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SUSTAINED ATTENTION AND EXECUTIVE FUNCTIONING PERFORMANCE IN ATTENTION-DEFICIT/HYPERACTIVITY DISORDER

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The aim of this study was to further refine the cognitive phenotype of attention-deficit/hyperactivity disorder (ADHD), with respect to the ability to sustain attention and executive functioning. Participants were 34 boys with ADHD (combined type) and 28 normal controls. The groups were closely matched for age and IQ. All participants were 12 years of age. Both groups performed a computerized sustained attention task and a response interference task. Measures related to speed, accuracy, and time on task were collected. We found that children with ADHD performed slower, less accurately, more impulsively, and with less stability than controls. Both groups produced more errors with increasing time on task, reflecting reduced vigilance. Importantly, no interaction with time on task was found. The overall pattern of results suggests that measures related to accuracy are more informative than measures related to speed of responding in refining the cognitive phenotype of ADHD.

Keywords: ***attention-deficit/hyperactivity disorder, response inhibition, sustained attention, executive functioning***

INTRODUCTION

The broad concept of attention can be subdivided into at least three major functions: orienting to sensory stimuli, performing executive functions, and maintaining the alert state (e.g., Posner & Raichle, 1994). These varieties of attention are implemented in different neural networks, and can be subject to different pathologies (Berger & Posner, 2000). There is a wealth of evidence suggesting that children diagnosed with ADHD have impairments in executive functions (most notably in inhibiting prepotent responses; Barkley, 1997), and in maintaining the alert state (e.g., Manly et al., 2001), although there is little evidence that children with ADHD have difficulty orienting to stimuli (e.g., Huang-Pollock

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& Nigg, 2003). Despite this body of evidence, neuropsychological studies comparing children with ADHD and controls sometimes yield conflicting results. For example, using the well-known Eriksen flanker paradigm (arrow version), Crone, Jennings, and van der Molen (2003) found that children with ADHD spent more time resolving the conflict between the competing responses than controls. Jonkman et al. (1999), in contrast, only found that children with ADHD made more errors than controls, whereas the response times (RTs) were essentially the same for both groups. Indeed, a large part of current research into ADHD is devoted to refining the cognitive phenotype of ADHD. This knowledge, in turn, may be used to elucidate the neurobiological underpinnings of ADHD. In this paper we will focus on two major attentional functions: maintaining the alert state and executive functions (EF). We will test whether, and to what extent, Dutch children diagnosed with ADHD show impaired performance on tasks that probe these functions relative to controls. We will first describe these two functions and their relation to ADHD in greater detail.

Sustaining attention involves the continuous maintenance over time of alertness and receptivity for a particular set of stimuli or stimulus changes (e.g., Davies, Jones, & Taylor, 1984). Maintaining performance over time requires sustained attention to a target, the organization of appropriate responses to signals, and inhibition of inappropriate responses. Sustaining attention is usually assessed using so-called continuous performance tasks (CPTs), in which subjects have to respond to a target signal and refrain from responding to nontarget signals. Crucially, the nontarget signals vastly outnumber the target signals, so that subjects (especially children with ADHD) tend to miss the target signals, and/or tend to produce false alarms to nontarget signals. Most studies using vigilance tasks (such as CPTs) provide summary measures of performance. However, in the experimenter's lab it might be that performance is also a function of time on task (see Swaab-Barneveld et al., 1998). Especially in children with ADHD, it could be the case that as the novelty of a new task 'wears off' with increasing time on task, subjects lose their interest, and become increasingly less attentive. To this end, we will adopt a CPT and investigate whether accuracy changes as a function of time on task, and whether this change is more marked for ADHD subjects than for controls.

In addition to diminished sustained attention capabilities, children with ADHD also show deficits in executive functioning, or EF. The broad concept of EF refers to a set of cognitive functions needed for self-regulation (Barkley, 1997) and for the performance of goal-directed behavior and complex tasks, including error detection and conflict resolution (Fernandez-Duque & Posner, 2001). In the current study, we tested two functions that are subserved by EF. The first is behavioral control, which refers to the ability to adjust ongoing behavior in the face of environmental circumstances. In general, after a participant produces an erroneous response, the level of cautiousness temporarily increases, leading to increased accuracy and elevated RTs on the following trial. This ability requires participants to monitor their own behavior and adjusting behavioral control accordingly. There is evidence that this ability is hampered in ADHD, so we predicted that the RT increase after an error is smaller, or even absent, in children with ADHD than controls. This prediction was tested using the RT patterns of the CPT-task (described above). A second EF function is the ability to withhold or inhibit a prepotent response. There is evidence from response interference tasks that children with ADHD suffer more than controls from Stroop interference (Carter, Krener, Chaderjian, Northcutt, & Wolfe, 1995; Salo, Henik, & Robertson, 2001) and flanker interference (discussed above). According to Barkley (e.g., 1997), poor behavioral inhibition can even be regarded as the core deficiency in ADHD, which causes secondary deficiencies in other executive functions. In this study we adopted a selective attention task in which children had to respond to a target, but only if it was present at a certain location. This thus required both identification and place determination of the target. Our main interest was in the subconditions in which the target is present, yet at the wrong place—in other words, a foil signal. In this condition, subjects have to refrain from responding to the target, arguably leading to higher RTs and/or more errors. Moreover, this foil effect was expected to be larger in children with ADHD than in controls. Finally, we tested whether children with ADHD are more prone to emitting a premature response than controls, which would indicate greater impulsivity.

The aim of this study was thus to investigate these major attentional functions in a group of children with ADHD (combined type) and a closely matched group of controls using a CPT task and a selective attention task.

METHODS

We tested two groups of children: a group of ADHD participants and a group of normal controls. The controls were matched for age and IQ with the ADHD group. All participants were males. The ADHD participants were tested at the Utrecht University Medical Center and the control group was tested at the Free University of Amsterdam.

ADHD participants

The participant group consisted of 34 boys with a mean age of 12 (mean = 11.96, SD = 1.10). The group was part of a large-scale study into neurological patterns of ADHD in high-risk families held at the University Medical Center in Utrecht. The children were all diagnosed with attention-deficit/hyperactivity disorder (combined types) using the criteria of the *Diagnostic Statistic Manual* (*DSM-IV;* American Psychiatric Association, 1994). The children who were selected had no comorbidities in other major child psychiatric problems, like conduct disorder (CD) or oppositional defiant disorder (ODD). Most participants received medication for their problem behavior. The participants stopped taking their medications 2 days before participating in the study (if they used methylphenidate) or gradually declined their use (if they used other sorts of medication). The children and their parents gave informed consent, and the study was approved by the local ethics committee. For a more detailed description of the assessment procedure, see Slaats-Willemse, Swaab-Barneveld, de Sonneville, van der Meulen, and Buitelaar (2003).

Controls

The control group consisted of 28 boys with a mean age of 12 (mean = 12.22, SD = 0.89). The children were all registered in the Netherlands Twin Registry (NTR), kept by the Department of Biological Psychology at the Free University of Amsterdam. The children were all twins or the siblings of those twins who participated in a longitudinal research project aimed at disentangling the genetics of externalizing disorders in children. There were 9 monozygotic twins (from 5 pairs), 15 dizygotic twins (from 12 pairs), and 4 additional younger or older brothers. Child Behavior Checklist (CBCL; Achenbach, 1991) data obtained from the parents revealed that the children had no major attention problems. In addition, parents of the children in the control group reported no behavioral or neurological problems. The children and parents consented to participation in the study, and the study was approved by the local ethics committee.

Procedures

Both the ADHD subjects and the controls followed the same procedures using the same materials. The children were tested on a range of neuropsychological tests and IQ tests in the morning and early afternoon. During testing a supervisor gave verbal instructions on the tasks. Supervisors were trained to give the same verbal instructions to each child, in which they placed equal emphasis on speed and accuracy. Each task was practiced as long as necessary until the child understood the tasks well enough to accurately perform the test. In between tests short breaks were given. At the end of the day, the control group was rewarded for participation with a book or CD token worth 10 euros.

Materials

The cognitive performance measures were collected using the Amsterdam Neuropsychological Tasks (ANT), a computerized neuropsychological test battery developed by de Sonneville (1999). The program records the response given and the interval between stimulus presentation and response. If a testee produced an incorrect response, the trial was repeated at the end of the test session. The program automatically generates a wide range of summary variables that are stored on the computer, which can be used in later analyses. The child was seated approximately 50 cm in front of the computer screen. Responses were given by pressing the left or right mouse button with the index fingers of each hand. The mouse was placed directly in front of the screen.

The Continuous Performance Task (CPT): Description

We used the Sustained Attention Dots task from the ANT. The task consists of a series of 600 trials. On each trial a pattern consisting of 3, 4, or 5 dots was presented (see Figure 1) on a computer screen in a random order. The dot pattern consists of random asymmetric configurations, presented within a frame of 10 × 10 cm.

A subject has to respond ‘yes’ if a 4-dot pattern is presented, and ‘no’ if a 3- or 5-dot pattern is presented. A yes-response is emitted by pressing the button of the mouse at the side of the dominant hand with the index finger of the dominant hand. A ‘no’ reaction is emitted by pressing the button of the mouse at the side of the nondominant hand with the index finger of the nondominant hand. Because of balanced presentations of the dot patterns, a noresponse (with 3 or 5 dots) is required twice as often as a yes-response (4 dots).

In case of an error response a beep signal is given by the computer. Reaction times are allowed to vary between 200 and 8000 ms. Responses made before 200 ms were

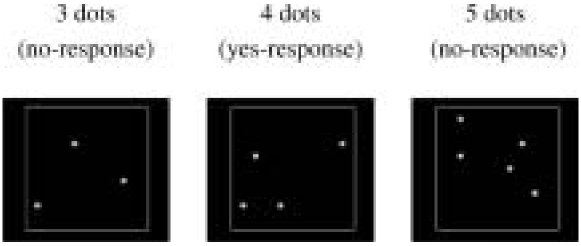

Figure 1 Example of the stimulus pattern used in the CPT task.

considered as impulsive hits on the mouse button, and were labelled accidental responses. The interval between a response and the next stimulus is fixed at 250 ms. Because of the variable response latencies, the task is self-paced.

CPT: Data Analysis

The 600 trials of the CPT were grouped into 50 series of 12 trials. For each series we determined the mean series time (mean tempo), the standard deviation in tempo (fluctuation), and percentage of errors. Mean tempo can be used as an indicator of processing speed, and the fluctuation in tempo can be used to assess the ability to maintain stable performance over time.

In order to study performance change over the course of the experiment the series were grouped into 5 blocks of 10 series (120 trials each). This allowed us to investigate whether accuracy would change as a function of time on task, and whether it does so differentially for the two groups. In order to be included in the analyses, participants' performance had to be at least 60% accurate in each of the 5 trial blocks.

Behavioral control was indexed by the extent to which RT was elevated directly after an error had been committed. To this end we derived a parameter called 'shift,' which is calculated as follows: $\text{shift} = 100 \times [(RT_{\text{after error}} - RT_{\text{after correct}})/RT_{\text{after correct}}]$. Shift is thus computed as a percentage of the regular RTs. Taking more time to process a signal after making an error is an adequate behavioral adjustment to feedback, so shift can therefore be used as a measure of behavioral control.

Response impulsivity was indexed by the number of accidental responses. Using a chi-square test, we examined whether the number of participants making at least two accidental responses was greater in the ADHD group than in the control group (cf. Slaats-Willemse et al., 2003).

The Selective Attention (SA) Task: Description

In the SA task participants are presented with two different consonant letters shown on either one of two diagonals, the top-left to bottom-right or the top-right to bottom-left diagonal. The task requires participants to respond by pressing the yes-key when the target consonant ('l') is shown, *only* when this consonant is shown on the relevant top-left to bottom-right diagonal. If the target letter is absent from the display, or if it is present but on the irrelevant top-right to bottom-left diagonal, a no-response is required. Examples of the possible stimulus signals are shown in Table 1. The most informative trials are the ones in which the target is present yet at the irrelevant diagonal (the T(+)D(-) trials), because with these trials participants have to suppress responding to the foil.

Table 1 Stimulus Types, Stimulus Signals, and Required Responses in the Selective Attention Task.

Stimulus type	T(+)D(+)	T(-)D(+)	T(+)D(-)	T(-)D(-)
Example of stimulus signal	W :: + :: L	H :: + :: S	:: L + D ::	:: K + R ::
Required response	Yes	no	no	no

Note. T(+) refers to the presence of the target letter; T(-) refers to the absence of the target letter; D(+) refers to the relevant diagonal; D(-) refers to the irrelevant diagonal. Participants had to press the yes-key when the target letter ("l") was present, and when it occurred on the relevant diagonal, otherwise they had to press the no-key.

The task consists of 120 trials. The presentation of signals is balanced for response so that an equal number of yes-responses and no-responses is required. The 120 trials consist of 60 T(+)D(+) trials, 20 T(+)D(-) trials, 20 T(-)D(+) trials, and 20 T(-)D(-) trials.

The stimulus appears for 300 ms. Reaction times are allowed to vary between 200 and 8000 ms. Responses made before 200 ms were considered as impulsive hits on the mouse button, and were labelled accidental responses. The interval between a response and the next stimulus is fixed at 1,200 ms, including a 500-ms period during warning signal/fixation point at the end of the interval. Because of the variable response latencies, the task is self-paced.

SA: Data Analysis

For both groups we calculated the mean response speed, fluctuations in response speed, and overall accuracy. In order to be included in the analyses, participants' performance had to be at least 60% accurate in each of the 4 trial categories. Of most importance is the performance *difference* between T(+)D(-) trials (i.e., trials that contain a foil) and the T(-)D(-) trials (no foil). It was expected that (a) participants would react more slowly to the T(+)D(-) trials, (b) participants would more often produce a false alarm to the T(+)D(-) trials, and (c) these differences would be exaggerated in children with ADHD. Similar to the CPT task, we examined whether the number of pariticipants making at least two accidental responses was greater in the ADHD group than in the control group.

RESULTS

CPT task. None of the participants made more than 40% errors, so all data were included in the analyses. Children with ADHD reacted slower overall than controls. The mean time to complete a series of 12 trials was 10.70 s for controls and 13.04 s for children with ADHD. This difference was significant (T(60) = 3.62, $p < .001$). Also, children with ADHD were more variable in their response time patterns within a series than controls (2.6 vs. 1.53 s, respectively). This difference was also significant ($T(60) = 4.18$, $p < .001$).

In order to study the putative effect of accuracy loss across the experimental session, we performed a 2 × 5 analysis of variance (ANOVA) on the percentage of correct responses, with group (ADHD vs. controls) as between-subject factor, and trial block (1 to 5) as within-subject factor. We found a main effect of blocks, $F(4, 240) = 3.87$, $p < .01$, indicating that accuracy decreased over the course of the experiment. There was also an effect of group: children with ADHD were overall less accurate than controls, $F(1, 60) = 9.00$, $p < .001$. As can be seen from Figure 2, the lines for both groups across trial block are virtually parallel, and the interaction between group and trial block was not significant.

In order to study the effects of performance adjustments after an error had been committed, we classified (correct) trials according to whether they were preceded by a correct trial, or whether they were preceded by an error, separately for both groups. For both groups we found an increase in reaction time after an error; for children with ADHD, RT increased from 1076.7 ms to 1533.8 ms (40.4% increase), and for controls, it increased from 882.1 ms to 1320.0 ms (46.0% increase). However, a *T*-test revealed that this increase was of equal magnitude for both groups.

The number of accidental responses differed significantly between the 2 groups ($\chi^2 = 5.47$, $p < .05$); 82% of the ADHD group made two or more errors, as opposed to 0% in the control group.

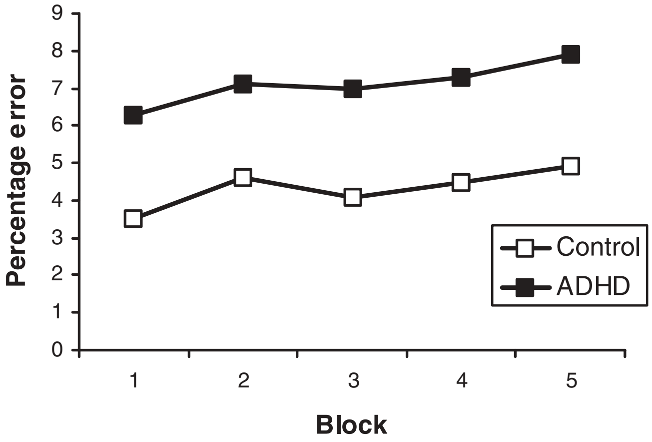

Figure 2 Accuracy (percentage error) for the CPT task as a function of trial block, plotted for both groups.

SA Task. The accuracy criterion resulted in 7 excluded cases (2 controls and 5 children with ADHD). A *T*-test revealed that children with ADHD responded slower overall than controls; 947 vs. 836 ms, respectively, $T(52) = 2.26$, $p < .05$. Also, children with ADHD had a significantly higher error rate than controls; 10.4 % vs. 5.0%, $T(52) = 3.15$, $p < .01$. However, the variability in response speed was equal across the groups (310 vs. 382 ms). The overall performance parameters thus revealed substantial performance deficits in children with ADHD.

In order to test for the effects of the foil on attention, we directly compared the subsets of trials with the target present, at the irrelevant diagonal [T(+)D(-)] to the trials with the target absent, and the irrelevant diagonal [T(-)D(-)], for both groups. In both cases participants have to give a no-response due to the irrelevant stimulus diagonal. It is expected that RTs will be slower and errors higher in the former case than the latter case, and that this difference is exaggerated in ADHD. We performed a 2 × 2 ANOVA on the RTs with target (present vs. absent) as within-participants factor, and group as between-participants factor. The main effect of target was significant, $F(1, 53) = 4.05$, $p < .05$, indicating that subjects took more time to give a no-response to the foil than to the nontarget signal (941 vs. 895 ms, respectively). Second, the main effect of group was significant, indicating again that ADHD children were slower than controls, $F(1, 53) = 4.72$, $p < .01$. However, the crucial group by target interaction failed to reach significance ($F < 1$), which means that the distracting effect of the foil is of equal magnitude for both groups.

We performed the same analysis on the error rates. All effects were significant. The main effect of target indicated that subjects produced more false alarms to the foil signal than to the nonfoil signal, $F(1, 53) = 32.40$, $p < .001$. The main effect of group indicated that ADHD children were less accurate than controls, $F(1, 53) = 10.97$, $p < .01$. Finally, the interaction revealed that the effect of the foil was greater for ADHD children than for controls, $F(1, 53) = 4.86$, $p < .05$. These effects can be seen from Figure 3, in which we plotted for both groups the error rates as a function of signal type.

Finally, the number of accidental responses differed significantly between the 2 groups ($\chi^2 = 7.56$, $p < .05$); 77% of the ADHD group made two or more errors, as opposed to 0% in the control group.

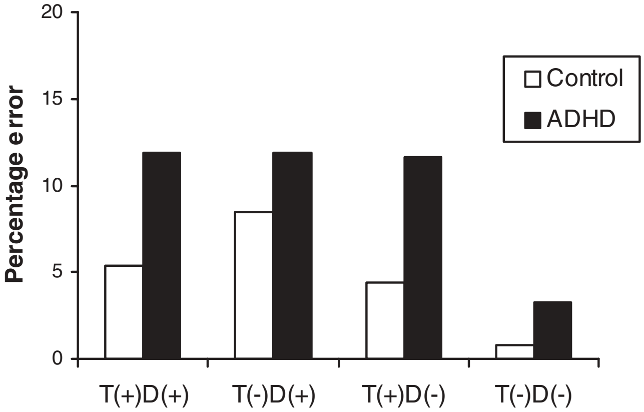

Figure 3 Accuracy (percentage error) for the selective attention task as a function of signal type, plotted for both groups.

DISCUSSION

A group of clinically referred boys with ADHD and a closely matched group of controls performed two tasks that index alertness and executive functioning. The results from our sustained attention task (the CPT task) revealed that overall children with ADHD (a) responded slower, (b) had a higher fluctuation in tempo, (c) were less accurate, and (d) were more prone to emit an accidental response than the control group. We also found that during the course of the experiment, subjects from both groups started to become less accurate, arguably as a result of a reduced level of vigilance due to the substantial time on task (600 trials). However, the *rate of increase* in errors was the same for both groups. We reasoned that the overall performance deficits often found in ADHD might start to emerge somewhat later in the experiment, and that at the beginning of a session children with ADHD are just as attentive as controls and may thus perform equally well. However, our results suggest that performance is already hampered at the start of the experimental session and does not decrease any further over time when compared to controls. These results are in line with a recent study by Epstein et al. (2003), who administered a CPT to a group of children with ADHD and a group of normal controls. These authors also observed higher fluctuation in speed and less accurate behavior (more errors of omission and commission) in participants with ADHD than in controls. However, contrary to our results, these authors also observed an interaction between time on task and group with respect to accuracy. The reason for this discrepancy is unclear.

Our CPT task also allowed us to index an important EF: the ability to adjust the level of cautiousness due to feedback. In the experiment subjects heard a beep directly after they had pressed the wrong button. This resulted in a dramatic RT increase on the following trial, reflecting an increased level of cautiousness. The percentage-wise increase was smaller for children with ADHD than for controls, but did not reach significance. The reason for this lack of significance might reside in the high variability of the data, and/or the somewhat small sample size, given that Swaab-Barneveld et al. (2000) reported a significant shift effect using the same task but with a larger group of (younger) subjects.

Another important EF concerned the ability to inhibit prepotent responses. In our selective attention task, children had to respond to the presence of a target letter, but only when it occurred along a certain diagonal. We reasoned that the presence of a foil signal—in other words, the target letter at the task-irrelevant diagonal—would strongly invite producing a yes-response. This response tendency thus needs to be suppressed, resulting in higher RTs, and/or a greater proportion of false alarms. Our overall performance parameters showed the same picture as in the CPT task; children with ADHD (a) responded slower, (b) had a higher fluctuation in tempo, (c) were less accurate, and (d) were more impulsive than the control group. With respect to the foil manipulation we found that both groups responded more slowly to the foil signal, and that they both had a higher error rate, compared to the nonfoil signal. Moreover, we found that the percentage of false alarms was significantly higher in children with ADHD than controls (see also Slaats-Willemse et al., 2003). In contrast, the RT increase due to the foil signal was equal for both groups.

To summarize, children with ADHD showed overall performance deficits compared to controls. Moreover, this deficit is already evident at the start of the experimental session and does not deteriorate (or improve) any further over time. As predicted, we also found evidence for greater impulsivity, but only with respect to the number of false alarms and the number of impulsive responses and not with respect to RTs. This suggests that accuracy of performance may qualify as a better phenotype for impulsive behavior than measures related to speed of responding.

Returning to the varieties of attention identified by Posner (e.g., Posner & Raichle, 1994), we found modest evidence for a hampered executive functioning network in ADHD but no evidence for a deficit in maintaining alertness. It is admittedly difficult to generalize from this sample, which consisted only of boys suffering from the ADHD combined subtype. There is evidence that the neuropsychological profile of ADHD is in part modulated by the ADHD subtype (e.g., Lockwood, Marcotte, & Stern, 2001) and by gender (e.g., Nigg, Blaskey, Huang-Pollock, & Rappley, 2002), and future studies using this protocol should be done with more inclusive samples so that the findings can be more widely applicable. Although our results may not directly translate to the clinician's practice, they provide a clearer picture of the cognitive processes that seem to be affected in ADHD, which thus leads to a more refined phenotype. This knowledge, in combination with emerging knowledge of which genes are involved in the functioning of different attentional networks (e.g., Fossella et al., 2002), may help to unravel the genetic pathways that are involved in this disorder.

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