. Only 36 trials are presented.

Appendix B

Parameters of the Multilevel Nominal Regression Model for Period 1 and Period 2

| Period 1 | | | | |
|----------------------------|-----------------------|----------------|--------------------|--------------------------|
| Group | Log | Intercept (SE) | Linear effect (SE) | Quadratic effect (SE) |
| ADHD Magnitude (n = 11) | (π_{ib}/π_{ia}) | 0.37 (0.18) | -0.57 (0.88) | 0.73 (0.63) |
| | (π_{ic}/π_{ia}) | 0.09 (0.20) | -0.23 (0.91) | 0.17 (0.66) |
| ADHD Frequency (n = 12) | (π_{ib}/π_{ia}) | 0.13 (0.18) | 0.13 (0.88) | -2.13 (0.67) ** |
| | (π_{ic}/π_{ia}) | 0.06 (0.19) | -0.48 (0.91) | -1.65 (0.72) * |
| NC Magnitude (n = 11) | (π_{ib}/π_{ia}) | 0.32 (0.18) | 0.10 (0.91) | -1.90 (0.70) ** |
| | (π_{ic}/π_{ia}) | -0.04 (0.20) | 0.94 (0.96) | -2.97 (0.76) ** |
| NC Frequency (n = 9) | (π_{ib}/π_{ia}) | 0.37 (0.20) | -0.23 (1.03) | -2.83 (0.82) ** |
| | (π_{ic}/π_{ia}) | -0.04 (0.22) | 0.90 (1.07) | -3.69 (0.87) ** |
| Period 2 | | | | |
| Group | Log | Intercept (SE) | Linear effect (SE) | Quadratic effect (SE) |
| ADHD (n = 11) ¹ | (π_{ib}/π_{ia}) | -0.30 (0.27) | -1.79 (0.90)* | 0.74 (0.70) |
| | (π_{ic}/π_{ia}) | -0.78 (0.28) | -1.21 (1.06) | -0.61 (0.93) |
| NC (n = 9) | (π_{ib}/π_{ia}) | 0.57 (0.30) | -4.42 (1.00) | 2.16 (0.80)* |
| | (π_{ic}/π_{ia}) | -0.40 (0.31) | -2.89 (1.11) | 1.59 (0.91) ² |

Note: ADHD = Attention-deficit/ Hyperactivity Disorder; NC = Normal Controls; $\text{Log}(\pi_{ib}/\pi_{ia}) = \beta_{0b}$ (intercept) + β_{1b} time (linear trend) + β_{2b} time² (quadratic trend); $\text{Log}(\pi_{ic}/\pi_{ia}) = \beta_{0c} + \beta_{1c}$ time + β_{2c} time². Time = trial 1 to trial 180.

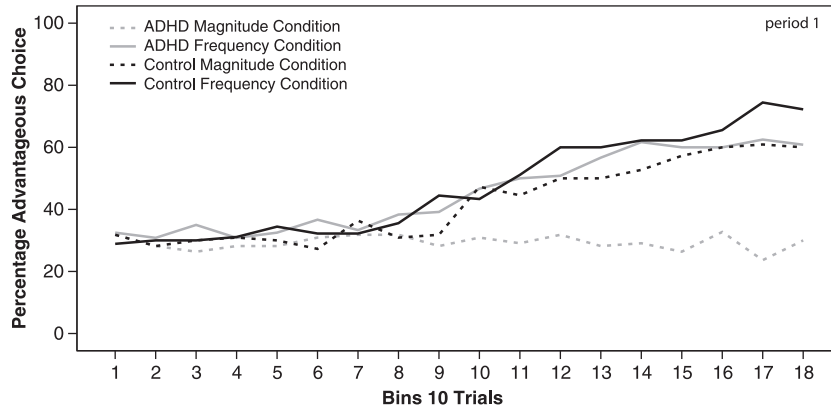
* $p < .05$, ** $p < .01$ for a two-sided test.

¹One child in the ADHD group did not complete the magnitude condition in period 2.

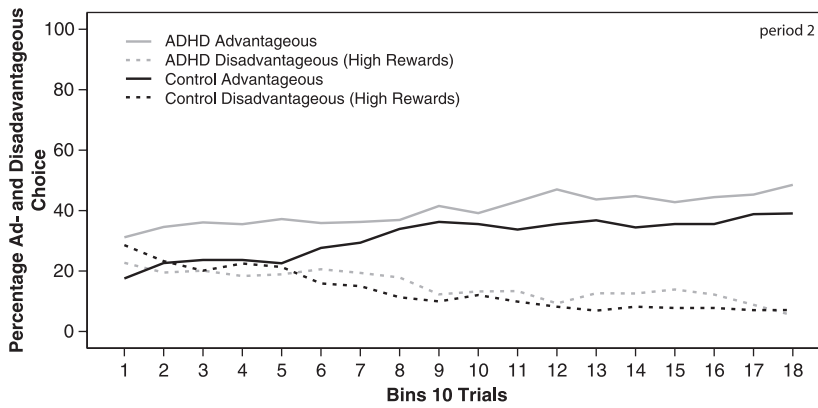
² $p < .10$

Appendix C

Real data of choice behaviour over time in Period 1 and Period 2



Note: Real data of choices in percentages for the advantageous alternative A (low reward, low penalty) over time (trial 1-180) for children with attention-deficit/ hyperactivity disorder (ADHD) and normal controls in period 1.



Note: Real data of choices in percentages for the advantageous alternative A (low reward, low penalty) and the disadvantageous choice B (high reward, high penalty) over time (trial 1-180) for children with attention-deficit/ hyperactivity disorder (ADHD) and normal controls in the magnitude condition in period 2.