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Hot and Cool Aspects of Cognitive Control in Children with ADHD: Decision-Making and Inhibition

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Abstract This study investigated hot and cool aspects of cognitive control in children with Attention Deficit Hyperactivity Disorder (ADHD). The study aimed to: (1) replicate the postulated response inhibition deficit of children with ADHD; (2) explore whether children with ADHD choose disadvantageously in a decision-making task and to explore the mechanisms underlying the expected response pattern; and (3) study whether performance on a combination of hot and cool executive control measures has predictive value for an ADHD diagnosis. The sample consisted of 20 children with ADHD and 22 normal developing children (NC, 8 to 12 years) matched on age, FSIQ, and gender. Two paradigms have been applied: (1) the stop signal paradigm, and (2) the adapted children's version of the IOWA Gambling task. There were no group differences for both paradigms. Both groups chose in a reward-oriented manner and seemed to develop the ability to take future consequences into account in making decisions. Moreover, feedback resulted in direct behavioral changes. Children with ADHD did not have a specific response inhibition deficit or a decision-making deficit.

Keywords Decision-making · Inhibition · ADHD · Dual-pathway · Prefrontal cortex

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Attention Deficit Hyperactivity Disorder (ADHD) is a childhood psychiatric condition characterized by symptoms of inattention, hyperactivity, and impulsivity (American Psychiatric Association [APA], 2000; Swanson et al., 1998). The dominant view on ADHD typifies ADHD as an executive dysfunction disorder (i.e., Barkley, 1997), because children with ADHD encounter difficulties with tasks regarding inhibition, working memory, and task-switching (e.g., Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, 2004; Sergeant, Geurts, & Oosterlaan, 2002; Pennington & Ozonoff, 1996). However, children with ADHD apparently react differently to reward and punishment than normally developing children (Luman, Oosterlaan, & Sergeant, 2005). These suboptimal reward processes cannot be explained by an executive dysfunction.

Dual-pathway model of ADHD

Both types of difficulties often observed in children with ADHD are incorporated by Sonuga-Barke (2003) in a dual-pathway model of ADHD. In this model two different neurodevelopmental pathways can lead to ADHD. The first pathway is the executive dysfunction pathway, which has been linked to deficits in response inhibition (Barkley, 1997; Solanto et al., 2001; Sonuga-Barke, 2003). The second is the motivational dysfunction pathway, which has been linked to suboptimal reward processes in children with ADHD (Sagvolden, Aase, Zeiner, & Berger, 1998).

The distinction of cognitive processes as proposed in the dual pathway model shows similarities with a neuropsychological subdivision of cognitive control (Zelazo, Muller, Frye, & Marcovitch, 2003). Zelazo and colleagues (2003) refer to the merely cognitive aspects of executive control as 'cool' cognitive control (the executive dysfunction pathway), which is the opposite from the more 'hot' or affective aspects of cognitive control (the motivational dysfunction pathway). Zelazo's division is also in line with a distinction proposed by Nigg (2000, 2001). Nigg distinguishes between behavioral inhibition and motivational inhibition. The first type of inhibition is related to response inhibition, while the second type is related to personality trait and motivation. Neuropsychological research has indicated that these different aspects of inhibition are related to different brain networks, which underlines the dual-pathway model (Sonuga-Barke, 2003).

'Cool' cognitive aspects

Patients with lesions in ventral lateral prefrontal cortex (VLatPFC) show difficulties on behavioral inhibition measures (e.g., Aron, Fletcher, Bullmore, Sahakian, & Robbins, 2003). A well-known paradigm and one of the most valid inhibitory control measures to study behavioral inhibition is the stop signal paradigm (e.g., Logan, 1994; Oosterlaan, Logan, & Sergeant, 1998). In this task participants are required to respond to a stimulus as fast as they can, however, sometimes they get a stop signal (a tone or a visual cue). If the stop signal is presented the participants have to inhibit their response. Several neuroimaging studies have shown that performance on variants of the stop signal task is partly mediated by the VLatPFC (e.g., Casey, Durston, & Fossella, 2001; Rubia et al., 1999; Rubia et al., 2001a, 2001b).

A large number of studies (e.g., see for overviews Lijffijt, Kenemans, Verbaten, & Van Engeland, 2005; Oosterlaan et al., 1998) used the stop signal paradigm to study the executive dysfunction pathway in children with ADHD. In general, these studies show that children with ADHD have a behavioral inhibition deficiency (e.g., Oosterlaan et al., 1998, Sergeant et al., 2002; but see Scheres, Oosterlaan, & Sergeant, 2001a, 2001b).

'Hot' cognitive aspects

Patients with ventral medial prefrontal cortex (VMedPFC) lesions have difficulties in anticipating future consequences (e.g., Bechara, Damasio, Damasio, & Anderson, 1994; Bechara, Damasio, & Damasio, 2000; but see Manes et al., 2002). A well-known paradigm to study affective decision-making in adults is the gambling task (Bechara et al., 1994). This task simulates real life decisions by manipulating reward and punishment. Participants are presented with four decks of cards and on each trial they have to choose one card. They are told that all cards will yield some reward, but some will also yield a cost (e.g., punishment). The goal of the task is that participants need to maximize their winnings. The four decks differ in their overall gain and size of the immediate rewards. The design of the gambling task results in an initial tendency to select cards with immediate high gratification, but this tendency should be overridden when learning that the punishments in these decks are also very high. Patients with VMedPFC lesions opt for choices that yield high immediate gains in spite of higher future losses, while controls override this tendency during the course of the task (Bechara et al., 1994). This decision-making failure in patients with VMedPFC lesions is in line with neuroimaging findings, which show that motivational inhibition as measured with the gambling task is related to the VMedPFC (Breiter, Aharon, Kahneman, Dale, & Shizgal, 2001; Cohen, Heller, & Ranganath, 2005; Knutson, Fong, Bennett, Adams, & Hommer, 2003; Ursu & Carter, 2005).

Besides patients with VMedPFC, other impulsive clinical groups, such as psychopaths and substance abusers, also have a tendency to choose the decks that are in the long term disadvantageous (e.g., Blair, Colledge, & Mitchell, 2001; Petry, 2001a, 2001b; Rolls, Hornak, Wade, & McGrath, 1994). This has been interpreted as insensitivity to future consequences of a decision. However, these disadvantageous gambling choices can also be associated with 1) insensitivity to punishment; or 2) hypersensitivity to reward (see also Bechara, Dolan, & Hindes, 2002; Bechara, Tranel, & Damasio, 2000). Bechara and colleagues (2000) tested these explanations by applying an alternative gambling task with contingencies opposite to the original gambling task.

In this reversed gambling task, punishment was placed upfront while the reward was delayed. This implies that in this task two decks were associated with large punishments and incidentally large rewards (the advantageous decks), while two other decks resulted in low punishments and regularly small rewards (the disadvantageous decks). By choosing the advantageous decks the overall loss will be smaller in comparison with a choice for the disadvantageous decks. To test the hypothesis that patients with VMedPFC lesions are insensitive for future consequences, it was expected that they would choose the disadvantageous desks in the reversed task (Bechara et al., 2000). The hypothesis was confirmed, which implies that the VMedPFC is indeed essential for anticipating future consequences.

A decision-making paradigm, as the gambling task, has seldom been applied to children with ADHD. Ernst, Grant et al. (2003) examined the performance of adolescents (12 to 14 years of age) with externalizing disorders (e.g., ADHD with and without comorbid disorders) on a standard gambling task. It was shown that adolescents with ADHD performed more poorly than normally developing adolescents. However, in an ADHD adult study, they failed to replicate these findings (Ernst, Kimes et al., 2003). Hence, it is not clear how children with ADHD will perform on a gambling task.

Separating 'hot' cognitive aspects from 'cool' cognitive aspects

Bechara and colleagues (2000) argued that, although disinhibited individuals fail the gambling task, there is no relation between behavioral inhibition and decision-making. Crone, Vendel, and Van der Molen (2003) directly tested this hypothesis and confirmed that in three different age groups (young adults, 15–16-year-olds, and 12–14 year-olds) adequate decision-making was indeed related to a motivational inhibition measure, but not to a behavioral inhibition measure. The motivational disinhibited individuals failed on the standard version but not on the reversed version of the gambling task, which implies that they are reward sensitive rather than future insensitive. In contrast to patients with VMedPFC lesions, motivationally disinhibited individuals seem to be focusing on immediate gain (Crone et al., 2003).

Based on the hypothesis that ADHD children have a poorly regulated motivation pathway (Sonuga Barke, 2003), it is possible that ADHD children perform poorly on a gambling task in which immediate and future rewards need to be integrated. Furthermore, if children with ADHD do perform more disadvantageously, this can be due to an inability to anticipate future outcomes (Bechara et al., 2000) or a reward-focused response tendency (Crone et al., 2003). These hypotheses have been directly tested in the current study.

In a recent paper of Crone and colleagues (Crone, Bunge, Latenstein, & van der Molen, 2005), it was tested whether the performance of children on the decision-making task might be due to their inability to switch response set. This hypothesis was disconfirmed (see also Bechara et al., 2000; Blair et al., 2001 for similar results in adults), but it is of interest when studying decision-making in children with ADHD. Besides inhibitory control deficits other executive control dysfunctions such as task-switching deficits have often been observed in children with ADHD (e.g., see Barkley, 1997; Pennington & Ozonoff, 1996; Sergeant et al., 2002). Thus, when children with ADHD fail on a gambling task, one needs to exclude the possibility that this is due to an inability to switch response sets.

The above overview of the literature led us to three main research questions: 1) Do children with ADHD simultaneously encounter difficulties with behavioral inhibition and decision-making? Can we distinguish two different inhibitory dysfunctions or are they related to the same underlying cause?; 2) If children with ADHD have difficulties with decision-making is this due future insensitivity, reward sensitivity, or an inability to switch decks?; and 3) Does a combination of two different paradigms related to possible different developmental pathways result in valid group assignments?

Both the "cool" and "hot" aspects of cognitive control will be studied in children with ADHD and a control group of normally developing children on a stop signal task and a standard and reversed version of the gambling task. Our expectation is that children with ADHD will show deficits in inhibitory control on the stop signal task (Lijffijt et al., 2005; Oosterlaan et al., 1998). Based on the findings of Crone and colleagues (2003) and the motivational explanation of ADHD (e.g., Sonuga-Barke, 2003), we hypothesize that children with ADHD are especially sensitive to reward and will prefer the disadvantageous choices in the standard task. If this response tendency is due to a failure to anticipate future consequences, then we expect that ADHD children also perform disadvantageously on a reversed version of the gambling task. If however, children with ADHD are mainly reward-focused, then we expect them to choose the advantageous choices in the reversed task, because these are the choices associated with the largest rewards.

The relation between behavioral inhibition and motivational inhibition can be studied by applying a combination of the two different paradigms. Based on the findings of Crone and colleagues (2003), we expect that performance on the stop signal paradigm is unrelated to performance on the gambling task. By combining two measures, we expect to reach better discriminant validity in comparison to using one of both measures (Sonuga-Barke, 2003).

Method

Participants

Normally developing group (NC group)

The children were recruited from regular schools located throughout the Netherlands. Information about the study was send to 210 households; 48 parents filled out an informed consent and the Disruptive Behavior Disorder rating scale (DBD, Pelham, Gnagy, Greenslade, & Milich, 1992; Dutch translation: Oosterlaan, Scheres, Antrop, Roeyers, & Sergeant, 2000). The DBD contains four scales composed of the *DSM-IV* items for Attention Deficit/ Hyperactivity Disorder (ADHD) Inattentive subtype, ADHD Hyperactive/Impulsive subtype, Oppositional Defiant Disorder (ODD), and Conduct Disorder (CD). Children were included when the score on all of scales of the DBD as rated by the parent and teacher did not exceed the 75th percentile.

Eight of these 48 children were excluded from the study because of a developmental disorder (2 PDD-NOS, 3 Dyslexia, and 3 ADHD diagnoses). Ten children were excluded because they scored above the cut off of the DBD. Of the remaining 30 children, 22 children were chosen to match the ADHD group on gender and age. Finally, 22 normally developing children (18 boys and 4 girls) in the age range of 8 to 12 years ($M = 10.0$, $SD = 1.3$) participated.

ADHD group

Twenty-two children from clinics specialized in the care of children with ADHD were asked to participate in the current study. Twenty of these children in the age range of 8 to 12 years ($M = 9.9$, $SD = 1.1$) with a clinical diagnosis of ADHD (17 boys and 3 girls) were willing to participate. The clinical diagnoses were confirmed by administrating the disruptive behavior disorders (ADHD, ODD, CD) section of the *Diagnostic Interview Schedule for Children for DSM-IV, parent version* (DISC-IV; National Institute of Mental Health [NIMH], Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000; Dutch translation: Ferdinand, Van der Ende, & Mesman, 1998) by a trained clinical psychologist (second author). The DISC-IV is a structured diagnostic interview and is based on the *DSM-IV* (APA, 1994) and the ICD-10 (WHO, 1993). Adequate reliability and validity have been reported for precursors of the DISC-IV (Schwab-Stone et al., 1996). During the interview we reminded the parents to answer the DISC-IV questions while keeping the behaviour of their child in mind while he/she was off medication to ascertain that we received a valid description of the children's current functioning and symptoms when they were not on medication.

Using the DISC-IV, 4 children were diagnosed as the inattentive subtype, 1 as the hyperactive/impulsive subtype, and 15 as the combined subtype. Eleven of these children had comorbid ODD, and one had comorbid CD. Parents and teachers also rated the child on the DBD, however this was not used to select the children for the current study (see Table 1).

Four subtests of the *Dutch Revised Wechsler Intelligence Scale for Children* (WISC-R; Van Haasen et al., 1986) were administered to assess intelligence in all children. These tests were: Vocabulary, Arithmetic, Block Design, and Picture Arrangement. These four subtests correlate between $r = .93$ to $r = .95$ with Full Scale IQ (FSIQ; Groth-Marnat, 1997). All children had an estimated IQ above 80 as measured by this short version of the WISC-R.

Table 1 provides the gender, age, estimated FSIQs, and raw rating scale scores for the two groups and includes symptom counts on the DISC-IV for the ADHD group. Group differences for these measures were tested using an overall alpha level of .05. The two groups did not differ on age, $F(1,41) < 1$, $p = 0.91$, $\eta^2 = .00$, FSIQ, $F(1,40) < 1$, $p = .55$, $\eta^2 = .01$, and gender, χ^2 (1, $N = 42$) = .076, $p = 0.78$. This implies that the groups were successfully matched on these variables. Matching on gender is essential because boys and girls differ in their responses on the gambling task (Hooper, Luciana, Conklin, & Yarger, 2004; Overman, 2004). In general, findings for the rating scale scores support the behavioral distinctiveness of the groups. As expected, the parents and teachers of the children with ADHD reported more problems when compared to normal controls on all scales.

Table 1 Clinical characteristics of the ADHD and the comparison control groups

Measure	NC ($n = 22$)	ADHD ($n = 20$)
Gender (Boys/Girls)	18/4	17/3
Age	10.0 (1.3)	9.9 (1.1)
Estimated FSIQ	108.9 (16.2)	106.9 (15.4)
DBD parent		
Inattention	3.1 (2.7)	14.8 (5.1)
Hyperactivity/impulsivity	3.1 (2.7)	12.8 (5.5)
ODD	2.5 (2.5)	8.4 (4.3)
CD	0.2 (0.4)	1.9 (2.7)
DBD teacher		
Inattention	2.7 (4.0)	12.0 (5.0)
Hyperactivity/impulsivity	2.8 (5.0)	12.5 (6.0)
ODD	2.6 (3.8)	6.6 (5.3)
CD	0.3 (0.8)	1.7 (2.2)
DISC-IV		
ADHD inattentive	–	15.4 (2.6)
ADHD hyperactive	–	13.5 (3.9)
ODD symptoms	–	4.1 (1.9)
CD symptoms	–	0.7 (1.0)

Note. ADHD: Attention deficit hyperactivity disorder; CD: conduct disorder; DBD: disruptive behavior disorder scale raw scores; DISC-IV: diagnostic interview schedule for children symptom counts; NC: normal controls; ODD: oppositional defiant disorder.

Task and design

Gambling task

A developmentally appropriate analogue (e.g., Hungry Donkey task: Crone & Van der Molen, 2004) of the IOWA Card Gambling Task originally developed by Bechara et al. (1994) was used. Participants were presented four doors (A to D) on a computer screen. All doors were equal in size and appearance and below the doors sat a donkey. Participants were told that they had to make a choice for one of the doors by pressing button C, V, B, and N from a standard keyboard. Each choice could result in a gain or loss of apples. The goal of the task was to maximize the amount of apples. A horizontal half green/half red bar on the bottom of the screen presented the status of the gain. Green represented gains and red losses.

The participants were told that they may turn any door by pressing the corresponding buttons, and that they may switch doors at any time and as often as they liked. For each choice the amount of gain was indicated by the amount of presented apples and the amount of loss was indicated by the amount of crossed apples. The amount of wins and losses varied between choices, however, the schedule of wins and loss was unknown to the participant. After 200 trials the task ended.

In the current study two versions of win/loss schedules were presented, the standard gambling task and the reversed gambling task. Both versions were presented to all participants and the order was counterbalanced between participants.

Standard gambling task

In the standard task participants encountered only rewards the first two times they sampled from each door (see also Crone & Van der Molen, 2004). After these first samples, they continued to receive rewards on each trial, but also punishment on a proportion of the trials. Therefore, rewards were constant and punishments were unpredictable. The immediate rewards for choice A and B were higher than for choice C and D. However, the penalty (losses) was higher at the high paying choices (A and B) and lower in the low paying choices (C and D). Choice A and B were equivalent in terms of overall loss over the trials but differed in the frequency of the penalties. For choice A there were more frequent penalties but of a smaller magnitude than for choice B (one unpredicted punishment). Choice C and D were also equivalent in their overall loss. For Choice C the penalty was more frequent but smaller than for Choice D. Choice A and B were disadvantageous in the long run (leading to a net loss) while choice C and D were advantageous in the long run (leading to a net gain).

Reversed gambling task

In the reversed task participants encountered only punishments the first two times they sampled from each door. After these first samples, they continued to receive punishments on each trial, but also reward on a proportion of the trials. Therefore, punishments were constant and rewards were unpredictable. In the reversed task, the immediate punishment was higher for choice A and B than for choice C and D. However, the rewards were higher at the high punishment choices (A and B) and lower in the low punishment choices (C and D). Choice A and B were equivalent in terms of overall gain over the trials but differed in the frequency of the rewards. In choice A there were more frequent rewards but off a smaller magnitude than in choice B (one unpredicted reward). Choice C and D were also equivalent in their overall gain. For Choice C the reward was more frequent but smaller than for Choice D. In contrast to the standard task, Choice A and B were advantageous in the long run (leading to a net gain) while choice C and D were disadvantageous in the long run (leading to a net loss).

Behavioral inhibition task

The inhibition task combined two different paradigms: A Go/NoGo paradigm and a Stop Signal Paradigm. In the middle of the computer screen there was a small square as constant fixation point. On each trial a visual stimulus (duration 500 msec, inter-stimulus interval [ISI] ranged from 1700 to 1800 msec) appeared. These stimuli were yellow dogs presented randomly in one of eight locations around the fixation point. The task involved three types of trials: Go-trials, NoGo-trials, and Stop-trials. Participants were asked to respond when they saw a Go-trial, and not to respond when they saw a NoGo-trial. Furthermore, they were instructed to inhibit their response when the Go-trial was followed by a stop-signal. Note that a NoGo-trial was never associated with a response (i.e. selective inhibition), while in a Stop-trial the stimulus was associated with a response and this well-learned response should be inhibited (i.e. inhibition of a planned motor response). In the current study we will only focus on inhibition of a planned response, e.g. the 'response' on the Stop-trials.

The participants were instructed to press a response key with their index finger if the stimulus appeared at the upper left location (Go-trial) whereas participants had to refrain from responding if the stimulus appeared in another location (NoGo-trial). The task consisted of 264 Go-trials and 165 NoGo-trials. Thirty percent of the Go-trials (88 trials) will change color after a variable delay, instructing the participants to inhibit their response (Stop-trial). The change of color from the dog (from yellow to red) was called the stop signal. The stop signal was usually presented shortly after the yellow dog appeared, but could also be presented directly dependent on the participants' performance. The timing of the color change was dynamically adjusted and targeted at 50% correct inhibitions using a tracking algorithm. In the current study the initial delay between the Go-trial and the stop signal was set at 200 msec. If the participant succeeded in inhibiting his/her response, the delay was increased with 25 msec on the next Stop trial. If the participant did not succeed in inhibiting, the delay of the next Stop trial was decreased with 25 msec.

Four dependent measures were calculated. First, the individual mean reactions times (MRTs) of correct Go-trials were calculated after removal of RTs faster than 100 msec on a subject-by-subject basis for each level. Second, the standard deviation of the RT was calculated for each participant. Third, the percentage of errors was calculated for each individual. The percentage of errors is the sum of the number omission errors (the participant did not respond to a Go-trial) and commission errors (the participant responded to a NoGo-trial) divided by the number of trials. Fourth, the stop signal reaction time (SSRT) was calculated. The SSRT reflects the latency of the inhibitory process. This variable cannot be observed directly and had to be estimated. The procedure of estimating SSRT was based on a well-established theory, the horse-race model (Logan, 1994). The assumption in this theory is that there are two processes, the stop process and the go process. Depending on which response wins, the response is executed (go process wins) or not (stop process wins). By using the tracking mechanism (described above) it was established that on average the go and stop process finished at the same time. In this way, the finishing time of the go process became an estimate of the finishing time of the stop process (for details see Logan, Schachar, & Tannock, 1997). This finishing time was the fourth dependent measure (SSRT).

Procedure

After the parents filled out an informed consent form and the DBD, the participants were tested. To avoid possible problems of fatigue, each participant was tested twice on different days for approximately one hour. In the first test session the WISC-R and the gambling task or the behavioral inhibition task were administrated. In the second session (with at least one week in between) the task, which was not administrated before, was run. We counterbalanced both between the two different tasks (e.g., behavioral inhibition task and gambling task) and within version of the gambling task (e.g., standard and reversed).

The participants were allowed to have short breaks between each task and between each of the different conditions of the gambling task. Two participants did not use any medication and 18 participants with ADHD were on methylphenidate, but discontinued medication at least 20 hours prior to testing (Barkley, DuPaul, & Connor, 1999) allowing for a complete wash-out (Greenhill, 1998). All participants received a small gift (worth approximately 1 USD) at the end of the second session.

Outliers

All analyses were conducted with and without the exclusion of outliers (the maximum number of outliers per analysis was three). Exclusion of outliers did not alter our findings and, therefore, all analyses are presented with all participants.

Results

Do children with ADHD encounter difficulties with decision-making?

In line with the IOWA Gambling Task literature net score differences were calculated between advantageous and disadvantageous choices (e.g., Bechara et al., 1998, 2000; Crone et al., 2003). For the standard task, the difference score was calculated between the total number of choices for doors C and D (advantageous) minus the total number of choices for door A and B (disadvantageous). For the reversed task, the difference score was calculated between the total number of choices for doors A and B (advantageous) minus the total number of choices for door C and D (disadvantageous). A positive score indicates an overall net gain while a negative score indicates an overall net loss. The net scores were calculated across 20 trials for 10 blocks (each task consisted of a total of 200 trials). In this way a possible strategy change during the course of task performance could be examined.

The repeated measure ANOVA with net scores and with Group (ADHD versus normal controls) as between subject factor and Type of Task (Standard versus reversed) and Trial Block (10) as within-subject factors resulted in main effects of Type of Task, $F(1,40) = 30,60$, $p < .001$, $\eta^2 = .43$, and Trial Block, $F(9,32) = 4.75$, $p < .001$, $\eta^2 = .57$. This was qualified by an interaction between Type of Task and Trial Block, $F(9,32) = 2.31$, $p < .05$, $\eta^2 = .39$. The children made more advantageous choices in the reversed task compared to the standard task and learned to differentiate between advantageous and disadvantageous choices more quickly in the reversed task than in the standard task.

There was no significant main effect of Group, $F(1,40) < 1$, $p = .90$, $\eta^2 = .00$, and no significant interactions of Group with Type of Task or Trial Block (respectively, $F(1,40) < 1$, $p = .74$, $\eta^2 = .00$ and $F(9,32) < 1$, $p = .92$, $\eta^2 = .10$). No differentiation could be made between children with ADHD and NC based on the net scores of the gambling task.

Are children with ADHD future insensitive or reward sensitive?

A repeated measure ANOVA of the actual choices, included two additional-within subject factors; Gain (advantageous versus disadvantageous) and Frequency (frequent versus occasional punishment/reward), resulted in a main effect of Gain, $F(1,40) = 13,54$, $p < .001$, $\eta^2 = .25$, showing that in general children made more advantageous choices than disadvantageous choices. This analysis did not result in a significant main effect of Frequency, $F(1,40) < 1$, $p = .45$, $\eta^2 = .01$. We found significant interactions of Gain by Task by Block, $F(9,32) = 2.62$, $p < .05$, $\eta^2 = .42$, Gain by Frequency, $F(1,40) = 11.68$, $p < .001$, $\eta^2 = .23$, Frequency by Task, $F(1,40) = 31,95$, $p < .001$, $\eta^2 = .44$.

The first interaction provided us with the same information as the net score analysis. The Gain by Frequency interaction revealed that the participants made more advantageous choices when the choices were associated with high frequency punishment/reward (e.g., regular but small) relative to infrequent punishment/reward (e.g., irregular but large), however there was no difference in the number of disadvantageous choices between the two frequencies. The Frequency by Task interaction showed us that on the standard task the participants preferred the choices associated with infrequent (but large) punishments and on the reversed task the participants preferred the high frequent (but small) rewards.

The other main effects and interactions failed to reach significance. There was only a marginal significant effect for the Task by Block by Gain by Frequency by Group interaction ($p = .063$). This effect might have been the result of a highly inconsistent response pattern of children with ADHD compared to healthy control participants (see Fig. 1).

Do children with ADHD have an inability to switch decks?

To be able to address this question, two new variables were computed: 1) Percentage of switch after gain trials in relation to the total number of gain on previous trials and 2) Percentage of switch after loss trials in relation to the total number of loss on previous trials.

A 2 (Group) × 2 (Switch after previous feedback) repeated measure ANOVA resulted in a main effect of Switch after previous feedback, $F(1,40) = 9.73$, $p < .001$, $\eta^2 = .20$, which means that the participants changed choices (e.g., doors) more often after they lost apples (43.2%) than after they won apples (38.0%). There was no a significant interaction with group, $F(1,40) = 1.02$, $p = .32$, $\eta^2 = .03$, or a significant main effect of group, $F(1,40) = 3.75$, $p = .06$, $\eta^2 = .03$. Children with ADHD (35.4%) seemed to make less switches than NC children (45.8%), but this was just a marginally significant effect ($p = .06$).

Do children with ADHD encounter difficulties with behavioral inhibition?

Children with ADHD and NC children did not differ significantly from each other on three dependent measures, namely, MRT, $F < 1$, $p = .70$, $\eta^2 = 0.00$, percentage of errors, $F(1,38) = 4.03$, $p = .05$, $\eta^2 = 0.10$, and SSRT, $F(1,38) = 1.83$, $p = .32$, $\eta^2 = 0.03$. The marginally significant effect on percentage of errors is due to the higher percentage of errors children with ADHD made when compared to NC children (see Table 2). However, we found a significant main effect on the SD of the RT, $F(1,37) = 4.99$, $p < .04$, $\eta^2 = 0.12$. Children with ADHD were more variable in responding than the NC group.

Does a combination of two different paradigms result in valid group assignments?

Correlations

The correlation between the dependent variables of the standard and reversed gambling task (choice A, B, C and D) with the dependent variables of the behavioral inhibition task ranged from low to moderate (standard: range

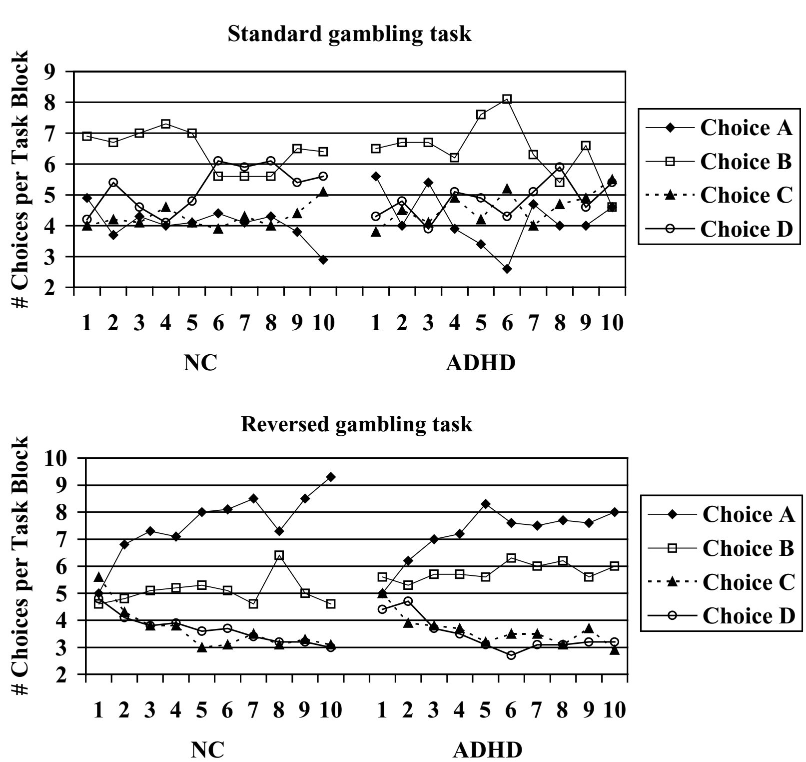

Fig. 1 Actual Choices per Task as Function of Trial Block, for Each Group Separately. Note that Choice A (high frequent) and B (low frequent) are in the Standard Task the Disadvantageous Choices and Choice C (high frequent) and D (low frequent) are the Advantageous Choices. In the Reversed task C and D are the Disadvantageous Choices and A and B the Advantageous Choices. ADHD: Attention Deficit Hyperactivity Disorder; NC: Normal Controls.

Table 2 Dependent measures of the behavioral inhibition task for the ADHD and the comparison control groups

Measure	NC ($n = 20$)	ADHD ($n = 20$)
MRT	351.8 (32.2)	347.6 (34.5)
% of errors	14.2 (7.7)	21.5 (13.5)
SD	70.7 (4.2)	77.1 (11.9)
SSRT	334.3 (26.4)	323.5 (38.5)

Note. ADHD: Attention deficit hyperactivity disorder; MRT: Mean reaction time; NC: Normal controls; SD: Standard deviation; SSRT: Stop signal reaction time. Note that due to technical difficulties there was missing data for the inhibition task for two normally developing children.

$r = |.02| - r = |.24|$ reversed: range $r = |.01| - r = |.44|$). There was little common variance between the gambling and behavioral inhibition variables. Only choice B in the Standard task (e.g., a disadvantageous choice) correlated moderately with the parent rating of CD (.34, $p < .03$) and the teacher rating of ODD (.31, $p = .05$). The behavioral inhibition task showed significant correlations with the parent ratings, but not with any of the teacher ratings of the DBD. SSRT correlated moderately with ADHD hyperactivity/impulsivity ($-.34$, $p < .05$), ODD ($-.35$, $p < .03$), and CD ($-.40$, $p < .02$). Percentage of errors correlated moderately with ADHD inattention (.39, $p < .02$), MRT with CD ($-.37$, $p < .03$), and SD of the RT correlated moderately with ADHD hyperactivity/impulsivity (.44, $p < .007$), and CD (.33, $p < .05$).

Discriminant analyses

A discriminant analysis was conducted to determine whether a combination of performance on the gambling task and inhibition task could predict group assignment (ADHD or NC). With a total number of 42 participants, the number of dependent variables to be entered was limited to a maximum of two in order to obtain stable solutions for the discriminant functions (Stevens, 1996, p. 265). However, at least one predictor from the standard task, one from the reversed task, and one from the inhibition task was needed, which implies possible low reliability of the obtained discriminant functions. Therefore, these results need to be interpreted very cautiously. The *z*-scores of the SSRT, netscore of the standard task and of the reversed task were included as predictors. Following Bechara (1997), the last 100 trails were chosen because this was expected to be the optimal learning stage.

The overall Wilks' lambda was not significant, $\Lambda = .93$, χ^2 (3, $N = 39$) = 2.45, $p = .48$, indicating that the predictors could not differentiate between the two groups. The discriminant function was strongly related to SSRT (.79), followed by the netscores on the standard task (.55) and the reversed task ($-.34$). Only 56% percent of the cases were correctly classified: 47% of the NC and 65% of the ADHD children.

In order to take into account chance agreement, the kappa coefficient was computed. A kappa value of .12 was obtained, which indicates that the group prediction was not accurate. To determine how well the discriminant functions would predict a new sample, the percentage of children classified accurately was estimated using the cross validation leave-one-out technique. Only 41% were classified correctly, which is even below chance level.

Using solely the *z*-score of SSRT as predictor, 60% of NC group and 60% of the children with ADHD were correctly classified. Using the *z*-scores of the standard and reversed netscores of the last five blocks as predictor, 90% of the NC group and 15% of the ADHD group was correctly classified.

Discussion

The present study explored patterns of decision-making and behavioral inhibitory control in children aged 8 to 12 years with and without ADHD. We compared these two groups on their overall performance and actual response differences on the gambling task and on their performance on the behavioral inhibition task. With these paradigms we addressed both the "hot" and "cool" aspects of cognitive control, which may be related to two separate developmental pathways that lead to ADHD (Sonuga-Barke, 2003). Based on earlier findings we hypothesized that children with ADHD would perform in a cognitively and behaviorally inhibited way on the two tasks in comparison with normally developing controls (Crone et al., 2003; Ernst, Grant et al., 2003; Lijffijt et al., 2005; Oosterlaan et al., 1998). We expected that children with ADHD would be more reward focused and would fail to inhibit their motor responses.

'Hot' cognitive aspects

Thus, a first goal of the study was to examine decision-making in ADHD children using a 'hot' cognitive control task (i.e., the Hungry Donkey Task). In contrast with our predictions, we found no differences between the children with ADHD and the normally developing children in response strategy (and reward sensitivity) in decision-making. The absence of a decision-making deficit in ADHD children was found in the context of a replication of decision-making strategy in all children (see Crone & Van der Molen, 2004; Overman, 2004). Both groups developed a preference for advantageous choices as the decision-making task progressed in the standard and reversed version of this task (see also Bechara et al., 1994, 1999; Blair et al., 2001; Crone et al., 2003). Both groups learned to dissociate between advantageous and disadvantageous options faster in the reversed task than in the standard task. This finding is also consistent with previous studies (Crone & Van der Molen, 2004; Bechara et al., 2000) and suggests that children aged 8 to 12 developed abilities to take future consequences into account and that they choose in a reward oriented manner.

Similar to previous findings, in the standard task children made more choices which were associated with infrequent but high losses, whereas in the reversed task, children preferred choices associated with high frequent, but small rewards (Crone et al., 2003). To be more specific, if reward was presented on each trial children made more choices associated with infrequent losses and if punishment was presented on each trial the children made more choices associated with high frequent rewards. These findings suggest that, while learning to make advantageous choices over the course of both tasks, children preferred immediate rewards and infrequent punishment. Note that the frequency did not influence the long-term outcomes; these were the same for choices associated with infrequent small and frequent large punishment. In a prior study, we found the same response pattern in adults and no differences between age groups (Crone & Van der Molen, 2004).

Finally, when confronted with higher magnitudes of the losses, children switched more often to another choice. This finding indicates that feedback resulted in direct behavioral changes reflected in the altered decisions the children made. A prior study (Crone et al., 2005), also suggests that individuals use performance feedback to change strategy. Interestingly, this prior study showed that children choose more disadvantageously than adults, but switched responses following punishment as often as adults did (Crone et al., 2005). Likewise, Bechara et al. (2000) showed that there were no differences in perseverative behavior between VMedPFC patients and healthy controls. Our results suggest that children with ADHD were sensitive to punishment feedback, since there were no differences between the ADHD and NC groups.

The general analyses did not reveal differences between control and ADHD children on the hot cognitive control task, but more specific comparisons suggest that children with ADHD seem to have a) a more inconsistent response pattern on disadvantageous choices in the standard gambling task, and b) more perseverative patterns of responding because overall they made less switches than NC children. Although just marginally significant, this finding is in line with earlier studies in which the ability to switch responses in ADHD has been studied (e.g., Cepeda, Cepeda, & Kramer, 2000; Pennington & Ozonoff, 1996). Notably, these differences were not caused by less inhibitory control capacities, as no group differences on the inhibition task were found. Since this is the first study that looks into gambling performance in this age group, the results should be interpreted with caution. However, the patterns of results could be an interesting starting point for future research.

'Cool' cognitive aspects

A second goal of this study was to examine whether we could replicate response inhibition deficits in ADHD children using a 'cool' cognitive control task (i.e., the stop-signal task). Contrary to expectations, children with ADHD did not encounter a core inhibitory control deficit, even though the mean SSRT (323.5 msec) is similar to the mean SSRT in earlier studies (e.g., Lijffijt et al., 2005; Oosterlaan et al., 1998). A number of studies who applied the stop signal paradigm with a tracking mechanism (e.g., Chhabildas, Pennington, & Willcutt, 2001; Nigg, 1999; Schachar, Mota, Logan, Tannock, & Klim, 2000) have shown that children with ADHD have slower SSRTs in comparison with NC children, but even more studies, like ours, did not replicate these findings (e.g., Kuntsi, Oosterlaan, & Stevenson, 2001; Manassis, Tannock, & Barbosa, 2000; Rubia et al., 2001a, 2001b; Scheres et al., 2001a, 2001b, Scheres et al., 2004). In line with previous findings, we found that children with ADHD were more variable in their responding when compared to normally developing children. This variability of responding might be one of the endophenotypes of ADHD (e.g., Castellanos & Tannock, 2002; Castellanos et al., 2005).

Associations between 'hot' and 'cool' cognitive aspects

A third goal of this study was to examine the relation between 'hot' and 'cool' cognitive control, and the prediction to ADHD diagnosis. Similar to previous findings, no strong relation between decision-making and behavioral inhibition (Bechara et al., 2000; Crone et al., 2003) was found. This underlines the idea of separate forms of executive control (Nigg, 2001; Zelazo et al., 2003), and is consistent with neuropsychological studies that suggest that behavioral inhibition and decision-making rely on different PFC regions, respectively, VLatPFC (Aron et al., 2003) and VMedPFC (Bechara et al., 2000). However, children with ADHD could not be distinguished from normally developing controls on these critical measures and a combination of these measures could not predict group membership properly. Therefore, the findings in the current study do not seem to support a dual-pathway model of ADHD (Sonuga-Barke, 2003). However, the findings do suggest that the behavioral inhibition paradigm is more sensitive to detect children with ADHD, while the gambling task is more specific to detect NC children.

Limitations/future directions

Some limitations should be noted. First, the lack of a group difference on the gambling task and the stop signal paradigm may be due to the rather small samples sizes and the inclusion of children with different ADHD subtype diagnosis. However, the small number of children of the inattentive and hyperactive/impulsive subtype excludes the possibility to explore whether subtypes differed on the applied tasks. However, excluding the children with ADHD inattentive subtype (4 children) did not alter our findings.[1]

Second, in the current study two different inhibition paradigms were combined: a Go-NoGo paradigm and a Stop signal paradigm. The hybrid nature of the current task might have resulted in less valid measures of the SSRT. Rubia et al. (2001a, 2001b) showed that, although there is considerable overlap, Stop-trials are related to other brain activation patterns than NoGo-trials. However, in both types of trials the VLatPFC is involved. Moreover, a change in the relative frequency of the NoGo-trials resulted in a change in associated activation in the lateral PFC (Casey et al., 2001). Thus, similar tasks seem to recruit exactly those regions that we were interested in for the current study. Given that we used an adaptation of those tasks, we cannot be sure that the task taps exactly those processes as in Casey et al. (2001) or Rubia et al. (2001a, 2001b). However, we believe that the task that we designed has highly similar characteristics. Nonetheless one could still argue that our null results on this task are due to the proportion of trials were the participant had to respond to (Go-trials) in relation to the number of the trials were the participant did not have to respond at all (NoGo-trials and Stop-trials). Casey et al. (2001) have shown that the VLatPFC was especially activated when the proportion of Go-trials was relatively large and that the DLPFC was active when the proportion of Go-trials was relatively little. Therefore, the current paradigm does not necessarily tap into the VLatPFC, but might be related more to adequate DLPFC functioning. The hybrid nature of the inhibition task might, therefore, have resulted in a cool cognitive control task that taps more into maintenance than into inhibition.

Third, there were no relations among the ADHD characteristics and the outcome measures of the decision-making task and only moderate relations between the ability to inhibit a response and ADHD characteristics. This might be due to method and measurement variance. The basis of the dual-pathway model of ADHD is that the fronto-dorsal striatal and frontal-ventral striatal circuit are differently involved in children with ADHD (e.g., Sonuga-Barke, 2003). Therefore, it is necessary to apply tasks that specifically tap into these different circuits. An earlier study by Solanto et al. (2001) showed that a combination of two very different tasks, have the potential to predict group assignment quite accurately. Although we used tasks that were more strongly embedded into the field of cognitive neuroscience, we could not replicate this finding. Tasks that are more specifically related to specific brain circuits might show a stronger relation with ADHD-characteristics as measured with questionnaires.

In sum, our study gives interesting starting-points for future research. For example, children with ADHD might fail on inhibition tasks under certain motivation conditions (Van Meel, Oosterlaan, Heslenfeld, & Sergeant, 2005), or may perform disadvantageously on the gambling task, when the amount of money that can be won or lost increases over the task (see Bechara et al., 2000). Children with ADHD might show a less consistent learning pattern for disadvantageous choices on the standard gambling task, and their deficits may not be restricted to cool executive control. All in all, this is the first study that combines hot and cool forms of executive control and provides interesting directions for future research.

[1]Results can be obtained from the first author.

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