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Characteristic neurocognitive profile associated with adult attention-deficit/hyperactivity disorder

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ABSTRACT

Background. It is now accepted that attention-deficit/hyperactivity disorder (ADHD) often persists into adulthood. However, relative to the considerable literature concerning the profile of neurocognitive deficits associated with this disorder in childhood, equivalent investigations in adult populations have been less common. The current study examined cognitive function in adults diagnosed with ADHD employing well-validated neuropsychological tasks.

Method. Nineteen adult patients who satisfied DSM-IV criteria for ADHD and 19 matched (gender, age and verbal IQ), non-clinical control subjects were recruited. Patients were either unmedicated or had abstained from a psychostimulant medication regime for at least 24 h prior to neurocognitive assessment. A functionally wide-ranging test battery was administered.

Results. Relative to controls, ADHD adults performed significantly worse on spatial working memory, planning, and attentional-set shifting tests and were significantly slower to respond to target stimuli on the go/no-go task. In contrast, the two subject groups performed equivalently on decision-making and pattern/spatial recognition memory assessments.

Conclusions. The demonstration of neuropsychological dysfunction in the adult ADHD cohort provides some support for the validity of this diagnosis in adulthood. In particular, there is broad consistency between the cognitive profile revealed in the current investigation and that previously demonstrated in a study of medication-naïve ADHD children. There is evidence that frontostriatal function is especially disrupted.

INTRODUCTION

Despite recognition of attention-deficit/hyperactivity disorder (ADHD) as a disabling syndrome affecting 3–7·5% of children (Castellanos & Tannock, 2002) and confirmation that the core features of inattention, restlessness and impulsivity often persist into adulthood (Weiss *et al*. 1985; Mannuzza *et al*. 1993; Kewley, 1998; Faraone *et al*. 2000), the diagnosis of adult ADHD remains controversial (Spencer *et al*. 1998). This reflects difficulties in accurate retrospective confirmation of childhood onset, lack of agreement on the range of characteristics of ADHD in adults (Wender *et al*. 2001), overlap with other disorders (such as borderline personality disorder and mood disorders), frequent co-morbidity (Biederman *et al*. 1993; Milberger *et al*. 1995) and differing diagnostic systems (Shaffer, 1994; Spencer *et al*. 1998; Sachdev, 1999; Faraone *et al*. 2000). However, a diagnosis of adult ADHD is associated with significant clinical impairment (Faraone *et al*. 2000) and there is evidence for stimulant treatment efficacy in some of these patients

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(Wender, 1998). Given that adult ADHD may be under-identified (Hornig, 1998), further examination of the characteristics of this disorder is required.

Neurocognitive deficits, particularly attentional and executive in nature, have been reported in numerous studies of children diagnosed with ADHD (Barkley *et al.* 1992; Grodzinsky & Diamond, 1992; Tannock *et al.* 1995; Pennington & Ozonoff, 1996; Seidman *et al.* 1997; Kempton *et al.* 1999; Williams *et al.* 2000; Barnett *et al.* 2001). For example, impaired performance has been demonstrated on various assessments of vigilance, sustained attention, response inhibition, planning and working memory. These cognitive dysfunctions are similar to those found in patients with acquired frontal lobe damage and has led to the hypothesis that ADHD is a neurodevelopmental disorder primarily affecting frontal cortex or those regions projecting to the frontal cortex (Shue & Douglas, 1992).

Converging evidence from neuroimaging investigations offers support for the hypothesis of frontostriatal brain dysfunction in ADHD. Studies employing magnetic resonance imaging (MRI) indicated abnormalities in the size and shape of the caudate and pallidum (Hynd *et al.* 1991, 1993; Castellanos *et al.* 1994, 1996), and reductions in right frontal cortex volume (Hynd *et al.* 1990; Castellanos *et al.* 1996). Investigation of cerebral blood flow using single photon emission computed tomography (SPECT) revealed frontal and striatal hypoperfusion in ADHD children, effects that were ameliorated by the administration of stimulant medication (Lou *et al.* 1984, 1989). More recently, functional MRI demonstrated atypical frontostriatal function in ADHD children performing two response inhibition tasks. In addition, it was shown that methylphenidate differentially modulated striatal activation in the ADHD group relative to the control group (Vaidya *et al.* 1998). In a recent review, it was concluded that frontostriatal and cerebellar dysfunction is consistently implicated in ADHD (Giedd *et al.* 2001). Although most neuroimaging investigations have focused upon ADHD in childhood or adolescence, there is now an emerging literature suggesting that abnormalities in the same brain regions underlie the adult form of the disorder (Faraone *et al.* 2000).

Recently, there has been growing interest in examining the neurocognitive profile associated with adult ADHD. Such enquiry is important in terms of rehabilitation as well as definition of phenotype. Studies have revealed deficits implicating a range of domains including attention, executive function, response inhibition, delay-aversion, time estimation, speed of information processing, arithmetic skills and response variability (Kovner *et al.* 1998; Gallagher & Blader, 2001; Johnson *et al.* 2001; Castellanos & Tannock, 2002; Woods *et al.* 2002). In the present investigation, a selection of wide-ranging neuropsychological tests was administered to a group of unmedicated adults diagnosed with ADHD. Some of these assessments have previously been employed to examine performance in separate groups of treated and untreated children diagnosed with ADHD (Kempton *et al.* 1999; Barnett *et al.* 2001) and to assess the effects of stimulant medication in a single case of adult ADHD (Mehta *et al.* 2000*a*). Most of the tasks employed were taken from the Cambridge Neuropsychological Test Automated Battery (CANTAB). This battery has been well-validated in studies of different patient groups including those with focal brain lesions and those with neurodegenerative diseases (Owen *et al.* 1990, 1991, 1995*a*, *b*, 1996*a*, *b*; Sahakian *et al.* 1990; Lawrence *et al.* 1998). In addition, a novel decision-making paradigm (Rogers *et al.* 1999) and a go/no-go test of response inhibition were utilized. The former task has been shown to be sensitive to the syndrome associated with orbitofrontal cortex damage (Rogers *et al.* 1999) and we believe that the current study provides the first structured assessment of decision-making cognition in ADHD.

METHOD

Adult ADHD patients and non-clinical control subjects

Nineteen patients (age range: 19–39 years) were recruited from a cohort of referrals to a psychiatric out-patient clinic specialising in the diagnosis and assessment of adult ADHD. All those recruited had received a diagnosis of one of the three DSM-IV (American Psychiatric Association, 1994) subtypes of ADHD at their initial adult assessment. As previously reported (van der Linden *et al.* 2000; Young & Toone, 2000),

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this assessment was performed by an experienced psychiatrist and incorporated a semi-structured interview based on the DSM-IV criteria for ADHD. First, patients were asked to rate themselves for the previous 6 months on each of the DSM-IV ADHD criteria for inattention and hyperactivity/impulsivity. A choice of 'never-sometimes-often' was offered and 'often' was taken as a positive self-rating. In order to achieve a final positive rating, it had to be subsequently endorsed by the assessor on the basis of supplementary questioning or other information. An informant, who was usually a parent, was also interviewed to establish whether there was a history of ADHD features during early childhood (i.e. before the age of 7). A score of $\geqslant 15$ was required on the informant-based Conners' Global Index-Parent Scale (CGI-P) (Conners, 2000). In addition, a positive informant-rating had to be confirmed by the assessor on the basis of supplementary questioning or other information such as school reports. Finally, a meeting was held between the assessor and another experienced psychiatrist during which an ADHD diagnosis was established only if a consensus was reached. Seven patients received the adult diagnosis of ADHD-Predominantly Inattentive Type, four of ADHD-Predominantly Hyperactive-Impulsive Type and eight of ADHD-Combined Type. Those patients who participated in the current study were all those available for assessment during the period of study, volunteered, and were not subject to the exclusion criteria. Potential patients were excluded if: (*i*) they were receiving medication (with the exception of methylphenidate, in which case they were asked to omit medication for a minimum of 24 h (at least six half-lives, see Gualtieri *et al.* 1982) prior to neuropsychological assessment); (*ii*) there was a history suggestive of 'psychosis' (except 'brief reactive psychosis' and 'psychotic disorder not otherwise specified' for <1 month) indicating DSM-IV schizophrenia, delusional disorder, a depressive disorder with psychotic features, manic episode or organic mental disorder (except psychoactive substance-induced organic mental disorders); (*iii*) if there was a history of a neurological disorder including head injury; (*iv*) if there was a history of alcohol dependence or abuse or substance use disorder in the previous 2 months; (*v*) if the initial psychiatric assessment indicated a current major depressive episode; or (*vi*) if estimated pre-morbid verbal IQ was <90.

Nineteen control subjects were recruited by advertisement in the community and were selected to match the patient group as closely as possible for age, sex and verbal IQ. An experienced psychiatrist interviewed all potential volunteers. Exclusion criteria were: a history of contact with psychiatric services; a history of having taken psychotropic medication; a history that indicated neuropsychiatric disorder; or, a current regime of any medication.

The Cambridge Local Research Ethics Committee and the Ethical Committee of the South London and Maudsley NHS Trust approved the study. All participants gave informed written consent prior to participation. The National Adult Reading Test (NART) (Nelson, 1982) was administered to all subjects in order to estimate verbal IQ. In addition, participants completed the Brief Symptom Inventory (BSI) (Derogatis, 1993). The 53-item self-report BSI reflects psychiatric symptom patterns in various settings and provides a 'Global Severity Index' (GSI) by which 'caseness', involving various clinically significant symptoms, such as depressive features, anxiety and phobias, has been thresholded at 0·6 for males and 0·8 for females. Consistent with previous reports (Downey *et al.* 1997; Pliszka, 1998), the GSI scores reflected co-morbidity in the patient group, i.e. symptoms related to those Axis I disorders which did not form part of the exclusion criteria. A summary of the demographic and clinical characteristics for the two subject groups is presented in Table 1.

Computerized neurocognitive assessment

This was carried out using a portable Advantech P100T with a touch-sensitive screen. Subjects were seated comfortably, approximately 0·5 m from the touchscreen. All participants were introduced to the touch-sensitive function of the screen by means of a simple motor screening task. The CANTAB (Cambridge Cognition, www.camcog.com) and other computerized neurocognitive tests, which were administered in the same order for all subjects, are described below. Each participant was assessed in a quiet room and was accompanied by an administrator (A. M. or E. B.) throughout the procedure.

Table 1. *Demographic and clinical characteristics of the adult ADHD patients and the matched control subjects. Data in parentheses are standard errors of the means*

	ADHD patients	Control subjects
N	19	19
Age*	27·7 (1·6)	29·5 (1·6)
Male : Female	15 : 4	15 : 4
NART predicted verbal IQ*	107·7 (1·8)	110·4 (1·6)
GSI	1·6 (0·2)	0·3 (0·08)

N, Number in group; NART, National Adult Reading Test; GSI, Global Severity Index of the Brief Symptom Inventory (Derogatis, 1993) – ratings were not available for four patients and seven controls.

* Analysis revealed that adult ADHD patients and control subjects did not differ significantly in terms of age ($t(36) = 0{\cdot}8$, $P > 0{\cdot}4$) or NART Verbal IQ ($t(36) = 1{\cdot}1$, $P > 0{\cdot}25$).

No session lasted more than 2 h and if necessary, subjects were encouraged to take short breaks.

Tests from the CANTAB batteries

Given that the spatial span and spatial working memory (Working Memory and Planning Battery), pattern and spatial recognition memory (Visual Memory Battery) and attentional-set shifting (Attentional Battery) tests have been frequently described elsewhere, only a brief summary of their respective key measures is presented in Table 2.

One-touch Tower of London

This test of spatial planning (Owen *et al*. 1995*a*) is based upon the Tower of London task (Shallice, 1982). Subjects are presented with two separate arrays of three coloured balls hanging in pockets. At the bottom of the screen is a row of numbers from 1 to 5. Subjects are required to compute 'in mind' the minimum number of moves needed to rearrange the coloured balls in one array in order to match the other array. Once decided, the subjects must touch the appropriate number at the bottom of the screen. If subjects perform incorrectly, they are able to retry until they make the correct response. Twenty problems of varying difficulty (1, 2, 3, 4 and 5 moves) are presented in a fixed pseudo-random order. The main dependent variables are the percentage of correct first choices and the mean latency of the first choices. These are taken as functions of problem difficulty.

Go/no-go task

This task examines ability to attend and respond to relevant targets while inhibiting responses to distractors. Subjects must respond to targets by pressing the space bar, but should withhold responses to distractors. Stimuli are rapidly presented in the centre of the screen, one by one. Half of the stimuli are letters (Ls) and the other half are digits (Ds). The task comprises two practice blocks followed by eight test blocks of 18 stimuli each (nine Ls and nine Ds). For each block of trials, either Ls or Ds are assigned as targets and this assignment switches on every second block. Thus, the targets for the 10 blocks can be LLDDLLDDLL or DDLLDDLLDD. As a consequence of this arrangement, four test blocks are 'shift' blocks, in which the distractors from the previous block become the targets, and four test blocks are 'non-shift' blocks, in which the targets from the previous block remain the targets. The two different target orders are counterbalanced across subjects. Subjects are encouraged to minimize errors while responding as quickly as possible to targets. The main measures of interest are target response latencies and the number of errors of commission (responses to distractors) and omission (missed targets). These variables are taken as functions of shift (shift *versus* non-shift).

Decision-making task

This computerized test of decision-making has been described in detail elsewhere (Rogers *et al*. 1999). Subjects are presented with a row of 10 boxes (some red, remainder blue) and are informed that a yellow token has been hidden, at random, inside one of them. They must decide whether this token is inside a blue or a red box and indicate their decision by touching the corresponding response panel. Next, subjects are offered a series of betting options, giving them the opportunity to place a 'bet' on their choice being correct. The location of the token is then revealed and depending on whether their original decision was right or wrong, the chosen bet is either added to or subtracted from their current points total. The task is performed in two conditions. In the 'ascending' condition, the series of offered bets starts low and becomes larger. In the 'descending' condition, the offered bets start high and become smaller. The order in which these two conditions are administered

Table 2. *Brief description of the Cambridge Neuropsychological Test Automated Battery (CANTAB) tests employed*

Task	Description	Reference	Key measures
Working Memory/Planning Battery			
Spatial span	Recall the order in which a series of boxes is highlighted	Owen *et al.* (1990)	Span score
Spatial working memory	Subjects are required to search through an array of boxes for hidden blue tokens	Owen *et al.* (1990)	Strategy score Between-search errors Within-search errors
Visual Memory Battery			
Pattern recognition	A two-choice test of abstract visual pattern recognition memory	Sahakian *et al.* (1988)	Percentage correct Correct response latency (ms)
Spatial recognition	A two-choice test of visuospatial recognition memory	Sahakian *et al.* (1988)	Percentage correct Correct response latency (ms)
Attentional Battery			
Attentional-set shifting	Visual discrimination learning paradigm designed to assess the ability to form, maintain and shift attentional-set	Downes *et al.* (1989)	No. of stages passed Errors made at the IDS and EDS stages Response latencies at IDS and EDS stages

IDS, intra-dimensional shift stage; EDS, extra-dimensional shift stage.

is counterbalanced across subjects. There are four blocks of nine trials (one trial for each of the nine possible colour ratios, 9:1 through to 1:9) in each of the two conditions. At the beginning of each of these blocks, subjects are given an initial points total of 100. The main measures of interest are the speed of decision-making (the time to decide whether the token is in a red or blue box), the quality of decision-making (the percentage of trials on which subjects chose the more likely outcome) and the percentage bets made (the percentage of the total points placed on a choice, when the choice was the more likely outcome). The former two variables are taken as functions of the ratio of red and blue boxes (9:1, 8:2, 7:3, 6:4). The latter measure is taken as a function of ratio (9:1, 8:2, 7:3, 6:4) and condition (ascend, descend).

Data analysis

As and when appropriate, *t* tests, univariate or repeated measures analysis of variance (ANOVA) or Mann–Whitney *U* tests were employed. For the attentional-set shifting test, the numbers of subjects either succeeding or failing to complete the entire task were cast into a contingency table and analysed using the likelihood ratio method as described by Robbins (1977). This test is especially useful when matrix cells contain fewer than five observations. The statistic reported is 2i and is distributed as χ^2. Although data presented are untransformed means, suitable transformations were carried out where necessary to stabilize variance or reduce skew in the distributions (Howell, 1997). In those instances in which there was departure from the assumption of homogeneity of covariance in repeated measures ANOVA, the degrees of freedom were adjusted using a value of epsilon calculated by either the Greenhouse–Geisser (Greenhouse & Geisser, 1959) or the Huynh–Feldt (Huynh & Feldt, 1976) procedure. As recommended by Howell (1997), when the value of epsilon computed by the Greenhouse–Geisser procedure is near or above 0·75, the value derived using the Huynh–Feldt procedure is preferred. With the exception of the likelihood ratio test, data were analysed using the Statistical Package for the Social Sciences (SPSS) (Nie *et al.* 1970). As the aim of this study was to determine the overall neuropsychological profile in adult ADHD, there was equivalent interest in demonstrating the absence as well as the presence of significant effects implicating group. Considering that these effects are subject to Type II and Type I errors, respectively, a significance threshold of $P = 0{\cdot}05$ was employed.

RESULTS

Spatial span (Table 3)

The main measure of interest was the longest spatial sequence correctly reproduced by each

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Table 3. *Mean scores for both subject groups on a selection of neuropsychological performance measures. Statistical analyses are described in the text. Data in parentheses are standard errors of the means*

	ADHD patients	Control subjects
Spatial span	5·7 (0·37)	6·6 (0·36)
Spatial working memory		
Within-search errors (total)	2·4 (0·9)	1·9 (0·6)
Strategy score	34·7 (1·3)	29·0 (1·4)
One-touch Tower of London		
First response latency (ms) – easy	6652 (591)	6649 (490)
First response latency(ms) – difficult	15 408 (2671)	16 284 (1100)
Pattern recognition memory		
Correct, %	84·9 (4·1)	89·2 (3·0)
Correct response latency (ms)	2474 (488)	2135 (93)
Spatial recognition memory		
Correct, %	74·2 (2·8)	72·6 (3·6)
Correct response latency (ms)	2182 (291)	2362 (108)
Attentional-set shifting		
Passing all 9 stages, *N*	14/19	17/19
IDS latency	1443 (141)	2048 (168)
EDS latency	1601 (162)	1806 (128)
Go/no-go		
Shift latency (ms)	417 (13)	373 (6)
Non-shift latency (ms)	410 (11)	370 (5)
Shift commission errors	4·0 (0·56)	3·8 (0·51)
Non-shift commission errors	3·5 (0·45)	2·0 (0·22)
Shift omission errors	0·95 (0·28)	0·53 (0·22)
Non-shift omission errors	0·84 (0·28)	0·16 (0·12)
Decision-making		
Quality of decision-making	0·946 (0·017)	0·952 (0·014)
Speed of decision-making (ms)	2434 (176)	2650 (131)

IDS, intra-dimensional shift stage; EDS, extra-dimensional shift stage.

subject. There was a tendency for the ADHD group to perform worse than the control group ($t(36) = 1{\cdot}7$, $P = 0{\cdot}09$).

Spatial working memory (Fig. 1 and Table 3)

Since both groups committed very few between-search errors in the 4-box trials, performance was only analysed across the 6-box and 8-box trials. As expected, there was a significant main effect of difficulty ($F(1,36) = 37{\cdot}0$, $P < 0{\cdot}001$), while the ADHD group made significantly more between-search errors than the control group ($F(1,36) = 14{\cdot}2$, $P < 0{\cdot}001$; see Fig. 1). However, the interaction effect between group and difficulty was non-significant ($F < 1$). Due to low frequencies of within-search errors, these were collapsed across the difficulty levels. Analysis found no significant difference between the two groups ($t(36) = 0{\cdot}5$, $P > 0{\cdot}6$; see Table 3). Finally, the ADHD patients were significantly less efficient in their use of strategy during performance of the 6-box and 8-box trials ($t(36) = 3{\cdot}1$, $P < 0{\cdot}01$; see Table 3). For each subject group, there was a significant positive correlation between this strategy measure and the number of between-search errors committed in the 6-box and 8-box stages (ADHD group, Pearson's $r = 0{\cdot}690$, $P < 0{\cdot}01$; Controls, $r = 0{\cdot}695$, $P < 0{\cdot}01$).

One-touch Tower of London
(Fig. 2 and Table 3)

For the purpose of analysis, trials were divided into 'easy' (two- and three-move) and 'difficult' (four- and five-move) problems. In relation to the percentage of correct first choices, there was a main effect of difficulty ($F(1,36) = 39{\cdot}6$, $P < 0{\cdot}001$) indicative of subjects solving fewer 'difficult' problems on their first response. There was also a significant main effect of group ($F(1,36) = 5{\cdot}0$, $P < 0{\cdot}05$; see Fig. 2) with the ADHD group performing worse than the matched control group. However, there was no interaction effect between group and difficulty ($F < 1$). Analysis of latencies for first choices (see Table 3) showed that, as expected, there was a significant main effect of difficulty ($F(1,36) = 145{\cdot}9$, $P < 0{\cdot}001$). In contrast, the main effect of group ($F(1,36) = 1{\cdot}0$, $P > 0{\cdot}3$) and the interaction between group and difficulty ($F(1,36) = 2{\cdot}7$, $P > 0{\cdot}1$) did not approach significance.

Pattern and spatial recognition memory
(Table 3)

Analysis of accuracy and correct response latency data from both tasks revealed no significant differences between the two subject groups (Pattern recognition, % correct, $t(36) = 0{\cdot}9$, $P > 0{\cdot}35$; latency, $t(36) = 0{\cdot}7$, $P > 0{\cdot}5$; Spatial recognition, % correct, $t(36) = 0{\cdot}3$, $P > 0{\cdot}7$; latency, $t(36) = 1{\cdot}5$, $P > 0{\cdot}15$).

Attentional set-shifting test (Fig. 3 and Table 3)

Initially, the two groups were examined in relation to the proportion of subjects passing all nine stages of the task. Employing the likelihood ratio method, it was shown that there was no difference in the overall pass rates of the two groups ($2i = 1{\cdot}62$, NS; see Table 3). Assessment of the number of errors committed at the

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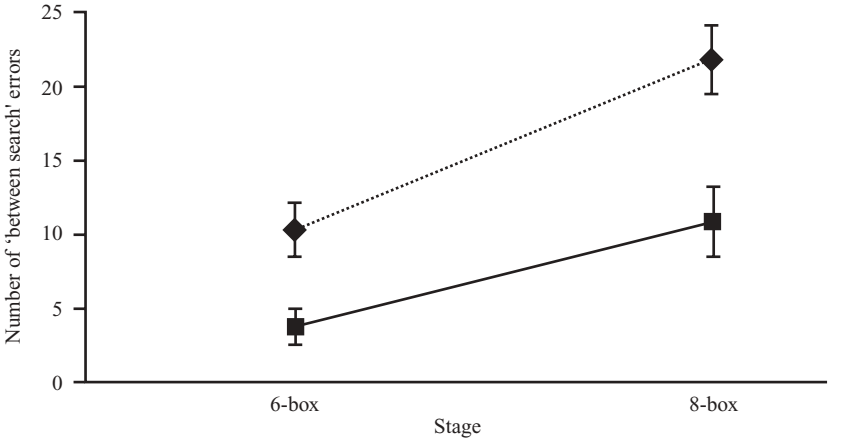

FIG. 1. Mean number of 'between-search' errors (◆·····◆, ADHD; ■—■, controls) committed during performance of the 6-box and 8-box stages of the spatial working memory task. (Bars represent ±1 S.E.M.)

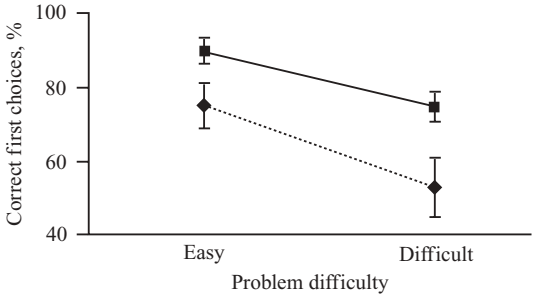

FIG. 2. Percentage of correct first choices (◆·····◆, ADHD; ■—■, controls) in the performance of the one-touch Tower of London task as a function of problem difficulty (easy *v.* difficult). (Bars represent ±1 S.E.M.)

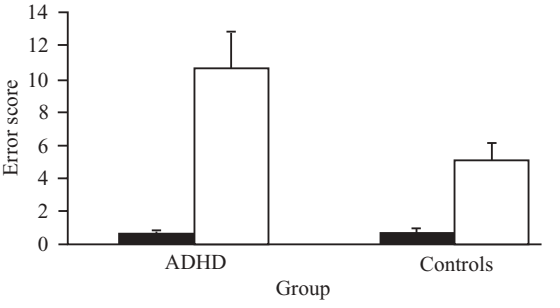

FIG. 3. Error scores at the intra-dimensional shift (■, IDS) and extra-dimensional shift (□, EDS) stages of the attentional set-shifting task. (Bars represent 1 S.E.M.)

critical intra-dimensional shift (IDS) and extra-dimensional shift (EDS) stages revealed a significant main effect of stage ($F(1,33) = 66{\cdot}9$, $P < 0{\cdot}001$). Therefore, as expected, subjects made significantly more errors at the EDS stage than at the IDS stage. Also, the interaction effect between group and stage was significant ($F(1,33) = 5{\cdot}2$, $P < 0{\cdot}05$; see Fig. 3). Analysis of simple main effects confirmed that relative to control subjects, ADHD patients committed significantly more errors at the EDS stage ($F(1,66) = 8{\cdot}4$, $P < 0{\cdot}01$), but not at the IDS stage ($F < 1$). Finally, the mean response latencies during the IDS and EDS stages were examined (see Table 3). There was a significant main effect of group ($F(1,33) = 6{\cdot}7$, $P < 0{\cdot}05$) and a significant interaction effect between the group and stage factors ($F(1,33) = 5{\cdot}2$, $P < 0{\cdot}05$). Analysis of simple main effects revealed that the control group was significantly slower in the IDS stage ($F(1,46) = 10{\cdot}9$, $P < 0{\cdot}01$), but not in the EDS stage ($F(1,46) = 2{\cdot}0$, NS).

Go/no-go task (Table 3)

The three variables of interest were target response latencies, number of commission errors, and number of omission errors. Each was taken as a function of shift (shift block *versus* non-shift block). Relative to the control group, the ADHD group was significantly slower overall at responding to target stimuli ($F(1,36) = 11{\cdot}4$, $P < 0{\cdot}01$). However, there was no evidence that subjects were slower in shift blocks compared to non-shift blocks ($F(1,36) = 1{\cdot}1$, $P > 0{\cdot}3$) and the interaction between the group and shift factors did not approach significance ($F < 1$).

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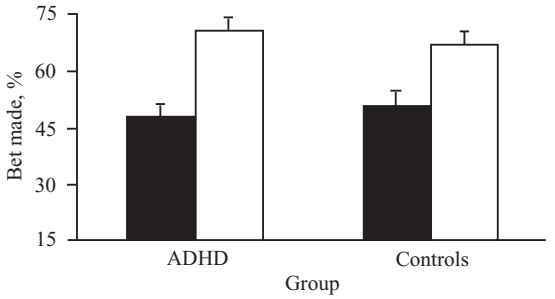

FIG. 4. Lack of effect of ADHD on bet size, as percentages of current points total, in the ascending (■) and descending (□) conditions of the decision-making paradigm. (Bars represent 1 S.E.M.)

Analysis of commission error data revealed a significant main effect of shift ($F(1,36)=6{\cdot}7$, $P<0{\cdot}05$), indicative of subjects making more of these errors in shift blocks. The main effect of group ($F(1,36)=2{\cdot}2$, $P>0{\cdot}1$) and the interaction effect between group and shift ($F(1,36)=2{\cdot}8$, $P>0{\cdot}1$) were non-significant. Finally, there was a near-significant tendency for the ADHD group to make relatively more omission errors ($F(1,36)=3{\cdot}9$, $P=0{\cdot}056$). In contrast, the main effect of shift ($F(1,36)=2{\cdot}4$, $P>0{\cdot}1$) and the interaction between group and shift ($F<1$) did not approach significance.

Decision-making task

Percentage bets (Fig. 4)

This analysis was restricted to those trials where subjects chose the most likely outcome enabling valid comparison between the performances of the two groups. As expected, percentage bets increased as the ratio of coloured boxes became more favourable ($F(1{\cdot}5,53{\cdot}9)=91{\cdot}7$, $P<0{\cdot}001$; i.e. participants bet more as ratios increased from 6:4 up to 9:1). Subjects also placed larger bets in the descend condition than in the ascend condition ($F(1,36)=33{\cdot}5$, $P<0{\cdot}001$). No other effects approached significance. In particular, there was neither a significant main effect of group ($F<1$), nor significant two-way interactions between group and condition ($F(1,36)=1{\cdot}1$, $P>0{\cdot}3$; see Fig. 4) or group and ratio ($F<1$).

Quality of decision-making (Table 3)

Subjects were significantly more likely to choose the more likely outcome as the ratio of coloured boxes increased ($F(1{\cdot}9,67{\cdot}9)=10{\cdot}9$, $P<0{\cdot}001$). However, there was no evidence that the ADHD group made the optimal choice less often than the control group ($F<1$). In addition, the two-way interaction between group and ratio was not significant ($F(1{\cdot}9,67{\cdot}9)=1{\cdot}1$, $P>0{\cdot}3$).

Speed of decision-making (Table 3)

For the deliberation time measure, no effects approached significance (Group, $F(1,36)=1{\cdot}9$, $P>0{\cdot}15$; Ratio, $F(3,108)=1{\cdot}1$, $P>0{\cdot}3$; Group × Ratio, $F<1$).

DISCUSSION

The current study demonstrated that adult ADHD is associated with cognitive impairment. Compared with controls, ADHD adults performed significantly worse on spatial working memory, planning, and attentional-set shifting tests and were significantly slower to respond to target stimuli on the go/no-go task. Furthermore, there was a tendency for these patients to attain lower spatial span scores and to make more omission errors during performance of the go/no-go test. Importantly, these impairments could not be accounted for by discrepancies in age, pre-morbid verbal IQ, or gender. In contrast, the two subject groups performed equivalently on the decision-making, and pattern/spatial recognition assessments.

Overall, these results confirm the notion that adult ADHD is associated with attentional-executive dysfunction. Moreover, our findings are consistent with the substantial literature reporting attentional and executive impairments in the childhood form of ADHD. For example, children with ADHD have been shown to be impaired on attentional-set shifting (Chelune *et al.* 1986; Gorenstein *et al.* 1989; Seidman *et al.* 1997; Pineda *et al.* 1998; Williams *et al.* 2000), spatial working memory (Tannock *et al.* 1995; Karatekin & Asarnow, 1998; Barnett *et al.* 2001), planning (Pennington *et al.* 1993; Nigg *et al.* 2002) and go/no-go tasks (Trommer *et al.* 1988; Shue & Douglas, 1992; Iaboni *et al.* 1995). Furthermore, the current results are particularly interesting when one considers a recent investigation conducted by Kempton and colleagues (1999). Employing a number of the tests used in the present study, these researchers assessed 15 stimulant-treated and 15 medication-naïve ADHD children. The untreated group exhibited

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impaired performance on spatial working memory, planning, attentional-set shifting, spatial recognition and spatial span tasks. Despite the discrepancy between findings for the spatial recognition test, this performance profile is broadly consistent with that observed for the current adult cohort. This degree of equivalence substantiates the view that, as well as clinical symptomatology, cognitive deficits persist into adulthood. In addition, Kempton *et al.* (1999) established that the executive impairments revealed in their unmedicated group were not seen in those patients receiving stimulant medication. Likewise, employing the spatial working memory task, Mehta *et al.* (2000*a*) demonstrated beneficial effects of methylphenidate administration in a single case of adult ADHD. While the latter study highlights the utility of the spatial working memory task in the cognitive assessment of stimulant treatment in adult ADHD, it is also clear that there is a need to investigate more wide-ranging neurocognitive effects of methylphenidate in larger samples.

The current study offers support for the proposition that frontostriatal dysfunction contributes to the pattern of neuropsychological deficits observed in ADHD (e.g. Shue & Douglas, 1992). For instance, in common with patients with frontal lobe lesions (Owen *et al.* 1990), the adult ADHD patients exhibited elevated between-search error scores and deficient strategy use in the spatial working memory task. Furthermore, this test has been shown to activate a neural network including the dorsolateral and ventrolateral prefrontal cortex (Owen *et al.* 1996*a*), and drug-induced changes (i.e. methylphenidate *versus* placebo) in brain activations associated with performance of this task have been observed in the dorsolateral prefrontal cortex (Mehta *et al.* 2000*b*). A similar correspondence of performance deficits between patients with frontal lobe lesions and the current ADHD group exists for both the attentional-set shifting (Owen *et al.* 1991) and planning (Owen *et al.* 1990) tasks. Also, neuroimaging investigations have revealed that these tasks, along with the spatial span task, activate defined neural networks including regions of prefrontal cortex (Baker *et al.* 1996; Owen *et al.* 1996*a*; Rogers *et al.* 2000). Thus, the deficits observed in our current ADHD sample suggest disruption to brain circuitry incorporating prefrontal cortex. This conclusion accords with the finding that the current ADHD group did not exhibit impairment in their performance of the pattern recognition task, a task that is known to be impaired following temporal, but not frontal lobe damage (Owen *et al.* 1995*b*). However, it should also be noted that the ADHD patients did not exhibit deficits on the spatial recognition memory test, an assessment that has previously been shown to be sensitive to frontal lobe damage (Owen *et al.* 1995*b*).

We believe that this study is the first to assess ADHD adults with regard to decision-making cognition. Overall, there was no evidence that the ADHD group was impaired in performing the decision-making task. Specifically, both subject groups consistently chose the more probable outcome. In addition, the groups bet almost identical percentages of their running total of points, suggesting that the ADHD patients did not have risk taking problems akin to those exhibited by patients with frontal lobe dementia (Rahman *et al.* 1999). Furthermore, both groups equivalently adjusted their bet sizes as the outcome varied in certainty, suggesting that the patients were able to evaluate and act upon reward contingencies without difficulty. Finally, and perhaps most importantly, although both groups bet more points in the descending relative to the ascending condition, this effect did not differentiate the two groups, indicating that the ADHD patients did not perform 'impulsively' (i.e. act with an increased tendency to obtain immediate reward). This is consistent with the finding that the ADHD group was not more likely to fail to inhibit responses to 'no-go' stimuli (commission error) during performance of the go/no-go task. Rather, there was a tendency for this group to miss more 'go' stimuli (omission error), indicative of inattention. Certainly, previous studies in childhood have revealed that ADHD is associated with an increased tendency to make both error types in go/no-go tasks (Trommer *et al.* 1988; Shue & Douglas, 1992) and in continuous performance tests (Corkum & Siegel, 1993). Overall, the current findings for the decision-making and go/no-go tasks suggest that disinhibition may be more prominent in childhood ADHD compared with adult ADHD, possibly reflecting the influence of maturational processes. While many children with ADHD display impulsivity in

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both everyday life and on neuropsychological testing, adults with this disorder may be, in general, more able to inhibit behaviour in structured environments (e.g. during formal testing).

The results of this study must be examined in the context of methodological limitations. First, 13 out of the 19 ADHD patients were being successfully treated with methylphenidate leading up to the study. As previously described, these subjects were required to discontinue this drug for at least 24 h prior to neuropsychological assessment, raising the possibility that the overall cognitive profile of the current ADHD group was, at least partly, accounted for by adverse transient 'rebound' effects in these subjects. Indeed, 'rebound' effects have been observed in ADHD children acutely abstaining from dextroamphetamine (Porrino *et al.* 1983). However, in a study employing behavioural rating scales, there were no significant 'rebound' effects in ADHD children omitting their regular methylphenidate doses (Johnston *et al.* 1988). Furthermore, the degree of overlap between the current findings and those of Kempton and colleagues (1999), who assessed medication-naïve ADHD children, suggests that the neuropsychological profile of our patient group is not simply an effect of stimulant withdrawal. Secondly, the current patient cohort consisted of a mixture of the three possible subtypes of ADHD, as determined by DSM-IV criteria. Regrettably, the small sample sizes for each subtype precluded statistical comparisons being performed. We acknowledge evidence suggesting that each subtype is associated with a distinct neurocognitive profile (Gansler *et al.* 1998; Dinn *et al.* 2001; Lockwood *et al.* 2001), and agree that this should provide the focus for future research. Indeed, the current DSM-IV concept of the ADHD diagnosis in adulthood may require revision in the light of further characterization of subtypes. Thirdly, consistent with previous reports (Downey *et al.* 1997; Sachdev, 1999), the current patient group demonstrated frequent co-morbidity including personality disorders, mood and anxiety disorders, and a history (not recent) of substance abuse. Given that such co-morbidity may be independently associated with cognitive deficits, it is important to acknowledge that the current findings may reflect, to some extent, this relationship. In future, it would be informative to compare the performance of an adult ADHD group with that of a matched psychiatric control group.

In conclusion, despite its limitations, the current study has demonstrated that adult ADHD is associated with characteristic impairments on a number of well-validated neuropsychological tasks. Not only does this investigation provide some support for the validity of this syndrome in adulthood, it reveals a number of potentially exciting avenues for future research. For instance, it would be interesting to investigate the wide-ranging neurocognitive effects of methylphenidate administration in sizeable adult ADHD cohorts.

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