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Executive functioning in boys with ADHD: primarily an inhibition deficit?

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Abstract

This study was aimed at: (1) testing whether boys with Attention Deficit/Hyperactivity Disorder (ADHD) demonstrate a deficit in response inhibition and deficits in other executive functions (EF), or alternatively, demonstrate a deficit in only response inhibition; (2) investigating which role associated factors, such as IQ, age, and performance on non-EF tasks play in EF in ADHD; (3) studying the association between the three different forms of inhibition studied here.

Boys with ADHD were compared with normal control (NC) boys on five domains of executive functioning: inhibition (inhibition of a prepotent response, inhibition of an ongoing response, and interference control), planning, set-shifting, working memory, and verbal fluency.

Boys with ADHD demonstrated deficits in interference control, inhibition of an ongoing response, planning, and letter fluency. After controlling for age, IQ, and non-EF measures, none of the EF deficits in ADHD remained. Finally, correlations between different inhibition measures were generally low, and correlations within domains of inhibition were not higher than correlations between domains of inhibition. This calls into question the distinctiveness of the different forms of response inhibition.

Keywords: ADHD; AD/HD; Hyperactivity; Executive function; Response inhibition

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Children with Attention Deficit/Hyperactivity Disorder (ADHD) suffer from symptoms of inattention, or demonstrate hyperactive and impulsive behavior, or suffer from a combination of these two symptom domains (American Psychiatric Association [APA], 1994). Children with ADHD have been suggested to have problems with executive functions (EF) thought to be mediated by the frontal lobes (e.g., Barkley, 1997a, 1997b; Pennington & Ozonoff, 1996). The term EF refers to a set of cognitive functions which enable one to demonstrate goal-directed behavior, usually in novel contexts with competing response alternatives (Denckla, 1996; Pennington & Ozonoff, 1996). The idea that the frontal cortex is involved in ADHD receives support from structural (Casey et al., 1997; Castellanos et al., 1996; Filipek et al., 1996) and functional (Casey et al., 1997; Castellanos, 1997; Rubia et al., 1999) neuroimaging research.

Barkley (1997a, 1997b) developed a model, predicting that children with ADHD demonstrate deficits in three forms of response inhibition: (1) inhibition of a prepotent response, i.e., a response that is or has been previously associated with reinforcement; (2) inhibition of an ongoing response, which allows for a delay in the decision to continue responding; and (3) interference control, i.e., protecting a response from disruption by competing responses or events. A deficit in response inhibition is considered the primary executive dysfunction in ADHD, which leads to deficits in other EF.

In congruence with Barkley's model, Pennington and Ozonoff (1996) concluded that children with ADHD demonstrate deficits in motor inhibition. This conclusion was based on a literature review of five EF domains (inhibition, planning, set-shifting, working memory, and fluency) in different developmental disorders. Less in agreement with Barkley's proposal is their suggestion that children with ADHD show less consistent deficiencies in other EF domains. Furthermore, they argued that developmental disorders may be distinguished based on the severity and/or the profile of EF deficits. For example, children with autism were suggested to demonstrate a deficit in verbal working memory but not (or less clear) in response inhibition, whereas children with ADHD were suggested to show the reverse pattern. In sum, disagreement exists as to whether or not an EF deficit in ADHD is specifically related to inhibition.

The current study focused on the EF profile of boys with ADHD and studied the five main EF domains as suggested by Pennington and Ozonoff (1996) and reviewed by Sergeant, Geurts, and Oosterlaan (2002). We will briefly review previous studies in which key EF tasks for these five domains were used (Sergeant et al., 2002). So far, the majority of studies on response inhibition employing the Stop Paradigm showed that children with ADHD have a deficit in inhibition of a prepotent response, as measured by the Stop Paradigm (see for review, Oosterlaan, Logan, & Sergeant, 1998). Recently, a number of studies have replicated this finding (Chhabildas, Pennington, & Willcutt, 2001; Konrad, Gauggel, Manz, & Schöll, 2000; Nigg, 1999; Schachar, Mota, Logan, Tannock, & Klim, 2000; Slusarek, Velling, Bunk, & Eggers, 2001; Solanto et al., 2001; Willcutt et al., 2001) while other studies have not (Kuntsi, Oosterlaan, & Stevenson, 2001; Manassis, Tannock, & Barbosa, 2000; Pliszka, Liotti, & Woldorff, 2000; Rubia et al., 2001; Scheres, Oosterlaan, & Sergeant, 2001a, 2001b). A common task for interference control is the Stroop Color-Word Test. While some describe greater Stroop interference in ADHD (Barkley, 1997b; Perugini, Harvey, Lovejoy, Sandstrom, & Webb, 2000), few show this when controlling for color naming (Carter, Krener, Chaderjian, Northcutt, & Wolfe, 1995; Seidman, Biederman, Mounteaux, Weber, & Faraone, 2000).

While studies with the Tower of Hanoi have reported planning deficits in ADHD (Aman, Roberts, & Pennington, 1998; Pennington, Groshier, & Welsh, 1993; Weyandt & Willis, 1993), studies using the Tower of London (ToL) have not (Houghton et al., 1999; Wiers, Gunning, & Sergeant, 1998).

A traditional set-shifting task is the Wisconsin Card Sorting Test (WCST). It differentiates between children with ADHD and normal controls in most studies (see for review, Sergeant et al., 2002). However, dependent variables differ across studies, and therefore studies can often not be compared.

In the domain of working memory, it has been shown that while using the Self Ordered Pointing Task (SOP), group differences between an ADHD and a normal control group did not increase when the load on working memory increased (Shue & Douglas, 1992; Wiers et al., 1998). Séguin, Boulerice, Harden, Tremblay, and Pihl (1999) found no correlation between symptoms of ADHD and SOP performance.

Children with ADHD cannot be distinguished from normal controls on semantic fluency (Sergeant et al., 2002). For letter fluency, the results are not conclusive. Some studies report poor letter fluency in ADHD (Grodzinsky & Diamond, 1992; Koziol & Stout, 1992; Pineda, Ardila, & Rosselli, 1999), while others do not (Fischer, Barkley, Edelbrock, & Smallish, 1990; Loge, Staton, & Beatty, 1990; Reader, Harris, Schuerholz, & Denckla, 1994; Schuerholz, Singer, & Denckla, 1998; Shallice et al., 2002).

A number of issues relevant to research on EF need to be considered. First, because EF tasks may tap non-EF, it is important to include control tasks (Denckla, 1996; Pennington & Ozonoff, 1996; Sergeant et al., 2002). Second, in order to conclude that possible EF deficits are related to symptoms of ADHD, comorbid behavioral problems should be taken into account. Third, other factors such as IQ and gender could confound results. There is debate as to whether IQ should be controlled for. Werry, Elkind, and Reeves (1987) emphasized the importance of controlling for variables such as age and IQ. If lowered IQ were a consequence or an essential feature of ADHD, then controlling for it would remove a portion of the variance that is specifically associated with ADHD (Nigg, 2001; Werry et al., 1987). In several studies that have controlled for group differences in IQ, the magnitude between groups on cognitive tasks decreased (Grskovic, Zentall, & Stormont-Spurgin, 1995; Murphy, Barkley, & Bush, 2001; Werry et al., 1987). Unless EF and IQ are a single latent construct, a stronger case would be made when EF deficits in ADHD were shown to exist independent of factors such as IQ.

Existing EF studies in ADHD differ on many factors, such as sample size, age, comorbidity, sex, IQ, selection criteria, the EF domain under study, and the operationalization of EF. This makes a direct comparison of study results difficult. Furthermore, none of the EF studies in children with ADHD investigated all five EF domains (Pennington & Ozonoff, 1996). Therefore, it is difficult to draw firm conclusions about the EF profile in ADHD based on the current literature.

The first aim of this study was to test two alternative hypotheses: (1) boys with ADHD demonstrate a deficit in response inhibition and deficits in other EF (Barkley, 1997a, 1997b); (2) boys with ADHD demonstrate a specific response inhibition deficit (Pennington & Ozonoff, 1996). The second purpose of the study was to investigate which role age, IQ, and non-EF task performance play in executive functioning in ADHD. Finally, we studied whether links between inhibition tasks and constructs are valid (Nigg, 2001). We examined whether the three forms of inhibition are distinctive, or reflect a common process.

In order to address these three aims, boys with ADHD were compared with NC boys on a range of EF tasks. The focus was on five frequently reported domains of EF (Pennington & Ozonoff, 1996): inhibition (inhibition of a prepotent response, inhibition of an ongoing response, and interference control), planning, set-shifting (flexibility), working memory, and verbal fluency. For each domain, widely used tests were selected which have been shown to rely on frontal lobe functioning. For inhibition of a prepotent response, two versions of the Stop Paradigm were employed (Logan, 1994) (see Section 1). For inhibition of an ongoing response, we used a Circle Tracing Task (Bachorowski & Newman, 1985, 1990), and a recently developed Follow Task with stop instructions (Morein-Zamir & Meiran, 2003). For interference control, the Stroop Color-Word Test (Stroop, 1935), and a Flanker Task (Eriksen & Eriksen, 1974; Ridderinkhof, van der Molen, Band, & Bashore, 1997) were used. For planning, the ToL (Krikorian, Bartok, & Gay, 1994; Shallice, 1982) was used; for set-shifting we used the WCST (Grant & Berg, 1948); for working memory a self-ordered pointing task was used (Petrides & Milner, 1982), and for verbal fluency we used a verbal fluency task (Benton & Hamsher, 1978). Furthermore, several non-EF tasks were included to control for non-executive components related to the EF tasks (see Section 1).

1. Method

1.1. Participants

Twenty-three boys with ADHD (15 ADHD combined type and 8 ADHD inattentive type) between 6 and 12 years ($M = 8.7$ years, S.D. = 1.7 years) and 22 NC boys in the same age range ($M = 9.6$ years, S.D. = 1.8 years) participated in this study.

1.2. Selection procedure for the ADHD group

Children in the ADHD group were referred by pediatricians and child psychiatrists at three clinics. These children were all identified as meeting the DSM-IV criteria (APA, 1994) for ADHD by the physician and/or a multidisciplinary team of professionals. Parents of all these children were administered the ADHD, Oppositional Defiant Disorder (ODD), and Conduct Disorder (CD) sections of the Diagnostic Interview Schedule for Children (DISC)-IV, parent version (Shaffer, Fisher, Lucas, Dulcan, & Schwab-Stone, 2000). While the parents were being interviewed, the following four subtests of the Revised Wechsler Intelligence Scale for children (WISC-R) were administered to the child: Vocabulary, Arithmetic, Block Design, and Picture Arrangement. Only when the DSM-IV criteria for ADHD were met (DISC-IV), and when the child's IQ was above 70 could the child enter the study. For all children, the DISC-IV confirmed and sometimes refined the DSM-IV diagnosis (in terms of establishing ADHD subtypes and comorbidity). The average IQ of the children with ADHD was 97.6 (S.D. = 14.7) (see Table 1). One child dropped out of the study after the interview, because parents withdrew consent.

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

	ADHD-I ($n = 8$)		ADHD-C ($n = 15$)		ADHD ($n = 23$)		NC ($n = 22$)		Pairwise group comparisons[a]
Measure	*M*	S.D.	*M*	S.D.	*M*	S.D.	*M*	S.D.	
IQ	101.0	16.8	95.8	13.8	97.6	14.7	104.7	19.1	*ns*
Age	9.9	1.6	8.1	1.5	8.7	1.7	9.6	1.8	i > c
DBD parent[b]									
Inattention	19.9[*]	3.8	18.9[*]	3.5	19.3[*]	3.6	2.3	1.7	a > n
H/I[c]	13.8	5.0	20.2[*]	3.4	17.9[*]	5.1	2.0	1.8	a > n, c > i
ODD	9.3	5.6	11.9[*]	4.3	11.0[*]	4.9	1.1	1.6	a > n
CD	3.4	2.9	2.1	1.4	2.6	2.1	0.3	0.5	a > n
DBD teacher									
Inattention	19.0[*]	5.2	18.6[*]	5.7	18.7[*]	5.4	3.0	2.8	a > n
H/I[c]	12.1[*]	8.2	18.3[*]	5.9	16.1[*]	7.3	2.6	2.2	a > n, c > i
ODD	8.1	4.7	9.1[*]	6.6	8.8	5.9	0.8	1.2	a > n
CD[b]	1.3	2.0	3.7	3.9	2.9	3.5	0.1	0.3	a > n
DSM-IV screener parent									
ADHD	55.1[*]	7.8	60.7[*]	5.3	58.6[c,*]	6.8	19.5[d]	7.3	a > n
ODD	17.4	9.3	20.8	4.6	19.5[c]	6.8	6.3[e]	3.0	a > n
CD	38.6	5.3	42.0	5.8	40.8[b]	5.8	28.8[d]	3.9	a > n
Anxiety	42.3	2.4	45.3	4.1	44.2[b]	3.8	31.0[d]	3.3	a > n
Depression	21.3	2.1	22.5	2.4	22.0[b]	2.3	15.1[d]	1.4	a > n
Schizophrenia	12.6	1.5	13.5	1.7	13.2[b]	1.6	8.8[d]	1.0	a > n
PDD	28.1	4.3	29.1	4.1	28.8[b]	4.1	19.1[d]	2.4	a > n
DSM-IV screener teacher									
ADHD	54.6[*]	13.3	60.3[*]	10.7	58.3[*]	11.7	18.8	6.6	a > n
ODD	14.9	8.9	18.0	9.0	16.9[b]	8.9	5.1	3.2	a > n
CD	37.6	10.2	41.9	9.8	40.4	10.0	27.5	3.3	a > n
Anxiety	41.6	2.9	44.1	8.0	43.2	6.7	31.0	4.4	a > n
Depression	21.3	1.9	22.2	4.8	21.9	4.0	15.0	2.2	a > n
Schizophrenia	12.4	1.3	13.3	3.1	13.0	2.6	8.7	1.3	a > n
PDD	27.4	3.9	28.5	7.6	28.1	6.5	18.5	2.9	a > n

Note. ADHD-I: Attention Deficit Hyperactivity Disorder inattentive subtype; ADHD-C: Attention Deficit Hyperactivity Disorder combined subtype; NC: normal control; a: ADHD; n: normal control; c: ADHD combined subtype; i: ADHD inattentive subtype; DBD: Disruptive Behavior Disorder Rating Scale; ODD: Oppositional Defiant Disorder; CD: Conduct Disorder.

[a] Student–Newman–Keuls (α set at .05).

[b] $n = 22$ for the ADHD group.

[c] Hyperactivity/impulsivity.

[d] $n = 21$.

[e] $n = 20$.

[*] Average scale score is at or above the 95th percentile.

From the DISC-IV, it was determined that 1 child met criteria for ADHD hyperactive/impulsive type (ADHD-HI), 9 children were of the inattentive subtype (ADHD-I), and 14 children met criteria for the combined subtype (ADHD-C). Eleven children (of which eight met criteria for ADHD-C, two met criteria for ADHD-I, and one for ADHD-HI) also met criteria for ODD, and one child with ADHD-I met criteria for CD. None of the children had been previously treated with MPH or other stimulant medication.

Twenty-four children with ADHD were selected for the study and participated. Because only one ADHD child was a girl, and because it is not clear whether ADHD in boys and girls is driven by the same psychological dysfunctions (Gaub & Carlson, 1997; Nigg, 1999), this girl (who met criteria for ADHD-I and ODD) was excluded from the sample for analyses.

Parents and teachers of the children with ADHD completed the Disruptive Behavior Disorder Rating Scale (DBD, Oosterlaan, Scheres, Antrop, Roeyers, & Sergeant, 2000; Pelham, Gnagy, Greenslade, & Milich, 1992) and a DSM-IV screener (Hartman et al., 2001). The DBD consists of: (a) two scales composed of the DSM-IV items for ADHD, i.e., an Inattention scale (IN) and a Hyperactivity/Impulsivity scale (HI), (b) a scale composed of the DSM-IV items for ODD, and (c) a scale composed of the DSM-IV items for CD. Items were rated on a scale from zero to three.

The average scores on the DBD IN scale were in the clinical range (95th–100th percentile), and ranged between 8 and 27 (Table 1). These scores were expected on the basis of the DISC-IV, because all children (except one) met DSM-IV criteria for ADHD-I or ADHD-C. Average scores on the HI scale were in the clinical range and varied between 3 and 27. This range indicates that some children fell in the clinical range, but others did not. This finding reflects that 15 children met DSM-IV criteria for hyperactivity/impulsivity.

As predicted, the ADHD-C group had higher scores on the DBD HI scales than the ADHD-I group. The two ADHD subgroups did not differ on the DBD IN scales, or any of the other scales. The average scores on the ODD scales were not in the clinical range, and ranged between 1 and 20. Average scores on the CD scales were not in the clinical range and varied from 0 to 13. The range of scores on the ODD and CD scales reflects that 12 children had comorbid ODD or CD symptoms and others did not.

The DSM-IV screener was developed to assess syndromes of childhood psychopathology based on the DSM-IV (Hartman et al., 2001). The screener contains seven scales: ADHD, ODD, CD, anxiety, depression, Pervasive Developmental Disorder (PDD), and schizophrenia. Items were rated on a scale from zero to three. Average scores on the parent and teacher ADHD scales were above the 95th percentile. Scores on all other scales were below the 95th percentile (see Table 1).

1.3. Selection procedure for the NC group

The NC children were selected from three regular schools. A four-stage selection procedure was used. In stage one, parents of all children in the age range of 6–12 received information, an informed consent form, and the DBD and the DSM-IV screener ($n = 403$). Parents of 98 children completed the questionnaires (response rate 24.3%). If scores on all parent DBD scales were below the 80th percentile, children entered selection stage two. Forty children met these initial inclusion criteria. At stage two, teachers completed the DBD and the DSM-IV screener. Forty sets of completed questionnaires were received (response rate 100.0%). In order for a child to enter stage three, scores on all teacher DBD scales had to be below the 90th percentile, which was the case for 31 children. At stage three, four subtests of the WISC-R were administered. All 31 children had an IQ score of 70 or higher and entered the final selection stage. At the final stage, all the girls were excluded from the NC group, because all the children in the ADHD group except one were boys. Twenty-two of the selected NC children were boys.

The average scores on all DBD scales were below the 70th percentile for the normal control group. The scores on all scales of both the parent and the teacher DSM-IV screener were below the 50th percentile. The average IQ of the children in the NC group was 104.7 (S.D. = 19.1) (see Table 1). Note that only one NC child had an IQ lower than 80.

1.4. Group descriptives

One-way ANOVAs showed that groups did not significantly differ with respect to mean age [$F(1, 43) = 2.66$, *ns*] and mean IQ [$F(1, 43) = 1.95$, *ns*]. However, significance levels were between .1 and .2, and group means on these variables were not identical (see Table 1). Importantly, some of the dependent variables correlated significantly with age and IQ.

Groups differed on the parent and teacher DBD scales which were used as the criterion measures for the NC group. In addition, the groups differed from one another on all DSM-IV screener scales. Elevated scores in the ADHD group on all scales were expected, because correlations between the syndrome scales range from $r = .32$ to .78 (Hartman et al., 2001). However, only scores on the ADHD scales were above the 95th percentile for the ADHD group (see Table 1).

1.5. Tasks

1.5.1. Inhibition of a prepotent response

1.5.1.1. The Stop Paradigm. The Stop Paradigm (Logan, 1994; Logan & Cowan, 1984) involves two types of trials: go trials and stop trials. Go trials were airplanes presented for 1000 ms in the center of the computer screen. A fixation point (500 ms in duration) preceded the go stimulus. Subjects were required to press the response button that corresponded to the direction the plane was pointing at. The inter-stimulus interval was 1500 ms. The inter-trial interval was 3000 ms. Stop trials consisted of a go trial and a stop signal (a 1000 Hz tone, 50 ms in duration), presented through earphones. The stop signal was usually presented shortly after the airplane. Children were instructed not to press either button when they heard the tone. The delay between the go and the stop signal varied. The longer this delay, the harder it is to inhibit the response. Seventy-five percent of the trials were go trials, and 25% were stop trials. The Stop Paradigm allows for measurement of both response execution (go trials) and response inhibition (stop trials).

The dependent variable that reflects the latency of the inhibitory process is stop signal reaction time (SSRT). SSRT cannot be observed, because the response to a stop signal is a covert one. Therefore, SSRT is estimated. This can be done using the race model (Logan & Cowan, 1984). This model assumes that the go process and the stop process are independent. The go stimulus triggers the go process and the stop signal initiates the stop process. The process that finishes first wins the race. If the go process wins the race, the response is executed. If the stop process finishes first, the response is inhibited. The outcome of the race depends on the speed and the variability of the go process, the delay between go stimulus and stop signal, and the speed and the variability of the stop process.

In this study, two versions of the Stop Paradigm were used for every child. In one version, SSRT was estimated by using fixed intervals between the go and the stop signal. In the other version, SSRT was estimated by applying a tracking mechanism to vary the interval between the go and the stop signal. For a detailed description of these procedures, the reader is referred to Scheres et al. (2003).

1.5.2. Inhibition of an ongoing response

1.5.2.1. Circle Tracing Task. The Circle Tracing Task is a task that requires subjects to trace a large printed circle with their index finger (Bachorowski & Newman, 1985, 1990). Wallace, Newman, and Bachorowski (1991) found that impulsive subjects traced the circle more quickly than normal controls when instructed to trace slowly. The circle was 50.80 cm (20 in.) in diameter, drawn on a cardboard square, and covered with Plexiglas. The circle had a small line indicating the starting and the finishing point of the tracing. The task was administered under two conditions: first with neutral instructions (“trace the circle”) followed by inhibition-instructions (“trace the circle again, but this time as slowly as you can”). A maximum of 12 min was allowed for both tracing conditions. Participants were not informed of this time limit. The calculated inhibition time was the tracing time in the slow condition minus the tracing time in the neutral condition.

1.5.2.2. Follow Task. A Follow Task (Morein-Zamir & Meiran, 2003) has been recently developed to measure inhibition of a continuous response. Advantages of using a continuous response that has to be inhibited is that it enables direct observation of the SSRT and that SSRT can be observed for each trial.

Each trial began with the target (a green square) presented in the center of the screen. When the child pressed the left mouse button, the target started to move randomly and children were instructed to follow it with the mouse cursor. After a variable delay (ranging from 10 to 20 s with an average of 15 s) a stop signal (a 1000 Hz tone, 100 ms in duration) was presented, which instructed children to stop their continuous response immediately. Trials were presented in 5 blocks of 10 trials, of which the first block was practice. Children were encouraged to follow the target very closely and to stop immediately when they heard the tone.

SSRT in this task was operationalized as follows: the time, computed by an analysis program, when the initial signs of stopping can be observed in the continuous following performance. For a detailed description of this procedure, see Morein-Zamir and Meiran (2003).

1.5.3. Interference control

1.5.3.1. Stroop Color-Word Test. The Stroop Color-Word Test (Stroop, 1935; Dutch version: Hammes, 1971) is a task that measures interference control (MacLeod, 1991). Children were presented with the word card (1), followed by the color naming card (2), and the color-word card (3). The main dependent variable in this task was the interference score for time (IS time), calculated by subtracting color naming speed on card 2 from color naming speed on card 3. This test was not administered to children younger than 8, because they did not have the required automatic reading skills necessary to perform this test.

1.5.3.2. Flanker Task. In Flanker Tasks, the ability to inhibit a response to irrelevant, interfering stimuli was measured. We used an arrow version of the Flanker Task developed by Ridderinkhof et al. (1997). Target stimuli were arrows pointing to the right or to the left, presented at the center of the screen. The direction of the target arrow indicated whether the child had to press the left or the right response button. The target stimulus was surrounded by two distracters on both sides (left and right). The distracters were either arrows or rectangles. Three trial types were used: neutral, congruent, and incongruent. In a neutral trial, the target arrow was flanked by rectangles (□ □ ⇨ □ □ or □ □ ⇦ □ □). In a congruent trial the target arrow was flanked by arrows pointing in the same direction as the target (⇨⇨⇨⇨⇨ or ⇦⇦⇦⇦⇦), whereas in incongruent trials the flankers pointed in the opposite direction (⇨ ⇨ ⇦ ⇨ ⇨ or ⇦ ⇦ ⇨ ⇦⇦).

The task commenced with four practice blocks of 45 trials (15 trials for each condition) each followed by 6 experimental blocks, consisting of 60 trials each (20 trials for each condition). The three trial types were presented randomly within each block. A warning cross (500 ms in duration) preceded the stimulus (1000 ms in duration). After the stimulus, the screen turned blank for 1500 ms. The inter-trial interval was 3000 ms.

The dependent variables for this task were an interference score for mean reaction time (MRT on incongruent trials minus MRT on congruent trials) and for number of errors (number of errors on incongruent trials minus number of errors on congruent trials).

1.5.4. Planning

1.5.4.1. Tower of London (ToL). The ToL (Krikorian et al., 1994; Shallice, 1982) is a task that measures the ability to plan. The materials include three wooden pegs of different lengths mounted on a strip of wood and three colored balls (red, yellow, blue) that are manipulated on the pegs to reproduce a pictured end state. The same initial position is set for the practice problem (which requires two moves to reach a solution) and for each of the 12 problems of graded difficulty. The demand for planning is manipulated by presenting problems that differ in the minimum number of moves required for solution. There were four problems requiring at least two or three steps to be solved, four problems requiring at least four steps to be solved, and four problems requiring at least five steps to be solved. A maximum of three attempts was allowed to solve each problem.

The main dependent variable of this task was the average score, which was based on the number of attempts a child needed to solve the problems in the required number of steps. For each problem, scores ranged from zero (the problem was not solved after the third attempt) to three (the problem was solved at the first attempt). Average item scores were calculated for each of the three difficulty levels (2 or 3 moves, 4 moves, 5 moves). A second variable was the average decision time on the first attempt for each of the three difficulty levels (time between presenting the problem and the moment that the child moves the first ball), which can be seen as an indicator of an impulsive style. It was expected that in the case of a planning deficit, average scores would decrease more significantly with increasing difficulty level than in the case of no planning deficit. Decision times were expected to increase less with increasing difficulty in impulsive children.

Because difficulty level was taken into account in calculating the dependent measures, the regression coefficients (beta) for the two dependent variables were calculated for each individual, with difficulty (three levels) being the predictor, and average item score and decision time being the dependent variables, respectively. These betas were entered as the dependent variables in ANOVAs. It was expected that the beta for the average item score would be negative for all children (average item scores would decrease with increasing difficulty), and that the beta would be larger for children with ADHD than normal controls, if they had a planning deficit (scores would decrease more with increasing difficulty). It was expected that the beta for the decision time would be positive for all children (children are expected to think longer before they start with increasing difficulty), but betas were expected to be closer to zero for children with ADHD (reflecting that they would slow down less than normal children with increasing difficulty of the task).

1.5.5. Set-shifting

1.5.5.1. Wisconsin Card Sorting Test (WCST). The WCST (Grant & Berg, 1948) is a task which measures the ability to adjust a strategy to changing demands (set-shifting). The task consisted of 4 stimulus cards and two sets of 64 response cards. On the first stimulus card, one red triangle is printed, on the second card two green stars, on the third card three yellow crosses, and on the fourth card four blue circles. The child received a set of response cards on which the features color, form, and number were varied systematically. The child was required to sort the response cards by placing them in front of one of the four stimulus cards. The experimenter told the child whether the child had sorted the card successfully. The experimenter used a sorting category and gave feedback to the child according to this sorting principle. Each time the child sorted 10 cards in a row successfully, the experimenter changed the sorting category without informing the child. The order of the sorting categories was color–form–number. The task was completed when a child correctly completed six sorting categories, or when the child had used all the response cards. The dependent variables were percentage of perseverative responses (answers in the new category that were sorted according to the previous sorting principle) and the percentage of perseverative errors (incorrectly sorted cards, sorted according to the previous sorting principle).

1.5.6. Working memory

1.5.6.1. Self Ordered Pointing Task (SOP)—abstract designs. The SOP (Petrides & Milner, 1982) is a task which measures working memory. The stimulus material consisted of abstract designs. Children were presented with four series of cards containing 6, 8, 10, and 12 abstract items, respectively. For each series, children were presented with one card at a time. On each card, the items were presented in a different order. Thus, each series consisted of the same number of cards as there were items on the cards.

Children were instructed to point to a different item on each card. Following the administration procedure of Petrides and Milner (1982), each series was presented three times in succession. Children were not allowed to respond consistently to the same location, because by adopting such a strategy, the child would not need to identify the abstract design.

The two main dependent variables were (a) the number of errors (i.e., the number of times an item was picked more than once), and (b) the number of perseverative errors (i.e., the number of times the same item was picked on a subsequent trial). Difficulty level (6, 8, 10, and 12 items) was taken into account in calculating the dependent variables. It was expected that there would be a linear relation between difficulty level and the dependent variable. Therefore, the regression coefficients for the two dependent variables were calculated for each individual, with difficulty (four levels) as the predictor, and number of errors and number of perseverative errors as dependent variables. These regression coefficients were entered as the dependent variables in ANOVAs. It was expected that the regression coefficient for errors would be positive, reflecting an increase in the number of errors with increasing difficulty level. We expected that, if children with ADHD have a deficit in working memory, the regression coefficient for errors would be larger for them compared to NC children.

1.5.7. Verbal fluency

1.5.7.1. Controlled Oral Word Association Test (COWAT). An adaptation of the COWAT (Benton & Hamsher, 1978) was used. In this task children were instructed to name as many words of a certain category in 1 min. Two semantic categories (animals, food), and two letter categories (words starting with k and m) were used. The dependent variables were number of correct responses in the semantic categories, and number of correct responses in the letter categories.

1.5.8. Non-EF control tasks

In some EF tasks, a non-EF control measure was built in the calculation of the dependent variable (Stop Paradigm, Stroop Color-Word Test, Circle Tracing Task), while for other EF tasks non-EF control tasks were used (see Table 2).

1.5.8.1. WISC-R. Vocabulary, Arithmetic, Block Design, and Picture Arrangement were used as a measure for IQ, because the estimation of IQ as obtained by these subtests correlates highly ($r = .93$ to .95) with full scale IQ (Groth-Marnat, 1997). Block Design served as a visuo-constructive non-EF control task for the ToL. Vocabulary served as a non-EF task controlling for language development and word knowledge for the COWAT. In all analyses, IQ was controlled for using the estimated IQ based on the four subtests. Because the standardized scores on Vocabulary and Block Design were part of the estimated IQ, these scores were not controlled for separately in the analyses of the ToL and the COWAT.

1.5.8.2. Categories Test of the Snijders-Oomen Non-verbal Intelligence Test—Revised (SON-R). The Categories Test of the SON-R (Snijders, Tellegen, & Laros, 1989; Tellegen & Laros, 1993) was developed to measure categorization, and served as a control measure for the WCST. Children were presented with three series of nine items each. Each item consisted of two pages. The left page contained three pictures of the same category, and two spaces with question marks. On the right page five pictures were presented, two of which belonged on the left page, and had to be picked by the child. The item difficulty was related to the degree of abstraction of the underlying concept. In each series, the degree of abstraction of the underlying concept increased with each item. Series were terminated when the child committed two errors. The dependent variable was number of correct items.

Table 2
Overview of the EF, the EF tasks, the non-EF and non-EF tasks, and the covariates entered in the ANCOVAs

EF and task	Non-EF	Non-EF task	Covariate
Inhibition			
Stop Paradigm	Response execution	Control in EF task	Discriminant score for age and IQ
Follow Task	Response execution	Control in EF task	Discriminant score for age and IQ
Circle Tracing Task	Tracing in neutral condition	Control in EF task	Discriminant score for age and IQ
Eriksen Flanker Task	MRT and errors in congruent condition	Control in EF task	Discriminant score for age and IQ
Stroop Color-Word Test	Color naming speed	Control in EF task	Discriminant score for age and IQ
Planning			
ToL	Visuo-constructive abilities	Block Design (as part of IQ)	Discriminant score for age and IQ
Fluency			
Verbal fluency	Language development and word knowledge	Vocabulary (as part of IQ)	Discriminant score for age and IQ
Working memory			
SOP	Visual short term memory	Corsi Block Tapping Task	Discriminant score for age, IQ, and visual memory span
Set-shifting			
WCST	Categorization	Categories Test	Discriminant score for age, IQ, and number correct on categories

Note. EF: executive functions; MRT: mean reaction time; ToL: Tower of London; SOP: Self Ordered Pointing Task; WCST: Wisconsin Card Sorting Test.

1.5.8.3. Corsi Block Tapping Test. The Corsi Block Tapping Test (Corsi, 1972; Milner, 1971; Schellig, 1997) was included to control for visual short term memory in the SOP. The test consisted of a gray board with nine black blocks randomly attached to it. The experimenter tapped the blocks with the index finger in a prearranged order at a rate of one block per second. The child was instructed to reproduce this tapping pattern. The test consisted of 18 items, with three items for each of four difficulty levels (3–8 blocks). The test ended after three consecutive errors within a difficulty level, or after the 8-block items had been administered. Tapping patterns were derived from Schellig (1997). The dependent variable was visual memory span, defined as the difficulty level (number of blocks) for which a child could correctly reproduce at least two items.

1.6. Procedure

Participants were tested during two sessions on two separate days. Standardized instructions were used for each of the tasks. During the first assessment the following tasks were administered in two blocks: Corsi, ToL, COWAT, SOP (block A), and WCST, Categories Test (block B). The order of the blocks was balanced over the children for each group. During the second test assessment the following tasks were administered in two blocks: Stop Paradigm with tracking mechanism, Circle Tracing Task, Stop Paradigm with fixed intervals (block C), and Flanker Task, Stroop Color-Word Test, Follow Task (block D). Again, the order of blocks was balanced over the children of each group.

1.7. Statistical analyses

1.7.1. ANOVAs

We performed ANOVAs with EF measures as the dependent variables, and group (two levels) as a between subjects factor.

1.7.2. ANCOVAs

In order to establish robustness of possible EF difference between the groups with respect to IQ, age, and non-EF measures, we performed ANCOVAs. Although groups did not significantly differ for age and IQ, these variables did correlated moderately with (some of) the dependent variables.

Initially, we planned to control for comorbid ODD/CD as well. However, when we checked whether possible covariates might have too much of an overlap with group assignment by performing a discriminant analysis with age, IQ, ODD/CD symptoms, Corsi Block Tapping, and Categorization as independent variables, and group membership (ADHD or normal control) as the grouping variable, we found that 93% of the children were correctly classified based on the independent variables. This almost perfect group assignment appeared to be due to symptoms of ODD/CD, which had a discriminant function coefficient of .97. Based on this result, we decided not to enter symptoms of ODD/CD as a covariate, since they did not contain any new information beyond what was contained in the ADHD group assignment.

IQ and age were covaried for all dependent measures. In the case of the SOP, visual memory span was entered as an additional covariate. For the WCST, the number of correct responses as measured by the Categories Test was entered as an extra covariate. Note that the non-EF control tasks for the ToL (Block Design) and for the COWAT (Vocabulary) were part of the estimated IQ. In the response inhibition tasks, non-EF functions were controlled for in the calculation procedure of the dependent measures. In order to reduce the number of covariates for power reasons, the discriminant scores were used for the set of covariates that was relevant to the task. For example, in the ANCOVA for the WCST, the discriminant score as calculated by a discriminant analysis with age, IQ, and the score on the Categories Test was entered as a covariate. See Table 2 for an overview of the EF tasks, the non-EF control measures, and the covariates.

As there is debate as to whether IQ should or should not be covaried, the ANCOVAs as described above were also conducted without IQ as part of the discriminant score. For the ToL and the COWAT, for which the non-EF control measure was part of the IQ, the discriminant score for age and Block Design, and the discriminant score for age and Vocabulary (COWAT) were entered as covariates, respectively.

1.7.3. Correlational analyses

In order to examine whether the three forms of inhibition are distinctive or reflect a common process, Pearson's correlation coefficients between tasks within and across domains of inhibition were calculated. All children were treated as a single group. If the three forms of inhibition were distinctive, correlations between tasks within a domain of inhibition are expected to be higher than correlations between tasks across domains. On the other hand, if the three forms of inhibition are not distinctive, correlations within and across domains are expected to be similar.

1.7.4. Missing data and outliers

For specific tasks, some cases were missing due to technical problems, or due to a child not attending. This resulted in no more than one case for each group missing in any of the ANOVAs and ANCOVAs. For the Stroop Color-Word Test, data of only 18 ADHD children and 20 NC children were available, since the other children were younger than 8 years.

Extreme cases (with values more than 3.5 interquartile ranges from the median) for each dependent measure in each group were excluded from the ANOVAs and ANCOVAs. This resulted in excluding not more than three cases due to extreme scores for the analysis of a given dependent variable.

With respect to the correlational analysis, extreme cases (with values more than 3.5 interquartile ranges from the median) on any of the inhibition variables were excluded from the analysis. This resulted in the exclusion of two cases.

2. Results

2.1. ANOVAs

The group means and standard deviations for all the tasks are presented in Table 3.

2.1.1. Inhibition of a prepotent response

Children with ADHD did not demonstrate significantly slower SSRTs than normal controls for the Stop Paradigm with fixed intervals [$F(1, 43) = 1.93$, *ns*; $\eta^2 = .04$].

As expected, for the Stop Paradigm with tracking mechanism groups did not differ on the mean percentage of inhibition, which was 50.0% for the ADHD group and 49.3% for the NC group [$F(1, 37) = 0.75$, *ns*; $\eta^2 = .02$]. This indicates that the tracking mechanism was successful. Although SSRTs of children with ADHD were slower compared to normal controls, this difference fell short of significance [$F(1, 37) = 3.77$, $P = .06$; $\eta^2 = .09$].

2.1.2. Inhibition of an ongoing response

A significant effect of group was observed for the inhibition times in the Circle Tracing Task [$F(1, 41) = 4.02$, $P = .05$; $\eta^2 = .09$]. Children with ADHD slowed down less than control children while tracing the circle in the inhibition condition.

Children with ADHD did not demonstrate significantly slower SSRTs than NC children in the Follow Task [$F(1, 42) = 0.78$, *ns*; $\eta^2 = .02$].

Table 3
Group means and standard deviations for EF measures and non-EF measures

	ANOVAs				ANCOVAs			
	ADHD		NC		ADHD		NC	
	M	S.D.	*M*	S.D.	*M*	S.E.	*M*	S.E.
EF measure								
Inhibition of a prepotent response[a]								
SSRT fixed	273.9	106.1	231.4	99.3	264.9	21.1	240.8	21.6
SSRT tracking[b]	226.2	111.3	168.7	63.0	222.5	21.1	173.0	22.9
Percent inhibition tracking[b]	50.0	3.1	49.3	1.5	49.9	0.7	49.4	0.6
Inhibition of an ongoing response								
Circle inhibition time[c]	**76.4**	44.2	**144.8**	150.3	88.1	24.7	133.7	24.1
Follow SSRT[d]	251.5	76.0	232.9	61.8	245.2	14.1	239.8	14.8
Interference control								
Eriksen IS MRT[e]	48.9	29.6	35.0	19.5	47.8	5.4	36.2	5.8
Eriksen IS errors[d]	**7.4**	6.4	**3.8**	4.2	7.1	1.1	3.8	4.2
Stroop IS time[f]	**97.8**	47.3	**64.5**	48.1	93.8	10.8	68.2	10.2
Planning, ToL								
Beta ToL average item score	−0.**43**	0.27	−0.**24**	0.28	−0.41	0.06	−0.26	0.06
Beta decision time 1st try[g]	0.54	1.5	0.97	1.3	0.72	0.26	0.76	0.28
Set-shifting, WCST								
Percentage perseverative responses	16.4	11.5	13.7	6.1	15.3	1.9	14.8	1.9
Percentage perseverative errors	14.7	8.8	12.5	5.0	13.8	1.4	13.4	1.5
Working memory, SOP								
Beta errors	1.2	1.1	1.1	0.8	1.1	0.2	1.3	0.2
Beta perseverative errors	0.0	0.5	0.0	0.5	0.0	0.1	0.0	0.1
Fluency								
Number correct, semantic	29.8	7.9	32.2	7.9	31.1	1.4	30.8	1.4
Number correct, letters	**11.5**	5.7	**15.4**	6.4	12.2	1.2	14.6	1.2
Non-EF measure								
Corsi memory span	**4.6**	0.8	**5.2**	0.9	n.a.	n.a.	n.a.	n.a.
Categories Test	**10.5**	3.5	**12.8**	4.2	n.a.	n.a.	n.a.	n.a.

Note. EF: executive functions; ADHD-I: Attention Deficit Hyperactivity Disorder inattentive subtype; ADHD-C: Attention Deficit Hyperactivity Disorder combined subtype; NC: normal control; SSRT: stop signal reaction time; IS: interference score; ToL: Tower of London; SOP: Self Ordered Pointing Task; WCST: Wisconsin Card Sorting Test.

[a] Two versions of the stop paradigm were applied: a version with fixed intervals between the stop tone and the expected reaction time, and a version with a tracking mechanism that adjusts the delay between go stimulus and stop signal contingent on the participant's performance (for further details, see text). Numbers in bold indicate significant group differences.

[b] $n = 21$ for ADHD group, $n = 18$ for NC group.

[c] $n = 21$ for ADHD group, $n = 22$ for NC group.

[d] $n = 21$ for NC group.

[e] $n = 20$ for NC group.

[f] $n = 18$ for ADHD group, $n = 20$ for NC group.

[g] $n = 23$ for ADHD group, $n = 20$ for NC group.

2.1.3. Interference control

Children with ADHD did not show a significantly higher interference score for MRT in the Flanker Task than normal controls [$F(1, 41) = 3.19$, $P = .08$; $\eta^2 = .07$], but they did have a significantly higher interference score for number of errors than normal controls [$F(1, 42) = 4.80$, $P < .05$; $\eta^2 = .10$].

A significant group difference was found for the interference score for time in the Stroop Color-Word Test [$F(1, 36) = 4.62$, $P < .05$; $\eta^2 = .11$].

2.1.4. Planning (ToL)

A significant effect of group was found for the beta for average score [$F(1, 43) = 5.63$, $P < .05$; $\eta^2 = .12$]. This means that the decrease in score with increasing difficulty was stronger for the ADHD group than for the NC group. No group difference was detected for the beta for average decision time at the first attempt [$F(1, 41) = 0.97$, *ns*; $\eta^2 = .02$]. This indicates that the ADHD group and the NC group showed similar increases in their decision times when difficulty increased.

2.1.5. Set-shifting (WCST)

No group effect was observed either for percentage perseverative responses [$F(1, 43) = 0.94$, *ns*; $\eta^2 = .02$], or for percentage perseverative errors [$F(1, 43) = 1.06$, *ns*; $\eta^2 = .02$].

2.1.6. Working memory (SOP)

No group difference was found for the beta for number of perseverative errors [$F(1, 43) = 0.02$, *ns*; $\eta^2 < .01$]. This indicates that the increase in perseverative errors with difficulty level was equal for the two groups. Note, however, that betas were close to zero, suggesting that perseverative errors were constant over the difficulty levels. Groups did not differ for the beta for total errors [$F(1, 43) = 0.02$, *ns*; $\eta^2 < .01$], meaning that the increase in total number of errors with difficulty level was similar for both groups.

2.1.7. Verbal fluency (COWAT)

Children with ADHD generated less correct responses than controls for the letter categories [$F(1, 43) = 4.57$, $P < .05$, $\eta^2 = .10$], but no group difference emerged for number of correct responses in the semantic categories [$F(1, 43) = 0.10$, *ns*; $\eta^2 = .02$].

2.1.8. Non-EF tasks

No significant group differences were found for Block Design [$F(1, 43) = 1.84$, *ns*; $\eta^2 = .04$] and Vocabulary [$F(1, 43) = 0.90$, *ns*; $\eta^2 = .02$]. Significant group differences were observed for number of correct items in the Categories Test [$F(1, 43) = 4.13$, $P < .05$; $\eta^2 = .09$] and for visual memory span as measured by the Corsi Block Tapping Task [$F(1, 43) = 5.90$, $P < .05$; $\eta^2 = .12$].

2.2. ANCOVAs

2.2.1. Inhibition of a prepotent response

Like in the ANOVA, no significant group difference was found for SSRT as measured by the Stop Paradigm with fixed intervals [$F(1, 42) = 0.61$, *ns*; $\eta^2 = .01$].

As expected, children with ADHD did not differ from normal controls for percentage inhibition [$F(1, 36) = 0.24$, *ns*; $\eta^2 < .01$] in the Stop Paradigm with tracking mechanism. Like in the ANOVA, groups did not differ for SSRT [$F(1, 36) = 2.35$, *ns*; $\eta^2 = .06$].

2.2.2. *Inhibition of an ongoing response*

The group difference for the inhibition time in the Circle Tracing Task became non-significant [$F(1, 40) = 1.63$, *ns*; $\eta^2 = .04$] when age and IQ were controlled for.

Like in the ANOVA, groups did not differ for SSRT in the Follow Task [$F(1, 41) = 0.07$, *ns*; $\eta^2 < .01$].

2.2.3. *Interference control*

Like in the ANOVA, no group difference for interference score for MRT was observed in the Flanker Task [$F(1, 40) = 2.08$, *ns*; $\eta^2 = .05$]. The group difference for interference score for number of errors disappeared [$F(1, 41) = 3.11$, $P = .09$; $\eta^2 = .07$].

The significant group difference for the interference score for time in the Stroop Color-Word Test disappeared [$F(1, 35) = 2.88$, $P = .10$; $\eta^2 = .08$].

2.2.4. *Planning (ToL)*

No significant effect of group was found for the beta for the average item score [$F(1, 42) = 3.19$, $P = .08$; $\eta^2 = .07$]. This indicates that, after controlling for IQ and age, the score for the ADHD group did not decrease significantly more with increasing difficulty than the score of the NC group. Similar to the ANOVA, no group difference was detected for the beta for the average decision time [$F(1, 40) = 0.01$, *ns*; $\eta^2 < .01$].

2.2.5. *Set-shifting (WCST)*

Results remained the same after controlling for age, IQ, and the score on the Categories Test. Groups did not differ with respect to percentage perseverative responses [$F(1, 42) = 0.03$, *ns*; $\eta^2 < .01$] or perseverative errors [$F(1, 42) = 1.50$, *ns*; $\eta^2 < .01$].

2.2.6. *Working memory (SOP)*

After controlling for age, IQ, and visual memory span, results for the SOP remained the same. No group difference was found for the beta for number of perseverative errors [$F(1, 42) = 0.01$, *ns*; $\eta^2 < .01$] or the beta for total errors [$F(1, 42) = 0.51$, *ns*; $\eta^2 = .01$].

2.2.7. *Verbal fluency (COWAT)*

Similar to the ANOVA, groups did not differ for number of correct responses in the semantic categories [$F(1, 42) = 0.02$, *ns*; $\eta^2 < .01$]. For the letter categories, the original group difference for the number of correct responses disappeared [$F(1, 42) = 1.86$, *ns*; $\eta^2 = .04$].

2.3. *ANCOVAs without IQ as a covariate*

The ANCOVAs as described above were also conducted without IQ as part of the discriminant score. Results were the same for both ANCOVAs, suggesting that especially age and non-EF control measures were responsible for the changes in the findings, whereas IQ played a minor role in this.

Table 4
Correlations between the inhibition variables

		1	2	3	4	5	6	7
1	SSRT fixed	–	.57**	−.07	.24	.05	.25	.15
2	SSRT tracking		–	.01	.08	.18	.25	.05
3	Circle inhibition time			–	.02	−.15	.03	.00
4	SSRT follow				–	−.15	.16	.23
5	Eriksen IS MRT					–	.11	.17
6	Eriksen IS errors						–	−.12
7	Stroop IS time							–

Note. SSRT: stop signal reaction time; IS: interference score; MRT: mean reaction time.
** $P < .01$.

2.4. Correlations between inhibition measures

Correlations between inhibition measures were low. Correlations between tasks within a domain of inhibition were not higher than correlations between tasks across domains of inhibition (see Table 4), suggesting that the inhibition measures were relatively independent of one another, both across and within domains of inhibition. The only exception was a high positive correlation between SSRT as measured by the two Stop Paradigms ($r = .57$, $P < .01$), which was expected, because the tasks both measure the latency of the inhibition process (SSRT).

3. Discussion

This study examined five domains of EF in boys with ADHD to see if they showed deficits in response inhibition only, or other EF deficits as well. To our knowledge, this is the first study in which five main EF domains (inhibition, planning, set-shifting, working memory, and verbal fluency) were studied in one sample. Three forms of inhibition were examined: inhibition of a prepotent response, inhibition of an ongoing response, and interference control. Secondly, we studied the role of IQ, age, and non-EF performance in order to show EF performance without and with these controls. We believe that this was necessary because it is unclear whether the claims for an EF deficit in ADHD can survive a stringent test. If they did, we would have vindicated a strong model of ADHD (Barkley, 1997b). If EF deficits disappeared after controlling for these factors, the primacy of the role of EF in ADHD would be called into question. Thus, both positive and negative findings are informative in this attempt. Finally, the association/independence between the different forms of inhibition was examined.

Boys with ADHD demonstrated a deficit in interference control (on both the Flanker Task and the Stroop Color-Word Test), and in inhibition of an ongoing response (on the Circle Tracing Task but not on the Follow Task) but not in inhibition of a prepotent response. Furthermore, planning and letter fluency deficits were observed in ADHD. Groups did not differ for semantic fluency, working memory or set-shifting. After controlling for age, IQ, and non-EF measures, none of these EF deficits remained. ANCOVAs without IQ yielded the same results as ANCOVAs with IQ, indicating that age and non-EF measures—and not IQ—were responsible for significant deficits in response inhibition, planning, and letter fluency to disappear.

Finally, correlations between inhibition measures were low, and correlations within domains of inhibition were not higher than correlations between domains of inhibition. The only exception was the high positive correlation between the two versions of the Stop Paradigm.

Although most studies that employed a Stop Paradigm with fixed intervals reported slower SSRTs in children with ADHD (Geurts, Verté, Oosterlaan, Roeyers, & Sergeant, in press; Konrad et al., 2000; Nigg, 1999; Oosterlaan et al., 1998; Schachar et al., 2000; Slusarek et al., 2001; Solanto et al., 2001; Willcutt et al., 2001), we did not replicate this finding, like some other recent studies did not (Kuntsi et al., 2001; Manassis et al., 2000; Pliszka et al., 2000; Rubia et al., 2001; Scheres et al., 2001a, 2001b). Three studies replicated slow SSRTs in ADHD using the Stop Paradigm with tracking mechanism (Chhabildas et al., 2001; Nigg, 1999; Schachar et al., 2000).

Possible reasons for the lack of a group difference for SSRT in the current study involve the rather small samples, the inclusion of not only children with ADHD-C but also children with ADHD-I (see below), and the comorbidity with ODD/CD. The argument that comorbid ODD/CD may play a role in the lack of replicating the SSRT finding is unlikely since SSRTs have been shown to be similar for ADHD and ADHD + ODD/CD groups (Oosterlaan et al., 1998). Moreover, Solanto et al. (2001) found no differences for SSRT between ADHD and ADHD + ODD. However, Schachar et al. (2000) reported slow SSRTs for children with ADHD + CD, but not for children with ADHD only.

For inhibition of an ongoing response, significant group differences on the Circle Tracing Task disappeared when age and IQ were controlled for. No group difference was observed on the Follow Task. The Follow Task seems a relatively pure measure of inhibition of a continuous response, but was not sensitive to ADHD here.

Boys with ADHD demonstrated poor interference control on the Stroop Color-Word Test when controlling for color naming. However, when age and IQ were controlled for, the effect, although still observed, became non-significant. Although Stroop studies are usually considered as providing supportive evidence for poor interference control in ADHD (Barkley, 1997b; Perugini et al., 2000), only few studies found this deficit when controlling for color naming (Carter et al., 1995; Seidman et al., 2000). The ADHD group in the current study showed more interference in the Flanker Task, but after controlling for age and IQ this effect became insignificant. The initial interference effect was only found for errors and not for MRT, which is consistent with an earlier study (Jonkman et al., 1999), but the reverse was found by Crone, Jennings, and Van der Molen (2003).

We found a planning deficit in ADHD as measured by the ToL average score, which deteriorated to a greater extent with increasing difficulty for ADHD boys than for normal boys. After controlling for age and IQ (containing the non-EF control measure Block Design) this deficit did not remain. No group differences emerged for average decision time, suggesting that low ToL scores in ADHD were not due to an impulsive style. Three other studies compared ADHD children with controls on the ToL (Geurts et al., in press; Houghton et al., 1999; Wiers et al., 1998), and failed to find group differences. Some studies with the Tower of Hanoi (Aman et al., 1998; Pennington et al., 1993; Weyandt & Willis, 1993), but not all (Ozonoff & Jensen, 1999) have reported a planning deficit in ADHD.

The absence of a set-shifting deficit in ADHD was robust in this study, as it was shown both in the ANOVAs and in the ANCOVAs. The dependent measures used were percentage perseverative responses and perseverative errors. Pennington and Ozonoff (1996) reported that WCST deficits in ADHD are less consistent than other EF deficits. However, a more recent review (Sergeant et al., 2002) concluded that most WCST studies could distinguish ADHD from normal controls, but findings depend on which variables were used. We calculated percentages in order to control for total number of trials administered. In most other studies, absolute numbers of perseverative responses or errors were used. Our findings are in concordance with the few ADHD studies using percentages perseverative responses and/or errors (Geurts et al., in press; Grodzinsky & Barkley, 1999; Grodzinsky & Diamond, 1992).

The absence of a deficit in working memory was robust, as shown in both ANOVAs and ANCOVAs. We used an abstract version of the SOP. Only if the increase in errors with increasing difficulty was larger for the ADHD than for the NC group, was this interpreted as a deficit in working memory. Three other studies have employed the SOP with ADHD and normal children (Geurts et al., in press; Shue & Douglas, 1992; Wiers et al., 1998). As here, Geurts et al. and Shue and Douglas did not find a group by difficulty interaction for the abstract version. In Wiers et al.'s study, the ADHD group committed more errors than normal controls. However, this is not necessarily a working memory deficit, since no group by difficulty interaction was demonstrated. Séguin et al. (1999) found no correlation between ADHD symptoms and SOP performance.

No deficit in ADHD was found for semantic fluency. The letter fluency deficit was eliminated after covariation of age and IQ (containing the non-EF control measure Vocabulary). This finding is in line with Pennington and Ozonoff's (1996) review. Grodzinsky and Barkley (1999) found the group classification rate (ADHD vs. NC) for fluency to be modest. Sergeant et al. (2002) reported that most semantic fluency studies have not found deficits in ADHD. However, a recent study reported a semantic fluency deficit in ADHD (Geurts et al., in press). For letter fluency, results of other studies are inconclusive. Some studies did not find group differences (Fischer et al., 1990; Loge et al., 1990; Reader et al., 1994; Schuerholz et al., 1998), whereas other studies did (Geurts et al., in press; Grodzinsky & Diamond, 1992; Koziol & Stout, 1992; Pineda et al., 1999). In Pineda et al.'s study, the deficit remained after covariation of age. Grodzinsky and Diamond found that a letter fluency deficit remained after controlling for language development, word knowledge, and age, although the effect size was small to medium. Their groups were almost three times as large as our samples, indicating that small to medium effects can be only demonstrated in large samples. In Koziol and Stout's study, age and IQ were not covaried, because groups did not differ on these variables. In our study, groups did not significantly differ for age or Vocabulary, but entering these variables as covariates resulted in a loss of group differences.

Taking the EF results together, no EF deficits in boys with ADHD remained after covariation of age and IQ. Although we cannot generalize to an ADHD population as a whole since this group consisted of *boys* with ADHD only, and a substantial portion of the group had comorbid ODD, these modest results do not provide supporting evidence for models proposing an EF deficit as *the* core problem in ADHD (e.g., Barkley, 1997a, 1997b). Furthermore, given the small to medium effects sizes in the current study, EF deficits would only be observed in large samples. Our findings are not in line with Barkley's model, which would predict a deficit in all three forms of response inhibition, and in other EF domains.

An important issue is the presence of comorbid ODD/CD in the current ADHD group. About half of the children with ADHD had ODD. This suggests that our ADHD sample was representative, because there is considerable overlap between ADHD and ODD (Angold, Costello, & Erkanli, 1999; Biederman, Newcorn, & Sprich, 1991). It is unknown what the role of comorbid ODD is in the current findings. Symptoms of ODD were not entered as a covariate, because ODD predicted group membership perfectly. Recent studies suggest that EF deficits in ADHD are independent of comorbid ODD (Klorman et al., 1999; Nigg, Hinshaw, Carte, & Treuting, 1998; Oosterlaan, Scheres, & Sergeant, submitted).

It could be argued that EF deficits were not found in ADHD, because such a deficit is expected to be found only in ADHD-C and not in ADHD-I (Barkley, 1997a, 1997b). However, there is equivocal evidence for the idea that EF deficits are specifically related to ADHD-C. Some studies have supported this idea (e.g., Houghton et al., 1999; Klorman et al., 1999; Lockwood, Marcotte, & Stern, 2001; Nigg, Blaskey, Huang-Pollack, & Rappley, 2002). However, Houghton et al.'s conclusion was largely based on scores on the interference condition in the Stroop Test, without controlling for color naming. When color naming was controlled for, children with different types of ADHD performed similarly. Another study showed that symptoms of inattention, and not symptoms of hyperactivity/impulsivity were responsible for the inhibition deficit in ADHD (Chhabildas et al., 2001). Recently, Murphy et al. (2001) did not find EF differences between different types of ADHD. Therefore, it remains unclear whether deficits in EF are specifically related to ADHD-C. Because of too small ADHD subtype sample sizes, we did not include subtype analyses in this paper. Exploratory subtype analyses, however, yielded no differences for any EF measure between children with different types of ADHD (data available from the first author).

Generally, the correlations between the different inhibition measures were low, and correlations between tasks within a domain of inhibition were not higher than correlations between tasks across domains of inhibition. Only for the two versions of the Stop Paradigm a high positive correlation was obtained. This was expected, since both versions are supposed to measure the same process. However, unexpectedly, there was an absolute difference in SSRT between the two versions of the task.

SSRT is most reliably estimated when percentage inhibition is 50 (Band, van der Molen, & Logan, 2003). Therefore, SSRT in the Stop Paradigm with fixed intervals is less reliable because percentage inhibition is not necessarily 50%. SSRTs are usually underestimated when percentage inhibition is below 50 and overestimated when percentage inhibition is above 50 (Band et al., 2003). Here, percentage inhibition was 58.3 in the Stop Paradigm with fixed intervals. Therefore, in order to investigate whether SSRT was overestimated, we calculated SSRT for the point in the inhibition curve at which percentage inhibition was 50. This yielded an SSRT of 225 ms, which is shorter than the SSRT averaged over the four intervals (244 ms), and closer to the SSRT in the Stop Paradigm with tracking mechanism averaged over the two groups (198 ms) (data available from the first author). This suggests that SSRTs in the Stop Paradigm with fixed intervals were overestimated. Future work on the two versions of the Stop Paradigm is recommended.

The low correlations between inhibition tasks provide no evidence for the idea that these tasks measure the same underlying construct. Secondly, as long as tasks thought to measure a certain domain of inhibition have not been proven to correlate higher with one another than with inhibition tasks thought to measure a different form of inhibition, the usefulness of a distinction between different forms of inhibition, as suggested by Barkley (1997b) is called into question. Other studies reported low correlations between different measures of inhibition or impulsivity (Olson, Schilling, & Bates, 1999; White et al., 1994). Currently, the only useful distinction seems to be the one between cognitive impulsivity (inhibitory control) and motivational components of impulsivity (Kindlon, Mezzacappa, & Earls, 1995; Nigg, 2001). Future research should focus on the validation of a subdivision of the domain of inhibition, and on the selection of valid and reliable measures.

In conclusion, the current study showed that boys with ADHD had deficits in two forms of response inhibition (inhibition of an ongoing response, and interference control), in planning, and in letter fluency. However, after controlling for age, IQ, and non-EF measures, none of these EF deficits remained. No deficits for working memory, set-shifting, and fluency were found. Finally, correlations between different inhibition measures were low, which calls into question the validity of a taxonomy of different forms of response inhibition, and the validity and reliability of current inhibition tasks.

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