Psychological Medicine (2014), **44**, 1989–2001. © Cambridge University Press 2013
doi:10.1017/S0033291713002547

ORIGINAL ARTICLE

A comprehensive assessment of memory, delay aversion, timing, inhibition, decision making and variability in attention deficit hyperactivity disorder: advancing beyond the three-pathway models

D. R. Coghill[1]*, S. Seth[1,2] and K. Matthews[1]

[1] *Division of Neuroscience, Medical Research Institute, University of Dundee, Ninewells Hospital, Dundee, UK*
[2] *NHS Tayside, Child and Adolescent Mental Health Service, Dundee, UK*

Background. Although attention deficit hyperactivity disorder (ADHD) has been associated with a broad range of deficits across various neuropsychological domains, most studies have assessed only a narrow range of neuropsychological functions. Direct cross-domain comparisons are rare, with almost all studies restricted to less than four domains. Therefore, the relationships between these various domains remain undefined. In addition, almost all studies included previously medicated participants, limiting the conclusions that can be drawn. We present the first study to compare a large cohort of medication-naive boys with ADHD with healthy controls on a broad battery of neuropsychological tasks, assessing six key domains of neuropsychological functioning.

Method. The neuropsychological functioning of 83 medication-naive boys with well-characterized ADHD (mean age 8.9 years) was compared with that of 66 typically developing (TYP) boys (mean age 9.0 years) on a broad battery of validated neuropsychological tasks.

Results. Data reduction using complementary factor analysis (CFA) confirmed six distinct neuropsychological domains: working memory, inhibition, delay aversion, decision making, timing and response variability. Boys with ADHD performed less well across all six domains although, for each domain, only a minority of boys with ADHD had a deficit [effect size (% with deficit) ADHD *versus* TYP: working memory 0.95 (30.1), inhibition 0.61 (22.9), delay aversion 0.82 (36.1), decision making 0.55 (20.5), timing 0.71 (31.3), response variability 0.37 (18.1)].

Conclusions. The clinical syndrome of ADHD is neuropsychologically heterogeneous. These data highlight the complexity of the relationships between the different neuropsychological profiles associated with ADHD and the clinical symptoms and functional impairment.

Received 5 July 2013; Revised 11 September 2013; Accepted 17 September 2013; First published online 31 October 2013

Key words: Attention deficit hyperactivity disorder, executive functioning, memory, neuropsychology.

Introduction

Although many psychiatric disorders are being increasingly recognized as syndromes that encompass heterogeneity across a range of levels of analysis, much research continues to assume both causal and phenotypic homogeneity (Hyman, 2010; Miller, 2010). Such oversimplification is likely to impede both scientific and clinical progress. From a clinical perspective, improved understanding of the causal and clinical heterogeneity within specific patient populations has the potential to improve the targeting and individualization of treatments. From a basic laboratory perspective, refinement of understanding of the different aetiological pathways underpinning such disorders will facilitate novel treatment development and foster the generation of an aetiologically based system of diagnosis.

Attention deficit hyperactivity disorder (ADHD), one of the most common and costly neurodevelopmental disorders (Polanczyk *et al.* 2007; Doshi *et al.* 2012), is an exemplar of a robust clinical neuropsychiatric syndrome with marked heterogeneity across multiple levels of analysis. In the past, causal models of ADHD have tended to posit a single core dysfunction (e.g. Barkley, 1997) and researchers have tended to focus on one particular aspect of functioning rather than explore potential alternative explanations (Coghill *et al.* 2005). More recently, this assumption of homogeneity has been challenged in several theoretical papers (Castellanos & Tannock, 2002; Sonuga-Barke, 2002, 2005; Nigg *et al.* 2005; Sonuga-Barke *et al.* 2008),

* Address for correspondence: Dr D. R. Coghill, Division of Neuroscience, Ninewells Hospital, Dundee DD1 9SY, UK.
(Email: d.r.coghill@dundee.ac.uk)

some of which included secondary analyses of data demonstrating substantial distributional overlap between ADHD and control samples, and marked heterogeneity at the neuropsychological level, with only a small proportion of those categorized as having ADHD demonstrating a 'deficit' on any one particular task (Nigg *et al.* 2005). Few studies have, however, formally explored neuropsychological heterogeneity within a single study. Solanto *et al.* (2001) tested Sonuga-Barke's 'dual pathway model' and demonstrated that delay aversion and inhibition could be partitioned into separable pathways, with some ADHD subjects showing inhibition deficits whereas others were delay averse. Sonuga-Barke *et al.* (2010) also demonstrated, in preschool children with ADHD, that executive dysfunction and delay aversion each made significant independent contributions to predictions of ADHD symptoms. The same group developed this work further and demonstrated a 'triple pathway', whereby children with ADHD and healthy controls differed at a group level on temporal processing, inhibitory control and delay-related tasks, with each of these representing an independent neuropsychological component with co-localization no greater than would be predicted by chance. These findings were broadly consistent with those of Kuntsi *et al.* (2001), who used three different neuropsychological tasks measuring response inhibition, working memory and delay aversion in a sample of pervasively hyperactive children identified from a general population sample of twin pairs. The hyperactive group performed worse than the control group on the delay aversion measure and on some aspects of the working memory tasks, although controlling for IQ eliminated the significant group differences on the working memory measures. No significant group differences were found on the inhibition variables. Our group has previously differentiated between high and low executive demand neuropsychological functioning in ADHD and demonstrated separable dysfunctions across these domains in both ADHD and oppositional defiant disorder (Coghill *et al.* 2007; Rhodes *et al.* 2012). Geurts *et al.* (2006) investigated the relationship between 'hot' and 'cold' aspects of neuropsychological functioning using a test of inhibitory control and a decision-making task, but did not find group differences on either task. Although important, each of these studies only addressed a subset of those aspects of neuropsychological functioning implicated in ADHD (for review, see Castellanos & Tannock, 2002; Willcutt *et al.* 2005). Only one group has previously extended this approach to a direct comparison across a broader range of cognitive processes. In a landmark study, Fair *et al.* (2012) demonstrated differences between children with ADHD and controls on a range of cognitive factors (inhibition, working memory, memory span, arousal/activation, response variability, temporal information processing and processing speed). They showed that typically developing (TYP) children can be classified into distinct neuropsychological subgroups with high precision and that some of the heterogeneity in individuals with ADHD might be 'nested' within this normal variation (Fair *et al.* 2012). Despite the many strengths of this study, a weakness, shared by many of the above-mentioned studies, is that it included children with ADHD who had previously taken, or were currently receiving, stimulant medications. Even with a 24–48-h wash-out period, it is not possible to exclude the possibility of medication effects on neuropsychological performance.

The aim of the present study was to investigate neuropsychological functioning systematically across a broad range of neuropsychological domains, previously implicated in ADHD, in a group of boys who had never been exposed to either stimulant or non-stimulant ADHD medications. Based on existing literature, we proposed a model whereby ADHD is characterized by deficits in at least six relatively independent neuropsychological domains. Accordingly, we included measures covering those domains: memory (Rhodes *et al.* 2005, 2006; Coghill *et al.* 2007), inhibitory control (Solanto *et al.* 2001; Bedard *et al.* 2003; Crosbie *et al.* 2008), delay aversion (Sonuga-Barke *et al.* 1992*a*, *b*), decision making (Garon *et al.* 2006; DeVito *et al.* 2008), timing (Toplak & Tannock, 2005) and response variability (Kuntsi *et al.* 2012). To avoid the use of an excessive number of redundant indicators in our analysis and to reduce measurement error, we adopted a confirmatory factor analysis (CFA) approach to test this model. Specifically, we predicted that, compared to TYP boys, boys with ADHD would, as a group, demonstrate poorer performance on each of these six aspects of neuropsychological functioning. However, we also predicted that each neuropsychological factor would demonstrate a degree of independence such that only a relatively small proportion of those with ADHD would demonstrate deficit on each factor.

Method

Participants

We tested two groups of boys aged between 6 and 12 years: ADHD boys and TYP healthy control boys. Exclusion criteria for both groups were: a history or current diagnosis of bipolar disorder, psychosis, major depressive disorder or post-traumatic stress disorder (PTSD), a diagnosis of pervasive developmental disorder, a history of any neurological disorder or

https://doi.org/10.1017/S0033291713002547 Published online by Cambridge University Press

seizure disorder (other than febrile seizures), intellectual impairment (IQ<80), chronic physical illness, sensory or motor impairment, current or previous exposure to stimulant medication or anticonvulsants, and a history of past or current misuse of alcohol or illegal drugs. Informed written consent to participate in the study was obtained from each child's parent(s)/guardian and assent was obtained from the child. The study was approved by the East of Scotland Research Ethics Committee (Reference number 06/S1401/36).

ADHD group

Participants were 83 boys aged between 6 and 12 years newly diagnosed with ADHD and not yet treated with medication. The boys were recruited from consecutive referrals to the Developmental Disorders Team, a public sector, specialist out-patient service situated within the Tayside Child and Adolescent Mental Health Services. The study participants were highly representative and typical of boys referred to such services in the UK. All participants were interviewed by an experienced child and adolescent psychiatrist trained in the use of the Kiddie Schedule for Affective Disorders and Schizophrenia – Present and Lifetime Version (K-SADS-PL; Kaufman *et al.* 2000) and, where feasible (n=52), the Child Attention-Deficit Hyperactivity Disorder Teacher Telephone Interview (CHATTI; Holmes *et al.* 2004), a validated telephone interview tool for the diagnosis of ADHD. Where the CHATTI could not be used, a structured narrative report from school was obtained. Data were collected from standardized questionnaires: the revised 48-item Conners' Parent Rating Scale (CPRS-48) and the revised 28-item Conners' Teacher Rating Scale, short version (CTRS-28). All participants met diagnostic criteria for ADHD as defined by DSM-IV (APA, 1994) and all three subtypes (combined, inattentive and hyperactive/impulsive) were permitted. The presence of commonly co-morbid conditions (oppositional defiant disorder, conduct disorder and anxiety disorder) were noted but did not result in exclusion.

TYP healthy control group

The control group consisted of 66 healthy boys between 6 and 12 years of age who were attending school within Tayside. This group were screened using three validated questionnaires: the Strengths and Difficulties Questionnaire (SDQ; Goodman, 2001), the 26-item revised Conners' Parent Rating Scale, short version (CPRS-26; Conners *et al.* 1998) and the CTRS-28. Symptom-free participants (within the normal range for all SDQ scales and a T score <60 on all subscales of the CPRS-26 and CTRS-28) and their parents were interviewed by an experienced child and adolescent psychiatrist using the K-SADS-PL to confirm health. Exclusion criteria were identical to those for the ADHD group, except that a previous, or current, history of any psychiatric disorder led to exclusion.

Design

The British Picture Vocabulary Scale – Second Edition (BPVS-II; Dunn *et al.* 1997) was used to estimate verbal ability. The BPVS was chosen for its ease of administration and applicability to children aged between 3 and 15 years, and because it is less heavily confounded with executive functioning abilities than other measures of cognitive ability. Family socio-economic status was estimated using the Scottish Index of Multiple Deprivation (SIMD; Office of the Chief Statistician, 2009). The SIMD uses 37 indicators in seven domains to define relative socio-economic deprivation and to map this across geographical areas in Scotland. Overall deprivation ranks are identified by postcode and converted into SIMD deciles based on the health domain rank, with a decile score of 1 being the most deprived and 10 being the least deprived. All participants attended a single neuropsychological testing session. All participants were naive to stimulant medications at both clinical assessment and neuropsychological testing.

Neuropsychological assessment

Participants were tested on a battery of seven tasks selected to represent the major neuropsychological domains previously identified to demonstrate group-level deficits in ADHD. All tasks had been extensively validated across a range of healthy and clinical populations. The tasks, apart from the Cambridge Gambling Task (CGT), have been used extensively in studies of ADHD populations. Three tasks [Delayed Matching to Sample (DMS), Spatial Working Memory (SWM) and the CGT] were selected from the Cambridge Neuropsychological Test Automated Battery (CANTAB; Morris *et al.* 1987). Additionally, we used the STOP task (Logan *et al.* 1984), the Choice Delay Task (CDT; Sonuga-Barke *et al.* 1992*a*,*b*) and two tasks assessing aspects of timing, tapping (Toplak & Tannock, 2005) and anticipation (Rubia *et al.* 1999; Tannock, 2013). Administration order was balanced across four task orders (CANTAB/non-CANTAB tasks and CGT ascending first/descending first). All tasks were presented on a high-resolution colour monitor with a touch-sensitive screen. A scheduled break of approximately 15 min was taken midway through the testing session and participants were informed that they could take further breaks as required. The tasks are described in Table 1.

https://doi.org/10.1017/S0033291713002547 Published online by Cambridge University Press

Table 1. *Descriptions of neuropsychological tasks*

Task	Description	Main outcome measures	Description	Proposed factor	References for fuller task description
Delayed Matching to Sample (DMS)	A test of the ability to remember the visual features of a complex, abstract, target stimulus and to select from a choice of four patterns either with simultaneous presentation or after a variable delay (0, 4 and 12 s)	Percentage correct simultaneous	Percentage of correct responses in the simultaneous condition	Working memory[a]	Kempton *et al.* (1999)
		Percentage correct all delays	Percentage of correct responses across the three delay conditions	Working memory	Rhodes *et al.* (2004)
Spatial Working Memory (SWM)	A self-ordered search task that assesses working memory for spatial stimuli and requires a subject to use mnemonic information to work towards a goal	Between-search errors	Number of times the subject returns to a previously searched box during a search	Working memory	Petrides & Milner (1982) Kempton *et al.* (1999)
		Strategy score[a]	Degree of organization used within the search	N.A.	Rhodes *et al.* (2004)
Cambridge Gambling Task (CGT)	A test of decision-making and risk-taking behaviours that dissociates risk taking from impulsivity by using two different conditions: ascending, where the subject must wait to make larger bets; and descending, where larger bets can be made quickly. Designed to place little demand on working memory as all the information that the subject requires is presented directly on the screen with no need to learn or recall information	Quality of decision making	The proportion of trials where the majority colour was chosen	Decision making	Clark *et al.* (2003)
		Risk adjustment	Quantifies how bets are calibrated across different levels of risk	Decision making	Rogers *et al.* (1999)
		Delay aversion	The difference in percentage bet in descending *versus* ascending conditions	Delay aversion Inhibition	
Stop Signal Task (SST)	A test of the ability to inhibit a prepared motor response. A visual choice RT task that involves two concurrent tasks, a go task and a stop task. Whether children are able to inhibit on a particular trial depends on the outcome of a race between the go and the stop processes. This version of the task used a tracking algorithm designed to find a stop signal delay that ties the race between the go process and the stop process	Stop signal reaction time	A measure of the duration of the inhibitory process, which starts from the presentation of stop signal	Inhibition	Schachar *et al.* (2000)
Choice Delay Task (CDT)	A test of the ability to tolerate delay by choosing between rewards of different values (1 and 2) that are associated with different pre-reward delays of 2 and 30 s respectively, with the stated aim being to maximize points	Percentage large reward	The percentage of times that the large reward is chosen	Delay aversion	Sonuga-Barke *et al.* (1992*a*, *b*)

Tapping Task	A test of the ability to keep time with an initially externally paced auditory stimulus with a latency of 1200 ms and then to continue at the same rate when the external stimulus is removed	Mean RT uncued	The mean RT for tapping during the uncued portion of the trial	Timing	Toplak & Tannock (2005)
		Tapping variability	The standard deviation of the RT for the uncued portion of the trial	Variability	
Anticipation Task	A test of time perception and reproduction. After a training with cued stimuli, the subject is tasked with responding within a certain time period but without cues. This task was presented in two conditions: 400 and 2000 ms	Percentage correct at 400 ms	Percentage of 'on time' responses during the 400-ms trial	Timing	Rubia *et al.* (1999) Tannock (2013)
		Variability at 400 ms	The standard deviation of the RT for the 400-ms trial	Variability	
		Percentage correct at 2000 ms	Percentage of 'on time' responses during the 2000-ms trial	Timing	
		Variability at 2000 ms*	The standard deviation of the RT for the 2000-ms trial	Variability*	

RT, reaction time; N.A., not applicable.

[a] Variables excluded from the final complementary factor analysis (CFA) model as significantly improved fit.

Data analysis

Statistical analyses were conducted using SPSS for Windows version 21 (SPSS Inc., USA) and AMOS version 21 (SPSS Inc., USA).

For the task-level comparisons between the ADHD and TYP groups, data meeting assumptions of normality and homogeneity of variance were analysed using ANCOVA (Winer *et al.* 1991). All other data were compared using appropriate non-parametric tests (e.g. the Mann–Whitney *U* test). Additional repeated-measures ANOVAs were conducted comparing groups on the SWM and DMS tasks across the various levels of difficulty. As ADHD boys tended to score lower on both the BPVS and the SIMD, these were used as covariates in the analyses.

A series of CFAs were performed to determine the best-fitting model for the different aspects of cognitive functioning (memory, delay aversion, decision making, timing, variability, inhibition). In addition to confirming the model, this approach has the added benefit that it reduces measurement error. All scores were transformed prior to CFA such that a positive score reflected superior performance. The maximum likelihood method was used. Fit of all models was evaluated using several indexes, including the χ^2 value, the Comparative Fit Index (CFI), Bollen's Incremental Fit Index (IFI) and the root mean square error of approximation (RMSEA). Smaller χ^2 and RMSEA values and larger CFI and IFI values indicate a better fit. In general, non-significant χ^2, RMSEA $\leqslant$0.08 and CFI and IFI>0.9 indicate a good fit (Browne & Cudeck, 1993; Kline, 2005). Several models were tested and the best model was determined by the best overall fit indices. For between-group analyses, factors were regressed for age and standardized across all participants to a mean of zero and a standard deviation of one. A series of ANOVAs were then conducted for each of these seven factors comparing the ADHD and TYP groups. Effect sizes were calculated using the methods of Cohen (1988), with an effect size of 0.3 defined as small, 0.5 medium and 0.8 large. In keeping with previous analyses within the field, 'deficit' was defined as performance within the bottom 10% of the control group (e.g. Nigg *et al.* 2005). Separate analyses regressed for age and BPVS and SIMD scores were conducted.

Results

Participant characteristics (Table 2)

Eighty-three boys with ADHD and 66 TYP boys were recruited. There were no differences between the groups with respect to age profile, but there were significant differences on BPVS scores, with ADHD boys

https://doi.org/10.1017/S0033291713002547 Published online by Cambridge University Press

Table 2. *Demographic and clinical characteristics*

	ADHD boys (n=83)	TYP boys (n=66)	F	p
BPVS standardized scores	96 (12.3) [72–137]	106 (10.6) [88–127]	29.7	<0.001
Age (years)	8.9 (1.7) [6.2–12.1]	9.0 (1.7) [6.1–12.7]	0.4	>0.05
SIMD	4.2 (2.5)	6.6 (2.0)	36.8	<0.001
CPRS inattention T score	72.3 (8.8)	48.7 (6.6)	320.5	<0.001
CPRS hyperactivity T score	79.3 (9.4)	49.5 (8.3)	403.7	<0.001
CPRS ADHD index T score	75.0 (6.0)	48.9 (7.4)	559.0	<0.001
CPRS oppositionality T score	73.5 (13.2)	49.0 (10.4)	149.6	<0.001
CTRS inattention T score	61.4 (11.3)	48.6 (8.9)	55.5	<0.001
CTRS hyperactivity T score	68.9 (10.9)	47.2 (7.1)	191.9	<0.001
CTRS ADHD index T score	68.3 (9.6)	47.7 (8.1)	187.8	<0.001
CTRS oppositionality T score	69.5 (17.9)	47.4 (7.3)	86.0	<0.001
K-SADS total inattentive symptoms	7.3 (1.5)	0.2 (0.5)	1307.0	<0.001
K-SADS total hyperactive/impulsive symptoms	7.2 (2.1)	0.3 (0.8)	649.4	<0.001
Co-morbid oppositional defiant disorder	58.3	0	N.A.	N.A.
Co-morbid conduct disorder	2.4	0	N.A.	N.A.
Co-morbid anxiety	22.6	0	N.A.	N.A.
Co-morbid depression	0	0	N.A.	N.A.
Co-morbid PTSD	1.2	0	N.A.	N.A.

ADHD, Attention deficit hyperactivity disorder; TYP, typically developing; BPVS, British Picture Vocabulary Scale; SIMD, Scottish Index of Multiple Deprivation; CPRS, Conners' Parent Rating Scale; CTRS, Conners' Teacher Rating Scale; K-SADS-PL, Kiddie Schedule for Affective Disorders and Schizophrenia – Present and Lifetime Version; PTSD, post-traumatic stress disorder; N.A., not applicable.

Values given as mean (standard deviation) [range] or percentage.

scoring lower than TYP boys. There were also differences with respect to estimates of socio-economic deprivation (SIMD), with the ADHD boys domiciled within areas of greater deprivation. Analyses were conducted with and without BPVS and SIMD as covariates. As the main findings for these analyses were very similar, only the non-covaried results are presented here. As expected, the two groups differed with respect to scores on clinical measures from both the CPRS-26 and the CTRS-28, and also in symptoms identified at interview with the K-SADS. Within the ADHD group, there were significant numbers of boys who met criteria for diagnoses of co-morbid oppositional defiant disorder and anxiety disorder. Analyses were conducted on both the task-level and factor-level data, comparing those boys with and without these co-morbidities. There were no group differences on any of the analyses (all p>0.05) and these data are not reported further here.

Task-level analysis of neuropsychological data

A summary of findings and means is presented in Table 3. Statistically significant group differences were found for DMS % correct all delays, SWM total between-search errors, CDT % large reward, CGT delay aversion and quality of decision making, Anticipation Task % on time at 400 and 2000 ms and variability at 400 m, and Tapping Task mean reaction time (RT) uncued trials. No group differences were found for DMS % correct at the simultaneous condition, SWM strategy score, CGT risk adjustment, Anticipation Task variability at 2000 ms, Tapping Task uncued variability or the STOP Task stop-signal reaction time (SSRT). The correlation matrix for the neuropsychological tasks included in the CFA is presented in Supplementary Table S1 online. Most tasks were moderately correlated apart from Tapping Task mean RT uncued trials and uncued variability, the Anticipation Task variability at 400 ms and the STOP Task SSRT, which showed significant correlations with only a proportion of the other tasks.

CFA

We conducted a CFA according to the conceptual model that had guided our work and informed our choice of tasks. The one-factor model did not fit the data adequately (χ^2_{55}=127, CFI=0.71, IFI=0.81, RMSEA=0.094), justifying the building of a multifactorial model. The best-fitting six-factor model that conformed to our theoretical approach, with factors for memory, inhibition, delay aversion, decision making, timing and variability, is shown in Fig. 1.

https://doi.org/10.1017/S0033291713002547 Published online by Cambridge University Press

Table 3. *Task-level neuropsychological performance*

Task	ADHD boys	TYP boys	*F*	*p*
DMS % simultaneous	88.2 (15.4)	92.2 (11.6)	1.3	>0.05
DMS % correct all delay	56.8 (17.3)	70.3 (17.6)	22.0	<0.001
SWM total BSE	55.8 (15.5)	44.8 (18.1)	5.6	0.019
SWM strategy score	37.4 (3.8)	35.8 (6.2)	1.1	>0.05
CDT % large reward	31.9 (23.7)	51.5 (34.2)	17.0	<0.001
CGT delay aversion	0.63 (0.18)	0.52 (0.22)	6.1	0.014
CGT quality of decision making	0.67 (0.19)	0.77 (0.17)	5.5	0.02
CGT risk adjustment	0.14 (1.14)	0.37 (0.93)	2.3	>0.05
Anticipation at 400 ms % on time	62.7 (20.0)	72.4 (17.4)	MWU 1731	0.006
Anticipation at 2000 ms % on time	22.6 (20.8)	37.4 (25.3)	MWU 1493	0.001
Tapping Task mean RT uncued trials	849 (1083)	994 (293)	MWU 1442	<0.001
Anticipation Task 400 ms variability	170 (53)	146 (58)	7.0	0.009
Anticipation Task 2000 ms variability	164 (85)	188 (61)	2.7	>0.05
Tapping Task uncued variability	209 (267)	167 (94.8)	MWU 2413	>0.05
STOP task SSRT	324 (177)	299 (164)	MWU 2128	>0.05

ADHD, Attention deficit hyperactivity disorder; TYP, typically developing; DMS, Delayed Matching to Sample; SWM, Spatial Working Memory; BSE, between-search errors; CDT, Choice Delay Task; CGT, Cambridge Gambling Task; RT, reaction time; SSRT, stop-signal reaction time; MWU, Mann–Whitney *U* test.

Values given as mean (standard deviation).

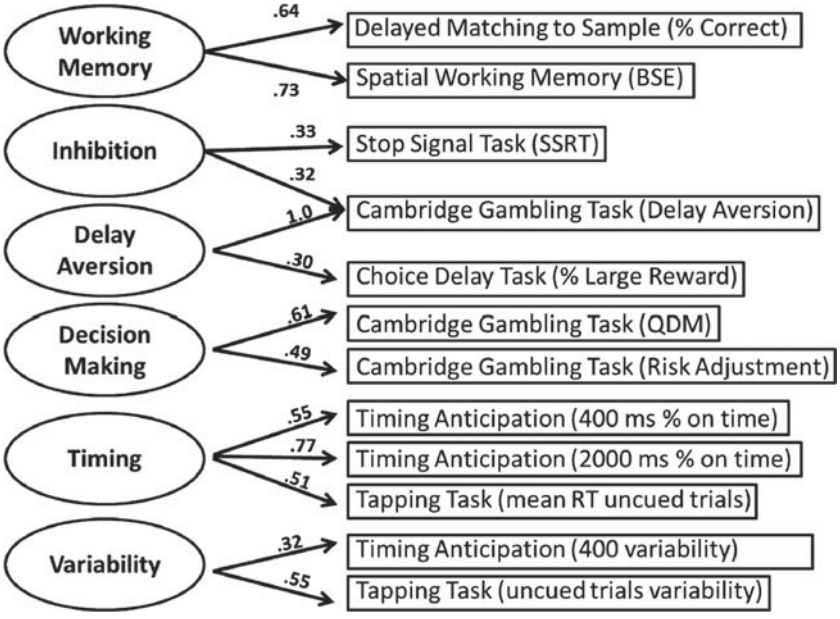

Fig. 1. Data reduction for neuropsychological measures. Confirmatory factor analysis (CFA) was used to conduct rational reduction of the measures listed in Table 1. Shown is the conceptual model that depicts how we hypothesized that our measured variables relate to six latent factors and displays the factor loadings for this six-factor model. For ease of presentation, the figure does not display error terms, cross-loadings or correlations among latent factors. BSE, Between-search errors; QDM, quality of decision making; SSRT, stop signal reaction time.

Fit was acceptable (χ^2_{38}=66, p<0.001, CFI=0.93, IFI=0.93, RMSEA=0.065) and was preferable to a model in which CGT delay aversion (which is described as an index of both impulsivity and delay aversion) was only associated with the delay aversion factor (χ^2_{39}=103, CFI=0.83, IFI=0.83, RMSEA=0.174). Three of the neuropsychological variables (DMS % correct at simultaneous condition, SWM strategy score and Anticipation Task variability at 2000 ms) were excluded from the final six-factor model as their inclusion

https://doi.org/10.1017/S0033291713002547 Published online by Cambridge University Press

Table 4. *Comparison of ADHD and TYP boys across six domains of neuropsychological functioning*

	Raw scores						Adjusted for age, BPVS and SIMD			
Factor	ADHD Mean (S.D.)	TYP Mean (S.D.)	*F*	*p*	Effect size (δ)	% with deficit	ADHD Mean (S.E.)	TYP Mean (S.E.)	*F*	*p*
Memory	−0.43 (1.00)	0.54 (1.04)	33.7	<0.001	0.95	30.1	−0.30 (0.11)	0.38 (0.13)	14.3	<0.001
Inhibition	−0.12 (0.44)	0.15 (0.44)	13.2	<0.001	0.61	22.9	−0.11 (0.05)	0.13 (0.06)	8.7	0.004
Delay aversion	−0.37 (0.96)	0.47 (1.10)	24.4	<0.001	0.82	36.1	−0.30 (0.12)	0.38 (0.13)	13.4	<0.001
Decision making	−0.20 (0.85)	0.25 (0.79)	10.8	<0.001	0.55	20.5	−0.13 (0.09)	0.17 (0.11)	4.2	0.04
Timing	−0.36 (1.16)	0.43 (1.07)	18.2	<0.001	0.71	31.3	−0.30 (0.13)	0.34 (0.15)	9.9	0.002
Variability	−0.10 (0.79)	0.13 (0.40)	4.9	0.029	0.37	18.1	−0.14 (0.6)	0.14 (0.40)	2.9	0.05

ADHD, Attention deficit hyperactivity disorder; TYP, typically developing; BPVS, British Picture Vocabulary Scale; SIMD, Scottish Index of Multiple Deprivation; S.D., standard deviation; S.E., standard error.

resulted in either inadmissible solutions or a poor fit. The model was also comparable to the best-fitting five-factor (χ^2_{44}=70, CFI=0.93, IFI=0.93, RMSEA=0.063) and four-factor models (χ^2_{48}=81, CFI=0.91, IFI=0.91, RMSEA=0.069). The relationship between the factors and variables for the four- and five-factor models is given in Supplementary Table S2. For our main analysis we present the results of the six-factor model as this is the most consistent with our conceptual and theoretical framework.

The impact of ADHD on neuropsychological functioning

The results of the ANOVAs comparing ADHD and TYP boys on each of the neuropsychological factors are detailed in Table 4. Compared to TYP boys, ADHD boys performed poorly on all six of the neuropsychological factors. The effect sizes for the comparison between ADHD and TYP were large for delay aversion (0.82) and memory (0.95), medium for impulsivity (0.61), decision making (0.55) and timing (0.71), and small for variability (0.37). Separate analyses regressed for age and BPVS and SIMD scores resulted in similar findings (Table 4). Based on the raw data analyses, the proportion of ADHD boys with a deficit on each factor was moderate, ranging from 18% to 36%. A quarter of ADHD boys did not exhibit a deficit on any of the six factors, with almost all of those who did have at least one deficit having deficits on no more than three factors (65%) (Table 5). No participant showed a deficit on more than four factors. The correlations between the neuropsychological factors are detailed in Table S3. Although there were several significant correlations, these were all weak, apart from the correlation between inhibition and delay aversion, which was moderate (Dancey & Reidy, 2004). To investigate the relative independence of these deficits, we further explored whether those ADHD boys who performed worse than the bottom 10% of controls on any one factor might significantly underperform with respect to the other factors, but might just miss the threshold for definition of a deficit. We conducted a series of 2 × 2 cross-tabulations comparing the proportions of boys with ADHD who scored above and below the 10th centile on one factor and between the 10th and 25th centiles on the other factors. Across all factors there were no differences in the proportion of boys performing between the 10th and 25th centiles dependent on whether or not they were in the bottom 10% on the index factor. This analysis supports the relative independence of the observed deficits and the contention of relatively distinct neuropsychological subgroups.

Table 5. *Number of neuropsychological factors on which a participant has a deficit*

	Number of tasks on which participant has a deficit						
	0	1	2	3	4	5	6
ADHD boys	25.3	28.9	16.8	19.3	9.6	0	0
TYP boys	60.6	25.8	12.1	1.5	0	0	0

ADHD, Attention deficit hyperactivity disorder; TYP, typically developing.

Deficit is defined as performing in the bottom 10% of TYP boys.

Discussion

This is the first study to compare directly the performance of a large, carefully phenotyped, medication-naive cohort of boys with ADHD with that of a

https://doi.org/10.1017/S0033291713002547 Published online by Cambridge University Press

matched cohort of healthy boys on a broad battery of neuropsychological tasks that address six of the main domains of neuropsychological functioning implicated in ADHD. Based on previous studies, we addressed two main hypotheses. First, that boys with ADHD would perform less well than TYP boys with respect to visual memory, inhibition, delay aversion, decision making, timing and response variability. This hypothesis was fully supported by the data. Second, that despite group-level differences across all neuropsychological factors, there would be considerable overlap between the neuropsychological performance of the ADHD and TYP boys and that this would be reflected by only a minority of ADHD boys demonstrating deficits in each domain. This proposition was also fully supported by the data.

These findings should be viewed with several limitations in mind. Although each of the factors in the CFA was dependent upon more than one behavioural outcome measure, it would have been preferable to have gathered data from a larger number of tasks. Sonuga-Barke *et al.* (2010) included three tasks for each domain of functioning. However, three of the seven factors assessed in the seminal study of Fair *et al*. (2012) were dependent on a single outcome measure. The decision not to increase the number of tasks was a considered and pragmatic one. Although it would have been theoretically possible to have increased the number of tasks, this would have increased the testing burden on the boys and would probably have resulted in test fatigue and increased drop-outs with data loss. One measure, the delay aversion measure of the CGT, contributed to two factors (delay aversion and inhibition) and this may account for the moderate correlation between these factors. The sample size is moderate for the statistical approaches used. In addition, as this was a cross-sectional study with an untreated newly diagnosed sample, there was limited variance in ADHD symptoms scores (all of the ADHD boys had high levels of ADHD symptoms) and it was not practical to look at the relationship between symptoms and cognition. This was a referred clinical sample that was representative of those referred and diagnosed with ADHD in the UK. However, it is not possible to say whether these findings would generalize to a population-based sample. As we only included males, and in view of the well-documented gender differences in clinical presentation of various psychiatric disorders (including ADHD), normative developmental course and normative cognitive performance, these results may not apply equally to girls with ADHD. Although the presence of co-morbid oppositional defiant disorder or anxiety disorder does not seem to have impacted on these findings, we did not assess for either specific learning disorders (e.g. difficulties with reading, writing, spelling or arithmetic) or developmental coordination disorder and it is possible that these may have exerted some impact on task performance.

Mindful of the limitations noted above, however, these are important new data that support earlier conclusions from indirect analyses and studies with a more limited scope. From a conceptual perspective, the aspects of neuropsychological functioning shown here to be associated with ADHD are mediated by a much broader distribution of brain circuitry than has traditionally been associated with ADHD. Furthermore, the confirmation that these deficits coexist, although not necessarily within the same individuals, within this sample, supports the importance of taking a broader view of the pathophysiology of ADHD. Certainly the corticostriatal circuits involved in inhibition, working memory, decision making and other aspects of executive functioning seem integral to the pathophysiology of ADHD. However, tasks such as the DMS have been demonstrated to be dependent on intact medial temporal lobe and amygdalo/hippocampal functioning (Owen *et al.* 1995), the timing tasks used here are dependent on intact cerebellar circuitry (Ivry & Spencer, 2004), and Sonuga-Barke (2002) has proposed that the motivational aspects of ADHD are dependent on mesolimbic reward circuitry. These different aspects of functioning are also dependent on different neurotransmitter substrates. For example, the DMS task has been shown to be sensitive to changes in cholinergic functioning (Robbins *et al.* 1997). It is therefore possible that the different neuropsychological profiles may predict differential responses to medications. This has yet to be tested, but may pave the way to an expanded rational pharmacology for ADHD.

From a clinical perspective, we see that, although ADHD is associated with a broad range of neuropsychological deficits, none of these are required (or necessary) for a diagnosis. Indeed, the finding that, even with such a broad battery of tasks and domain of functioning, a quarter of those with ADHD did not show deficit on any of the six neuropsychological factors is striking. This is not, of course, entirely unexpected and the proportion without a deficit is similar to that found in previous studies (Nigg *et al.* 2005; Sonuga-Barke *et al.* 2010). Nevertheless, it is not clear why increasing the breadth of neuropsychological functions assessed did not increase the proportion of individuals with a deficit in at least one domain.

Recent evidence suggests that the relationships between ADHD symptoms and cognitive performance are much more complex than originally thought. We have recently proposed that, although the symptoms of ADHD and the cognitive impairments often

https://doi.org/10.1017/S0033291713002547 Published online by Cambridge University Press

associated with ADHD are both likely to result in significant impairments, the traditional view that cognitive impairments lead directly to the symptoms of ADHD is not borne out by the data (Coghill *et al*. 2013). For example, although methylphenidate reduces symptoms and improves some aspects of cognitive functioning, the two processes do not seem to be linked, with some individuals improving symptomatically whereas other improve cognitively (Coghill *et al*. 2007). Similarly, in a study investigating the impact of methylphenidate on driving and cognition, there was an apparent dissociation between the time course of effects of a dose of OROS methylphenidate. When given at 08:00 h, the effects on both cognition and driving performance lasted until 23:00 h whereas the effects on symptoms wore off (as expected) at around 20:00 h (Wilson *et al*. 2006). Of interest, similar effects were not seen for a long-acting amfetamine preparation in the same study, suggesting the possibility of differential medication effects on cognitive functioning and performance. Further evidence for this dissociation between symptoms and cognition comes from a recent longitudinal study conducted by our group. We again found evidence that changes in symptoms, this time over a 4-year period, were not associated with changes in cognitive performance (Coghill *et al*. 2013). These findings are supported by van Lieshout *et al*. (2013), who systematically reviewed the literature pertaining to cognitive predictors of persistence of ADHD. They concluded that, although cognitive impairments in early childhood seemed to predict the development of ADHD a few years later, they did not find evidence to support the hypothesis that changes in cognitive functioning predicted either persistence or remission of ADHD.

One conclusion from these studies could be that cognition is not important in ADHD. However, we consider this would be premature. The deficits associated with ADHD are neither mild nor transient. We previously demonstrated that the performance of boys with ADHD on the DMS task used in the current study was similar to that of elderly individuals with Alzheimer's dementia (Sahakian *et al*. 1988; Rhodes *et al*. 2004). It is extremely unlikely that deficits of this magnitude do not result in significant 'real-world' behavioural impairments. The effect sizes reported here are in the moderate to large range, with only variability below 0.5. In themselves, these suggest a significant impact. However, as only a proportion of individuals had a deficit on any of the factors (range 18–36%), it seems likely that those individuals with a deficit will be very significantly impaired.

When trying to understand the relationship between the symptoms that define ADHD and associated cognitive impairments, it is important to remember that the definitions of disorders in the classification systems are designed to help differentiate between those with and those without a disorder, and also to differentiate between different disorders. By no means do they provide a complete experiential description of what it means to have a disorder. The symptoms of ADHD touch upon several of the cognitive domains investigated here, but do not necessarily address the depth of the difficulties that arise from them. For example, there are only two symptoms that address the notion of memory problems: 'Loses things' and 'Is forgetful in daily activities'. It is not surprising that deficits identified during detailed assessments of memory functioning do not correlate with such crude measures of symptom change. More work is required to better understand these complex relationships between symptoms, cognition and impairment.

In conclusion, we have demonstrated for the first time that, although at a group level, medication-naive boys with ADHD demonstrate deficits in memory, inhibition, delay aversion, decision making, timing and response variability, these performance deficits exist relatively independently of each other. In addition, within each domain of functioning, the overall group differences are driven by poor performance by only a relatively small proportion of the whole group, with the performance of most ADHD boys overlapping with healthy TYP boys. These data reinforce the notion of causal heterogeneity in ADHD and highlight the importance of considering both cognitive and symptomatic aspects of ADHD in clinical practice.

Supplementary material

For supplementary material accompanying this paper, visit http://dx.doi.org/10.1017/S0033291713002547.

Acknowledgements

We thank the patients and investigators who took part in this study. This study was supported by a small programme support grant from the Chief Scientist Office of the Scottish Government's Health Department.

Declaration of Interest

The following authors have received compensation for serving as consultants or speakers, or they or the institutions they work for have received research support or royalties from the companies or organizations indicated: D. R. Coghill (Flynn, Janssen-Cilag, Lilly, Medice, Novartis, Otsuka, Oxford University Press, Pfizer, Schering-Plough, Shire and Vifor Pharma); S. Seth (Lilly, Shire Janssen-Cilag and Oxford

University Press); K. Matthews (Bristol Myers Squibb, Cyberonics Inc,, GSK, Medtronic, Merck Serono, Reckitt Benckiser, Schering-Plough and St Jude Medical).

References

APA (1994). *Diagnostic and Statistical Manual of Mental Disorders*, 4th edn. American Psychiatric Association: Washington, DC.

Barkley RA (1997). Attention-deficit/hyperactivity disorder, self-regulation, and time: toward a more comprehensive theory. *Journal of Developmental and Behavioral Pediatrics* **18**, 271–279.

Bedard AC, Ickowicz A, Logan GD, Hogg-Johnson S, Schachar R, Tannock R (2003). Selective inhibition in children with attention-deficit hyperactivity disorder off and on stimulant medication. *Journal of Abnormal Child Psychology* **31**, 315–327.

Browne MW, Cudeck R (1993). Alternative ways of assessing model fit. In *Testing Structural Equation Models* (ed. K. A. Bollen and J. S. Long), pp. 136–162. Sage: Newbury Park, CA.

Castellanos FX, Tannock R (2002). Neuroscience of attention-deficit/hyperactivity disorder: the search for endophenotypes. *Nature Reviews Neuroscience* **3**, 617–628.

Clark L, Manes F, Antoun N, Sahakian BJ, Robbins TW (2003). The contributions of lesion laterality and lesion volume to decision-making impairment following frontal lobe damage. *Neuropsychologia* **41**, 1474–1483.

Coghill D, Nigg J, Rothenberger A, Sonuga-Barke E, Tannock R (2005). Whither causal models in the neuroscience of ADHD? *Developmental Science* **8**, 105–114.

Coghill DR, Rhodes SM, Matthews K (2007). The neuropsychological effects of chronic methylphenidate on drug-naive boys with attention-deficit/hyperactivity disorder. *Biological Psychiatry* **62**, 954–962.

Coghill DR, Hayward D, Rhodes SM, Grimmer C, Matthews K (2013). A longitudinal examination of neuropsychological and clinical functioning in boys with attention deficit hyperactivity disorder (ADHD): improvements in executive functioning do not explain clinical improvement. *Psychological Medicine*. Published online: 19 July 2013. doi:10.1017/S0033291713001761.

Cohen J (1988). *Statistical Power Analysis for the Behavioral Sciences*, 2nd edn. Lawrence Earlbaum Associates: Hillsdale, NJ.

Conners CK, Sitarenios G, Parker JD, Epstein JN (1998). The revised Conners' Parent Rating Scale (CPRS-R): factor structure, reliability, and criterion validity. *Journal of Abnormal Child Psychology* **26**, 257–268.

Crosbie J, Perusse D, Barr CL, Schachar RJ (2008). Validating psychiatric endophenotypes: inhibitory control and attention deficit hyperactivity disorder. *Neuroscience and Biobehavoral Reviews* **32**, 40–55.

Dancey C, Reidy J (2004). *Statistics Without Maths for Psychology: Using SPSS for Windows*. Prentice Hall: London.

DeVito EE, Blackwell AD, Kent L, Ersche KD, Clark L, Salmond CH, Dezsery AM, Sahakian BJ (2008). The effects of methylphenidate on decision making in attention-deficit/hyperactivity disorder. *Biological Psychiatry* **64**, 636–639.

Doshi JA, Hodgkins P, Kahle J, Sikirica V, Cangelosi MJ, Setyawan J, Erder MH, Neumann PJ (2012). Economic impact of childhood and adult attention-deficit/hyperactivity disorder in the United States. *Journal of the American Academy of Child and Adolescent Psychiatry* **51**, 990–1002.

Dunn L, Dunn L, Whetton C, Burley J (1997). *British Picture Vocabulary Scale*, 2nd edn. NFER-Nelson: London.

Fair DA, Bathula D, Nikolas MA, Nigg JT (2012). Distinct neuropsychological subgroups in typically developing youth inform heterogeneity in children with ADHD. *Proceedings of the National Academy of Sciences USA* **109**, 6769–6774.

Garon N, Moore C, Waschbusch DA (2006). Decision making in children with ADHD only, ADHD-anxious/depressed, and control children using a child version of the Iowa Gambling Task. *Journal of Attentional Disorders* **9**, 607–619.

Geurts HM, van der Oord S, Crone EA (2006). Hot and cool aspects of cognitive control in children with ADHD: decision-making and inhibition. *Journal of Abnormal Child Psychology* **34**, 813–824.

Goodman R (2001). Psychometric properties of the Strengths and Difficulties Questionnaire. *Journal of the American Academy of Child and Adolescent Psychiatry* **40**, 1337–1345.

Holmes J, Lawson D, Langley K, Fitzpatrick H, Trumper A, Pay H, Harrington R, Thapar A (2004). The Child Attention-Deficit Hyperactivity Disorder Teacher Telephone Interview (CHATTI): reliability and validity. *British Journal of Psychiatry* **184**, 74–78.

Hyman SE (2010). The diagnosis of mental disorders: the problem of reification. *Annual Reviews of Clinical Psychology* **6**, 155–179.

Ivry RB, Spencer RM (2004). The neural representation of time. *Current Opinion in Neurobiology* **14**, 225–232.

Kaufman J, Birmaher B, Brent DA, Ryan ND, Rao U (2000). K-SADS-PL. *Journal of the American Academy of Child and Adolescent Psychiatry* **39**, 1208.

Kempton S, Vance A, Maruff P, Luk E, Costin J, Pantelis C (1999). Executive function and attention deficit hyperactivity disorder: stimulant medication and better executive function performance in children. *Psychological Medicine* **29**, 527–538.

Kline RB (2005). *Principles and Practice of Structural Equation Modeling*, 2nd edn. Guilford Press: New York.

Kuntsi J, Frazier-Wood AC, Banaschewski T, Gill M, Miranda A, Oades RD, Roeyers H, Rothenberger A, Steinhausen HC, van der Meere JJ, Faraone SV, Asherson P, Rijsdijk F (2012). Genetic analysis of reaction time variability: room for improvement? *Psychological Medicine* **43**, 1323–1333.

Kuntsi J, Oosterlaan J, Stevenson J (2001). Psychological mechanisms in hyperactivity: I. Response inhibition deficit, working memory impairment, delay aversion, or

something else? *Journal of Child Psychology and Psychiatry* **42**, 199–210.

Logan GD, Cowan WB, Davis KA (1984). On the ability to inhibit simple and choice reaction time responses: a model and a method. *Journal of Experimental Psychology: Human Perception* **10**, 276–291.

Miller G (2010). Psychiatry. Beyond DSM: seeking a brain-based classification of mental illness. *Science* **327**, 1437.

Morris RC, Evendon JL, Sahakian BJ, Robbins TW (1987). Computer-aided assessment of dementia: comparative studies of neuropsychological deficits in Alzheimer-type dementia and Parkinson's disease. In *Cognitive Neurochemistry* (ed. S. M. Stahl, S. D. Iversen and E. C. Goodman), pp. 21–36. Oxford University Press: Oxford.

Nigg JT, Willcutt EG, Doyle AE, Sonuga-Barke EJ (2005). Causal heterogeneity in attention-deficit/hyperactivity disorder: do we need neuropsychologically impaired subtypes? *Biological Psychiatry* **57**, 1224–1230.

Office of the Chief Statistician (2009). *Scottish Index of Multiple Deprivation (SIMD) 2009*. Scottish Government National Statistics: Edinburgh.

Owen AM, Sahakian BJ, Semple J, Polkey CE, Robbins TW (1995). Visuo-spatial short-term recognition memory and learning after temporal lobe excisions, frontal lobe excisions or amygdalo-hippocampectomy in man. *Neuropsychologia* **33**, 1–24.

Petrides M, Milner B (1982). Deficits on subject-ordered tasks after frontal- and temporal-lobe lesions in man. *Neuropsychologia* **20**, 249–262.

Polanczyk G, de Lima MS, Horta BL, Biederman J, Rohde LA (2007). The worldwide prevalence of ADHD: a systematic review and metaregression analysis. *American Journal of Psychiatry* **164**, 942–948.

Rhodes SM, Coghill DR, Matthews K (2004). Methylphenidate restores visual memory, but not working memory function in attention deficit-hyperkinetic disorder. *Psychopharmacology* **175**, 319–330.

Rhodes SM, Coghill DR, Matthews K (2005). Neuropsychological functioning in stimulant-naive boys with hyperkinetic disorder. *Psychological Medicine* **35**, 1109–1120.

Rhodes SM, Coghill DR, Matthews K (2006). Acute neuropsychological effects of methylphenidate in stimulant drug-naive boys with ADHD II – broader executive and non-executive domains. *Journal of Child Psychology and Psychiatry* **47**, 1184–1194.

Rhodes SM, Park J, Seth S, Coghill DR (2012). A comprehensive investigation of memory impairment in attention deficit hyperactivity disorder and oppositional defiant disorder. *Journal of Child Psychology and Psychiatry* **53**, 128–137.

Robbins TW, Semple J, Kumar R, Truman MI, Shorter J, Ferraro A, Fox B, McKay G, Matthews K (1997). Effects of scopolamine on delayed-matching-to-sample and paired associates tests of visual memory and learning in human subjects: comparison with diazepam and implications for dementia. *Psychopharmacology* **134**, 95–106.

Rogers RD, Everitt BJ, Baldacchino A, Blackshaw AJ, Swainson R, Wynne K, Baker NB, Hunter J, Carthy T, Booker E, London M, Deakin JF, Sahakian BJ, Robbins TW (1999). Dissociable deficits in the decision-making cognition of chronic amphetamine abusers, opiate abusers, patients with focal damage to prefrontal cortex, and tryptophan-depleted normal volunteers: evidence for monoaminergic mechanisms. *Neuropsychopharmacology* **20**, 322–339.

Rubia K, Taylor A, Taylor E, Sergeant JA (1999). Synchronization, anticipation, and consistency in motor timing of children with dimensionally defined attention deficit hyperactivity behaviour. *Perceptual and Motor Skills* **89**, 1237–1258.

Sahakian BJ, Morris RG, Evenden JL, Heald A, Levy R, Philpot M, Robbins TW (1988). A comparative study of visuospatial memory and learning in Alzheimer-type dementia and Parkinson's disease. *Brain* **111**, 695–718.

Schachar R, Mota VL, Logan GD, Tannock R, Klim P (2000). Confirmation of an inhibitory control deficit in attention-deficit/hyperactivity disorder. *Journal of Abnormal Child Psychology* **28**, 227–235.

Solanto MV, Abikoff H, Sonuga-Barke E, Schachar R, Logan GD, Wigal T, Hechtman L, Hinshaw S, Turkel E (2001). The ecological validity of delay aversion and response inhibition as measures of impulsivity in AD/HD: a supplement to the NIMH multimodal treatment study of AD/HD. *Journal of Abnormal Child Psychology* **29**, 215–228.

Sonuga-Barke E, Bitsakou P, Thompson M (2010). Beyond the dual pathway model: evidence for the dissociation of timing, inhibitory, and delay-related impairments in attention-deficit/hyperactivity disorder. *Journal of the American Academy of Child and Adolescent Psychiatry* **49**, 345–355.

Sonuga-Barke EJ (2002). Psychological heterogeneity in AD/HD – a dual pathway model of behaviour and cognition. *Behavioral Brain Research* **130**, 29–36.

Sonuga-Barke EJ (2005). Causal models of attention-deficit/hyperactivity disorder: from common simple deficits to multiple developmental pathways. *Biological Psychiatry* **57**, 1231–1238.

Sonuga-Barke EJ, Sergeant JA, Nigg J, Willcutt E (2008). Executive dysfunction and delay aversion in attention deficit hyperactivity disorder: nosologic and diagnostic implications. *Child Adolescent Psychiatric Clinics of North America* **17**, 367–384, ix.

Sonuga-Barke EJ, Taylor E, Heptinstall E (1992*a*). Hyperactivity and delay aversion – II. The effect of self versus externally imposed stimulus presentation periods on memory. *Journal of Child Psychology and Psychiatry* **33**, 399–409.

Sonuga-Barke EJ, Taylor E, Sembi S, Smith J (1992*b*). Hyperactivity and delay aversion – I. The effect of delay on choice. *Journal of Child Psychology and Psychiatry* **33**, 387–398.

Tannock R (2013). Time perceptive tasks (www.sickkids.ca/Research/Tannock-Lab/Cognitive-Tasks-Battery/Time-Perceptive-Tasks/index.html). Accessed 30 June 2013.

Toplak ME, Tannock R (2005). Tapping and anticipation performance in attention deficit hyperactivity disorder. *Perceptual and Motor Skills* **100**, 659–675.

van Lieshout M, Luman M, Buitelaar J, Rommelse NN, Oosterlaan J (2013). Does neurocognitive functioning predict future or persistence of ADHD? A systematic review. *Clinical Psychology Review* **33**, 539–560.

Willcutt EG, Doyle AE, Nigg JT, Faraone SV, Pennington BF (2005). Validity of the executive function theory of attention-deficit/hyperactivity disorder: a meta-analytic review. *Biological Psychiatry* **57**, 1336–1346.

Wilson HK, Cox DJ, Merkel RL, Moore M, Coghill D (2006). Effect of extended release stimulant-based medications on neuropsychological functioning among adolescents with attention-deficit/hyperactivity disorder. *Archives of Clinical Neuropsychology* **21**, 797–807.

Winer BJ, Brown DR, Michels KM (1991). *Statistical Principles in Experimental Design*, 3rd edn. McGraw Hill: New York.

https://doi.org/10.1017/S0033291713002547 Published online by Cambridge University Press