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Time perception deficits in attention-deficit/hyperactivity disorder and comorbid reading difficulties in child and adolescent samples

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Background: Our objective was to investigate time perception in Attention-Deficit/Hyperactivity Disorder (ADHD) with and without comorbid reading difficulties (RD) in child and adolescent participants. **Method:** In study 1, 50 children with ADHD (31 ADHD, 19 ADHD+RD) and age-matched healthy controls ($n = 50$) completed three psychophysical tasks: duration discrimination (target duration of 400 ms versus a foil duration), frequency discrimination (a control condition to evaluate general perceptual ability), and a duration estimation task using the method of reproduction for intervals of 400 ms, 2000 ms, and 6000 ms. Study 2 used the same tasks with an adolescent sample (35 ADHD, 24 ADHD+RD, 39 controls). **Results:** In both studies, children and adolescents with ADHD and ADHD+RD displayed some impairments in duration discrimination and the precision with which they reproduced the intervals on the estimation task, particularly the shorter 400 ms interval. The most severe impairments tended to occur in the comorbid ADHD+RD group. No impairments were found on the frequency discrimination task. ADHD participants also displayed significant intra-individual variability in their performance on the estimation task. Finally, short-term and working memory, estimated full-scale IQ, and teacher report of hyperactivity/impulsivity were found to differentially predict performance on the time perception measures in the adolescent clinical sample. **Conclusions:** Deficits in duration discrimination, duration estimation, and intra-individual performance variability may have cascaded effects on the temporal organisation of behaviour in children and adolescents with ADHD and ADHD+RD. **Keywords:** Time perception, working memory, attention-deficit/hyperactivity disorder, reading difficulties, teacher report, behaviour ratings.

Time perception is an adaptive function that facilitates the ability to predict, anticipate, and respond efficiently to coming events. For example, the preparation of fast responses benefits from the ability to predict precisely the point in time when an impending event requires a response. Also, precise representation of temporal information is required for the ability to organise and plan sequences of actions, particularly when sequences of novel or unskilled movements are required (Gibbon, Malapani, Dale, & Gallistel, 1997; Hazeltine, Helmut, & Ivry, 1998; Ivry, 1997). Time perception is a complex cognitive ability and comprises multiple component processes that engage multiple brain regions, including the neocerebellum, basal ganglia and prefrontal cortex (e.g., Casini & Ivry, 1999; Mostofsky, Kunze, Cutting, Lederman, & Denckla, 2000; Gibbon et al., 1997; Harrington, Haaland, & Hermanowicz, 1998a; Harrington, Haaland, & Knight, 1998b; Ivry & Keele, 1989; Ivry & Hazeltine, 1995; Jueptner et al., 1995; Jueptner, Flerlch, Weiller, Mueller, & Diener, 1996; Mangels, Ivry, & Shimizu, 1998; Meck, 1996; Nichelli, Always, & Grafman, 1996a; Nichelli, 1996b; Rubia et al., 1999a; Rubia, Taylor, Taylor, & Sergeant, 1999b). Recent work suggests that the neocerebellar cortex and prefrontal cortex (particularly, the dorsolateral prefrontal cortex) participate in a working memory system, which is involved in discrimination of intervals ranging from a few milliseconds to several seconds. Moreover, the neocerebellum may subserve a central timing mechanism, whereas the prefrontal cortex subserves supplementary functions implicated in the acquisition, maintenance and organisation of temporal representation in working memory (Casini & Ivry, 1999; Mangels et al., 1998).

Time perception is postulated to be impaired in Attention Deficit Hyperactivity Disorder, according to current models of ADHD and impulsivity (e.g., Barkley, 1997a, b, c; Barkley, Koplowitz, Anderson, & McMurray, 1997; Barkley, Murphy, & Bush, 2001; Barratt & Patton, 1983; Gerbing, Ahadi, & Patton, 1987; Stanford & Barratt, 1996). For example, one recent theoretical model of ADHD proposes that four executive neuropsychological functions are compromised by an underlying impairment in behavioural inhibition, which is believed to be the fundamental deficit in ADHD (Barkley, 1997a). One of these executive functions is working memory, which supports some components of time perception. Impaired time perception in ADHD is also predicted independently by models of impulsivity, which propose a link between time perception and impulsive behaviour – the latter being a core feature of ADHD (e.g.,

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Barratt & Patton, 1983; Gerbing et al., 1987; Stanford & Barratt, 1996).

Clinical phenomenology and empirical evidence is consistent with the hypothesised time perception deficits in ADHD. For example, clinical descriptions indicate that individuals with ADHD have marked difficulties in conforming to directions containing time parameters, meeting deadlines for work assignments, and in adjusting the timing of their behaviour to the pacing of the immediate context (e.g., calling out in class, interrupting an ongoing conversation, difficulty waiting turn). Also, a diverse array of findings from studies of cognitive processes involved in motor response control supports the hypothesis of impaired time perception in ADHD. Findings include: 1) deficits in working memory that are believed to play a major role in time perception; 2) adverse effects on task performance of either very brief or long delays between stimuli, and of temporal uncertainty; 3) production of slow and variable responses on tasks with a 'fast' instruction set; 4) a high rate of premature responses in experimenter-paced tasks; and 5) impairments in timing motor output (e.g., Barkley, Murphy, & Kwasnik, 1996; Karatekin & Asarnow, 1998; Mariani & Barkley, 1997; Rubia et al., 1999a, b; Sergeant & Scholten, 1985; Sonuga-Barke, Saxton, & Hall, 1998; Zahn, Kruesi, & Rapoport, 1991). Some recent findings from neuroimaging studies of ADHD have also reported structural anomalies in the cerebellum, basal ganglia, and prefrontal cortex (e.g., Berquin et al., 1998; Castellanos, 2001; Castellanos et al., 1996, 2001; Mostofsky, Reiss, Lockhart, & Denckla, 1998).

Direct evidence of time perception deficits in ADHD is not only extremely limited, but also findings are inconsistent (Barkley et al., 1997; Capella, Gentile, & Juliano, 1977). Moreover, the few available studies differed in sampling procedures (school vs. clinic sample), diagnostic criteria (clinical diagnosis of ADHD vs. ratings of hyperactivity or inattention), methods of assessing time perception (duration discrimination vs. time production or time reproduction), and inconsistency in the range of intervals used (often in the range of 7 sec to 60 sec). This makes it difficult to integrate findings across the different studies. Furthermore, none of the existing studies considered the possible impact of comorbidity. In particular, the failure to control for comorbid reading difficulties (RD) is potentially problematic given the evidence of impairment in time-related performance in children with RD (Farmer & Klein, 1995; Fawcett & Nicolson, 2001; Nicolson, Fawcett, & Dean, 2001; Wolf, 2001).

The purpose of the two studies presented here was to provide a further test of the hypothesised time perception deficits in ADHD, and to examine the persistence of deficits developmentally via a child (study 1) and an adolescent (study 2) sample. Specifically, both studies evaluated *duration discrimination* (i.e., perception) and *duration estimation* (by method of reproduction) in participants with ADHD by using psychophysical tasks that afford more precise measurement than the tasks used in the previous studies. The duration discrimination task required participants to determine which of two intervals was the longest – a target duration of 400 ms versus a comparison duration. A non-temporal task was included as a control condition to evaluate whether the design of the task, generalised perceptual impairment, or difficulty with auditory signals may have influenced performance on the duration discrimination task. This task was called the frequency discrimination task, and used a target frequency of 3000 Hz versus a comparison frequency. Duration estimation was evaluated using the method of reproduction, a reliable method that does not require verbal responses or knowledge of culturally determined temporal units (Zakay, 1990). A wider range of duration was used than in previous studies, since there is evidence that timing of very short intervals (milliseconds) and longer intervals (seconds) may be distinguished behaviourally and neurally. That is, timing in the range of milliseconds can be achieved relatively automatically by direct readout from an internal timing mechanism with little or no demand on working memory or strategy use. Neurally, timing in this range – a range associated with motor control – has been linked with the cerebellum (Ivry, 1996; Mangels et al., 1998). By contrast, timing in the range of several seconds involves working memory (to hold and manipulate information on-line) and strategy use (e.g., counting), and may be subserved by a neural network involving basal ganglia and prefrontal cortex (Meck, 1996; Ivry, 1996; Mangels et al., 1998; Gibbon et al., 1997). Also, in both studies 1 and 2, the ADHD sample was stratified for comorbid reading difficulties to determine the impact of this comorbidity on time perception performance.

Importantly, the use of these three measures provides an important range of time perception measures that have never before been examined in a sample of children and adolescents, or in a sample of participants with ADHD and RD. The frequency discrimination task, directly analogous to the duration discrimination task, provides an important control for general auditory perception. In the duration discrimination task, the participant's task is to discriminate the longer from the shorter duration. The dependent measure in this task has no speeded responding or motor timing component, therefore providing a purely cognitive index of duration discrimination ability. The duration estimation task is a somewhat different paradigm of time perception than the duration discrimination task (Block, 1990), as participants must reproduce an interval of time. In addition, this task has a motor component that may factor into the dependent measures of this task. If in fact ADHD is characterised by time perception deficits, it is expected that both children and adolescents with ADHD will display impaired performance on the duration discrimination and estimation tasks, but *not* on the frequency discrimination control task. If individuals with reading difficulties also have deficits in time perception, the ADHD+RD child and adolescent groups may display significantly more impaired performance than ADHD and control participants. Regression analyses were also performed with the clinical groups to examine predictors of time perception performance, specifically to examine whether there are associations between time perception and working memory measures (Ivry, 1996).

Study 1

Participants

Two groups of children participated: 50 children (22% female) with a confirmed clinical diagnosis of ADHD and 50 comparison children (40% female). Approximately 40% ($n = 19$) of the children with ADHD had comorbid reading difficulties, according to the criteria described below. All children were between the ages of 6.4 years and 11.9 years (mean = 9.2 years). The children with ADHD were recruited from an outpatient department of psychiatry in a paediatric academic health sciences centre for assessment of attention, behaviour, and learning problems. Data from children with ADHD were compared with those from an age-matched subset of healthy children, who had been recruited from visitors to the Ontario Science Centre to participate in a developmental study of time perception.

ADHD sample. All children had a diagnosis of ADHD confirmed by a multidisciplinary clinical diagnostic assessment. The assessment comprised two semi-structured clinical diagnostic interviews (face-to-face interview with parents; telephone interview with teachers), standardised behaviour rating scales completed by the parents and teacher, and a comprehensive child assessment. The parent interview (Parent Interview for Child Symptoms-IV (PICS-IV); Ickowicz et al., submitted) covers the child's development and current behaviour and uses the DSM-IV criteria for externalising and internalising disorders of childhood. The PICS-IV is modelled on the Schedule for Affective Disorders and Schizophrenia for School-Age children-Present and Lifetime Version (K-SADS-PL; Kaufman et al., 1997), but does not use skip-out criteria for the externalising disorders and only probes for descriptions of behaviour in the home and community settings (i.e., not school setting). The PICS-IV was the diagnostic interview of choice in the hospital clinic at this time. The teacher interview (Teacher Telephone Interview-IV (TTI); Tannock, Hum, Masellis, Humphries, & Schachar, 1999) follows the same basic format as the PICS, but restricts probes to descriptions of behaviour in the school setting, covers symptoms of ADHD, ODD, and CD in detail, and screens for internalising disorders. Reliability and validity for the DSM-III-R versions of both interviews are high, with kappa of .84 for diagnosis (Schachar, Tannock, Marriott, & Logan, 1995). The PICS-IV and TTI-IV were administered independently by trained clinicians who rated the behaviour on a four-point scale of severity and frequency based on the elicited descriptions of behaviour. To be classified as ADHD, children had to meet DSM-IV criteria for ADHD, defined as at least six of nine inattentive or hyperactive-impulsive symptoms, or both. To ensure pervasive impairment, children were required to meet criteria for ADHD in the parent or teacher interview, but also exhibit a minimum of four inattentive or four hyperactive-impulsive symptoms according to the other informant.

The child assessment included the Wechsler Intelligence Scale for Children – Third Edition (WISC-III; Wechsler, 1991), the arithmetic and reading subtests of the Wide-Range Achievement Test-3 (WRAT-3; Wilkinson, 1993), and the Word Attack and Word Identification subtests of the Woodcock Reading Mastery Test-Revised (Woodcock, 1987). Children with a full-scale intelligence quotient (IQ) score of less than 80, any evidence of neurological dysfunction, poor physical health, uncorrected sensory impairments, or a history or current presentation of psychosis were excluded from the study. Sample characteristics and scores on these tests are displayed in Table 1.

Classification of reading difficulties. For the present study, a definition of low achievement in single-word reading was used to classify reading difficulties, since there is little or no evidence to support the validity of an IQ-discrepancy model (Fletcher et al., 1998; Francis, Fletcher, Shaywitz, Shaywitz, & Rourke, 1996; Stanovich & Siegel, 1994). Specifically, children with a composite standardised reading score of less than 90 (i.e., less than 25th percentile) were classified as having comorbid reading difficulties. The composite reading score was calculated from the average of the standardised scores on three measures of reading; the Reading subtest of WRAT-3 (Wilkinson, 1993) and the Word Identification and Word Attack subtests of the WRMT-R (Woodcock, 1987). The precise cut-point score is arbitrary but a standardised reading score of 90 is used widely in the USA to represent the definition of reading disability (Fletcher et al., 1998; Frankenberger & Fronzaglio, 1991).

Comparison sample. Parents had confirmed on a questionnaire that their child was in good physical health, had no known problems with attention, behaviour or learning, nor any neurological dysfunction, sensory impairment, major medical or mental health problems, and were not on any medication for

Table 1 Diagnostic characteristics of the ADHD and ADHD+RD groups[a] in the child sample (study 1)

	ADHD	*n*	ADHD+RD	*n*	*df*	*F*
Age	8.9 (1.3)	31	8.9 (1.3)	19	2, 97	1.35b
WISC-III Scale Scores						
Estimated Verbal IQ	110.6 (15.3)	30	101.2 (11.8)	19	1, 47	5.18*
Estimated Performance IQ	102.7 (16.2)	30	103.5 (12.5)	19	1, 47	.03
WISC-III Index Scores						
Verbal Comprehension	111.1 (16.3)	29	102.0 (13.9)	19	1, 46	4.03
Perceptual Organisation	102.4 (15.7)	29	104.1 (14.8)	19	1, 46	.13
Freedom from Distractibility	99.3 (12.1)	29	95.3 (8.0)	19	1, 46	1.60
Processing Speed	107.2 (17.1)	28	100.11 (12.4)	18	1, 44	2.31
WISC-III Subtest Standard Scores						
Vocabulary	12.0 (3.6)	29	10.3 (3.0)	19	1, 47	2.93
Block Design	10.7 (3.9)	29	11.5 (3.7)	19	1, 47	.49
Digit Span	9.0 (3.1)	29	8.9 (2.5)	19	1, 47	.03
Arithmetic	10.7 (2.5)	29	9.3 (1.6)	19	1, 47	5.14*
Reading Measures						
WRAT-3 Reading	104.5 (10.3)	30	86.0 (7.5)	19	1, 47	45.99***
WRMT-R Word Identification	105.1 (11.5)	30	80.5 (5.4)	19	1, 47	75.79***
WRMT-R Word Attack	99.0 (8.3)	30	81.3 (5.8)	19	1, 47	66.19***
Arithmetic Measures						
WRAT-3 Arithmetic	94.1 (10.2)	30	88.7 (9.9)	19	1, 47	3.40
Diagnostic Characteristics (# symptoms)						
PICS Inattention	5.3 (2.0)	31	5.6 (2.1)	19	1, 48	.33
PICS Hyperactivity/Impulsivity	5.7 (1.8)	31	6.0 (1.9)	19	1, 48	.29
TTI Inattention	5.5 (2.4)	28	5.7 (1.8)	18	1, 44	.08
TTI Hyperactivity/Impulsivity	4.0 (2.5)	28	3.8 (2.5)	18	1, 44	.05
Comorbidity (% of sample)						
Oppositional Defiant Disorder	39%	12	42%	8		
Conduct Disorder	16%	5	21%	4		
Separation Anxiety	10%	3	11%	2		
ADHD Subtypes (% of clinical sample)						
Inattentive Subtype	23%	7	21%	4		
Hyperactive/Impulsive Subtype	0%	0	0%	0		
Combined Subtype	77%	24	79%	15		

[a]No psychometric data were available for the normal controls.
[b]Comparison with ADHD, ADHD+RD, and normal controls.
****p* < .001, **p* < .05.

any clinical condition. Standardised measures of intellectual function and academic achievement were not available for this comparison group of children, which is one limitation of this first study. The mean age of children in this comparison group was 9.3 years (SD 1.3 years). Information on parental education and ethnicity was not collected, but most parents would be likely to have a strong educational background (e.g., completed at least some post-secondary education), based on our previous studies conducted at this science centre (e.g., Williams, Ponesse, Schachar, Logan, & Tannock, 1999).

Time perception tasks

Each child completed two implicit timing tasks including a duration discrimination task (with frequency discrimination as a control task) and a duration estimation task. All children were tested individually. Children with ADHD were tested in a quiet testing room in the paediatric academic health sciences centre, whereas the healthy comparison group was tested in a quiet testing room at the science centre using the same apparatus, tasks, and testing procedures as used with the children with ADHD.

The tasks, which were developed by Hetherington, Dennis, and Spiegler (2000), were programmed in Turbo Pascal for an IBM-compatible Pentium series computer that presented the stimuli and collected the data. The internal tone generator of the computer was used to generate the auditory signals. Each computer was equipped with adjustable padded headphones through which the auditory signals could be presented without the hindrance of background noise. Participants responded to the stimuli by pressing the appropriate response button on a three-button response box: the two outer buttons were used for the duration and frequency threshold tasks and the centre button was used for the duration estimation task.

Duration and frequency discrimination tasks. Both tasks were presented in similar two-alternative forced choice trials. In the duration discrimination task, participants were presented with two unfilled intervals (target, comparison), each defined by brief tones (50 ms, 1000 Hz) at the beginning and end of the interval. Unfilled intervals were used to minimise any confound from ongoing processing of the auditory stimuli (Ivry, 1996); however, the psychological significance of filled versus unfilled intervals in timing measures is a contentious issue in the time perception literature (Block, 1990). The target interval of 400 ms was randomly presented as either the first or second duration. The comparison interval was always longer than 400 ms and was adjusted up or down in 10 ms increments depending upon the accuracy of the participant's responses. The target and comparison interval were separated by 800 ms and the inter-trial interval was 1000 ms. Participants were instructed to press the left button if they thought the first interval tone was longer, and the right-hand button if they thought the second one was longer. On-screen cues in the form of numbered boxes mapping the tones in each trial to the left–right response buttons were always available to provide a guide for participants' responses. Response buttons and on-screen cues were colour coded for further clarity, and the on-screen cues would flash to register the participants' responses. Thus, working memory demands for on-line maintenance of instructions were minimal. No feedback about errors was provided. An up-down-transformed-response (UDTR) adaptive psychophysical procedure was used to track 80% accuracy (Wetherill & Levitt, 1965). The procedure stopped after 6 reversals of direction, averaging the last 5 reversal values to produce the estimate of discrimination (i.e., the threshold). The format of the frequency discrimination task was similar, with a target frequency of 3000 Hz. The target and comparison tones were each presented for a duration of 200 ms and were separated by 500 ms. The inter-trial interval was 800 ms. Parameters were set based on pilot studies and Monte Carlo simulations to minimise the number of trials to convergence and the overall run time, while optimising performance. Dependent measures were the estimated mean duration threshold and mean frequency threshold that could be discriminated from the target duration and target frequency, respectively, with about 80% accuracy.

Duration estimation by method of reproduction task. The duration estimation task used the method of reproduction for intervals of 400 ms, 2000 ms, and 6000 ms. The intervals were chosen to vary in demand on working memory (i.e., the 400 ms interval placed little or no demand, whereas the 6000 msec interval had the greatest demands). Each interval was signalled with 1000 Hz boundary tones of 50 ms duration. The experimental task comprised 4 blocks of 15 trials per block, with 5 trials of each interval presented in a quasi-random order that remained constant across all participants. Each block began with an on-screen countdown from five. The inter-trial interval was set at 1500 ms. Each trial began with the initial boundary tone of the interval, followed by the second boundary tone. After 500 ms, subjects were prompted for their response with a question mark presented in the middle of the screen for 200 ms. Participants reproduced the interval by tapping the beginning and end of the interval on the centre button of a three-button response box. At 500 ms after responding, the subject's response was acknowledged with 'OK' displayed centrally for 200 ms. Dependent measures included the mean (and standard deviation) of the estimated duration for each of the three intervals. While the standard deviation of the mean reflects the within group variability (that is, variability between participants), the standard deviation measure of performance reflects intra-individual variability, or variability of performance within a given individual.

Results

Outliers. There were some individuals who displayed extreme performance on individual tasks but were within a normal range on others, specifically on tasks where reaction times were the dependent measure. The data from these univariate outliers were included in the statistical analyses. Tabachnick and Fidell's (1989) most conservative score changing option was selected for only those tasks on which these participants deviated extremely. Each deviant score was changed to equal the next highest score in the distribution, plus one unit. Thus, the score remained as the most extreme in the distribution while at the same time minimised the skew they created in the sample. This procedure was applied on the following measures: mean performance on the duration discrimination task ($n = 2$; 1 ADHD, 1 ADHD+RD), and scores on the duration estimation task (400 ms duration ($n = 1$, ADHD+RD)); and the standard deviation score on the 2000 ms duration ($n = 1$; ADHD+RD).

Group differences in duration and frequency discrimination. Group differences were tested using one-way analysis of variance for each dependent measure. Study results are summarised in Table 2. The groups differed in duration discrimination, but not frequency discrimination. Scheffé's post-hoc procedure was used in both study 1 and study 2 because it is the most conservative and robust in the face of unequal *n*'s in groups and violations of the homogeneity of variance assumption (Kirk, 1982). In the post-hoc analyses, both children with ADHD ($p < .01$) and ADHD+RD ($p < .05$) were less able to discriminate among durations in the 400 ms range, compared to the age-matched comparison group. However, the children with ADHD and ADHD+RD did not differ from each other or from the comparison group in their ability to discriminate frequencies in the 3000 Hz range.

Table 2 Means (standard deviation) for frequency and duration discrimination tasks and three interval reproduction tasks for ADHD and control groups

	ADHD (1)	ADHD+RD (2)	Control group (3)	Post-hoc analyses
Frequency and duration discrimination[a]				
Frequency (3000Hz)	3022.8 (8.8)	3018.0 (7.7)	3019.9 (9.8)	n.s.
Duration (400 ms)[b]	563.1 (67.1)	558.6 (67.7)	514.6 (38.7)	1, 2 > 3
Duration estimation by method of reproduction[c]				
400 ms: Mean	579.0 (203.0)	628.3 (246.2)	501.2 (129.6)	2 > 1, 3
: SD	423.4 (409.4)	565.1 (551.0)	230.6 (301.3)	2 > 1, 3
2000 ms: Mean	1957.5 (519.8)	1728.6 (361.9)	1983.2 (292.2)	n.s.
: SD	748.6 (346.5)	877.1 (527.6)	523.9 (224.8)	1, 2 > 3
6000 ms: Mean	4122.7 (1402.5)	3390.4 (1317.5)	4524.3 (1055.2)	1, 3 > 2
: SD	1571.3 (584.9)	1811.8 (710.8)	1102.9 (392.8)	1, 2 > 3

[a]Frequency discrimination: $F(2, 97) = 1.80$, ns; Duration discrimination: $F(2, 97) = 8.82$, $p < .001$.
[b]Data missing for 1 ADHD and 2 control subjects due to equipment problems; corresponding change in *df* for the F-ratio (2, 94).
[c]Estimation task reproductions: Main effect for group: $F(2, 97) = 4.67$, $p < .05$; Main effect for interval: $F(2, 194) = 580.94$, $p < .0001$; Group × interval interaction: $F(4, 194) = 6.60$, $p < .0001$. Estimation task variability: Main effect for group: $F(2, 97) = 17.66$, $p < .0001$]; Main effect for interval: $F(2, 194) = 223.49$, $p < .0001$; Group × interval interaction: $F(4, 194) = 3.30$, $p < .05$.

Group differences in duration estimation by reproduction. Inspection of the mean scores for duration estimation presented in Table 2 indicate that the pattern of reproduction for each of the intervals was similar across all three groups. That is, the average duration of their reproductions was longer than the target 400 ms interval, somewhat shorter than the 2000 ms interval, and much shorter than the 6000 ms target interval. Also, all children were highly variable in their estimations and reproduced intervals. An analysis of variance for repeated measures across interval (3 levels: 400 ms, 2000 ms, and 6000 ms) was conducted separately for mean duration and variability (SD) of the reproduced intervals. For mean duration, both the main effects for group and interval were significant, as well as the group × interval interaction. Simple effects analysis revealed that the ADHD+RD group exhibited significantly longer reproductions of the 400 ms interval than the comparison group ($p < .05$), but significantly shorter intervals for the 6000 ms ($p < .01$) interval compared to both the ADHD and comparison groups, who did not differ. For the variability (SD) of the duration of the reproduced intervals, the repeated-measures ANOVA revealed significant main effects for group, interval, and a significant group × interval interaction. Simple effects analysis indicated that both children with ADHD and ADHD+RD were significantly more variable than the comparison group at the 2000 ms ($p < .05$) and 6000 ms ($p < .001$) interval levels. The ADHD+RD ($p < .01$) group also displayed significantly more variability at the 400 ms interval level than the ADHD and comparison groups.

Effects of ADHD subtype, gender, and other comorbid disorders. Analyses of variance were conducted to determine the effects of ADHD subtype, gender, and other comorbid disorders (specifically, Oppositional Defiant Disorder, Conduct Disorder, and Separation Anxiety). In the child study, 82% of the sample met criteria for the combined subtype. In analyses to examine whether ADHD subtype (inattentive or combined collapsed across reading difficulties) was related to performance on the time perception measures, no such differences were obtained. On the time perception measures, only one effect of gender was significant on the time estimation task. Specifically, boys displayed significantly more variability at the 2000 ms interval than girls on the estimation task ($F(1, 98) = 9.60$, $p < .01$). No effects of comorbid disorders were observed on the time perception measures.

Relationships between time perception, intellectual, achievement and behaviour rating measures. Correlational analyses were conducted to determine relationships between performance on the time perception measures, ADHD symptoms (from parent and teacher reports), and intellectual and academic functioning. This analysis included the clinical sample (ADHD, ADHD+RD), as not all of this data was available for the comparison group. Full data was available for 48 of the clinical participants, and overall, few significant relationships were obtained. A significant correlation was obtained between duration threshold and WISC-III full-scale IQ ($r = -.32$, $p < .05$) on the duration discrimination task. A significant relationship was obtained between the 400 ms reproduction on the estimation task and the WISC-III Digit Span Standard score ($r = -.32$, $p < .05$). Finally, a significant relationship was also obtained between the intra-individual variability at the 2000 ms interval on the estimation task and the Digit Span Standard score ($r = -.30$, $p < .05$). No other significant relationships were obtained.

In summary, children with ADHD and ADHD+RD exhibited impairments in the ability to discriminate brief intervals of around 400 ms, but not in the ability to discriminate tone frequencies around 3000 Hz. Also, children with ADHD+RD were less precise and reliable in their reproduction of intervals in the range of 400 ms and 6000 ms, and both children with ADHD and ADHD+RD displayed considerable variability in their performance. Few relationships were obtained between the time perception measures and the intellectual, achievement, and behaviour rating measures, although the relationships obtained did suggest some dissociation of performance between the duration discrimination and estimation tasks. The same time perception measures were investigated in a sample of adolescents in study 2.

Study 2

Participants

Two groups of adolescents participated: 59 adolescents (40.7% female) with a confirmed clinical diagnosis of ADHD and 39 comparison adolescents (53.8% female). Approximately 41% ($n = 24$) of the adolescents with ADHD had comorbid reading difficulties, according to the criteria described below. All adolescents were between the ages of 13 years and 16 years (mean 15.0 years). Thirty-three (55.9%) of the adolescents with ADHD were recruited from patients who were previously assessed in the Department of Psychiatry with a confirmed diagnosis of ADHD in childhood based on a standard clinical diagnostic protocol: the Parent Interview for Child Symptoms (PICS-IV, Schachar & Ickowicz, unpublished), and standardised parent and teacher behaviour rating scales. The remaining clinical participants were recruited through advertisements at paediatric offices as well as from new referrals to the Hospital for Sick Children. Adolescents in the control comparison group were recruited through hospital staff and community resources. All adolescents participating in the study were native English speakers.

ADHD sample. All adolescents had a diagnosis of ADHD confirmed by a multidisciplinary clinical diagnostic assessment. The assessment comprised a semi-structured clinical diagnostic interview (face-to-face interview with parents and adolescents separately), and two standardised behaviour rating scales completed by parents, teachers, and adolescents. The diagnostic interview (Schedule for Affective Disorders and Schizophrenia for School-Age Children-Present and Lifetime Version (K-SADS-PL)) generates both DSM-IIIR and DSM-IV diagnoses. A PhD-level clinical psychologist (JR) conducted all interviews. This semi-structured interview has been used extensively to make diagnostic decisions based on DSM criteria and has been validated with children aged 6 to 17 (Kaufman et al., 1997). The PICS-IV was not used in this study, as the PICS-IV was designed for school-aged children and has not been validated for use with adolescents. The Conners Rating Scales-Revised (Conners, 1997) was given to parents and teachers to obtain additional behaviour rating measures. To assess for presence or absence of ADHD, the following diagnostic algorithm was used: 1) the child met DSM-IV criteria for ADHD according to the clinician summary based on the K-SADS parent and adolescent interview, 2) met the clinical cut-offs for the externalising symptoms of ADHD on the Conners teacher questionnaires in order to ensure pervasiveness of symptoms across settings, and 3) showed evidence of ADHD symptoms prior to the age of seven established either through a past diagnosis of ADHD or, in new cases, according to parental report and school report cards. The presence/absence of DSM-IV internalising disorders was based on a clinician summary based on the information gathered from both the parent and adolescent K-SADS interview. Note that the information from the adolescent K-SADS did not supersede parental report for the presence/absence of externalising symptoms.

The adolescent assessment included parts of the Wechsler Intelligence Scale for Children – Third Edition (WISC-III; Wechsler, 1991), including the Vocabulary, Block Design, Digit Span, Arithmetic, Coding, and Symbol Search subtests. Other assessment included the Arithmetic, Spelling, and Reading subtests of the Wide Range Achievement Test-3 (WRAT-3; Wilkinson, 1993) and the Word Attack and Word Identification subtests of the Woodcock Reading Mastery Test – Revised (Woodcock, 1987). Adolescents with an estimated IQ of at least 80 (using the Block Design and Vocabulary subtests of the WISC-III), any evidence of neurological dysfunction, serious medical problems, uncorrected sensory impairments, or a history or current presentation of psychosis were excluded from the study. Notably, the ADHD adolescents were comprised of a high proportion of Inattentive subtypes as compared to the child sample in study 1. Table 3 presents demographic characteristics and participants' scores on these tests.

Classification of reading difficulties. A definition of low achievement in single-word reading or spelling was used to classify reading difficulties. Adolescents were classified as having comorbid reading difficulties if they had a standard score below the 25th percentile (SS 90) on at least *one* of the following subtests: Word Identification or word attack subtests of the Woodcock Reading Mastery Test-Revised (WRMT-R; Woodcock, 1987) or the Spelling or Reading subtests of the Wide-Range Achievement Test (WRAT-III; Wilkinson, 1993).

Table 3 Diagnostic characteristics of the ADHD, ADHD+RD, and comparison control groups in the adolescent sample (study 2)

	ADHD (1)	*n*	ADHD+RD (2)	*n*	Controls (3)	*n*	*df*	*F*	Post-hoc
Age	15.2 (1.4)	35	14.9 (1.4)	24	15.0 (1.2)	39	2, 95	.45	n.s.
WISC-III Standard Scores									
Estimated Full-Scale IQ	102.2 (8.7)	35	101.1 (12.1)	24	110.1 (13.0)	39	2, 95	6.24**	3 > 1, 2
Vocabulary Standard Score	10.3 (2.1)	35	8.5 (2.2)	24	11.6 (2.7)	39	2, 95	12.18***	1, 3 > 2
Block Design Standard Score	10.5 (1.9)	35	11.5 (3.9)	24	11.8 (3.4)	39	2, 95	1.75	n.s.
WISC-III Index Scores									
Freedom from Distractibility	102.3 (14.2)	34	84.1 (13.7)	23	106.9 (14.2)	37	2, 91	19.54***	1, 3 > 2
Processing Speed	99.1 (17.3)	33	102.6 (16.2)	23	118.4 (13.6)	37	2, 90	15.22***	3 > 1, 2
Achievement Measures Standard Scores									
WRAT-3 Reading	105.7 (7.6)	35	87.2 (13.3)	24	110.9 (7.4)	39	2, 95	50.68***	3 > 1 > 2
WRAT- 3 Spelling	103.9 (7.9)	35	81.4 (10.4)	24	111.6 (8.6)	39	2, 95	88.69***	3 > 1 > 2
WRAT-3 Arithmetic	96.8 (12.9)	35	87.3 (16.9)	24	111.3 (10.6)	39	2, 95	26.72***	3 > 1 > 2
WRMT-R Word Identification	103.9 (7.9)	35	86.0 (13.4)	24	105.9 (5.7)	39	2, 95	42.36***	1, 3 > 2
WRMT – R Word Attack	102.0 (5.5)	35	87.1 (8.2)	24	103.3 (7.1)	39	2, 95	46.93***	1, 3 > 2
Diagnostic Characteristics (# symptoms)									
KSADS Inattention – Parent	7.8 (1.4)	35	7.3 (1.4)	24	0.5 (1.8)	39	2, 95	241.44***	1, 2 > 3
KSADS Hyperactivity/Impulsivity – Parent	4.8 (2.9)	35	5.5 (2.4)	24	0.6 (1.4)	39	2, 95	47.40***	1, 2 > 3
Conners Inattention – Parent	74.3 (12.2)	35	70.5 (19.0)	24	47.1 (5.6)	39	2, 95	51.25***	1, 2 > 3
Conners Hyperactivity/Impulsivity – Parent	68.8 (14.2)	35	70.0 (19.9)	24	49.1 (5.3)	39	2, 95	26.61***	1, 2 > 3
Conners Inattention – Teacher	66.7 (17.6)	35	68.0 (18.0)	24	42.3 (13.0)	39	2, 95	28.47***	1, 2 > 3
Conners Hyperactivity/Impulsivity – Teacher	65.7 (20.0)	35	63.5 (20.8)	24	42.9 (13.2)	39	2, 95	17.80***	1, 2 > 3
Comorbid Disorders (% of sample)									
Oppositional Defiant Disorder	37%	13	25%	6	0%	0			
Conduct Disorder	11%	4	4%	1	0%	0			
Generalised Anxiety Disorder	23%	8	21%	5	3%	1			
ADHD Subtypes (% of clinical sample)									
Inattentive Subtype	83%	29	71%	17	N/A				
Hyperactive/Impulsive Subtype	0%	0	0%	0	N/A				
Combined Subtype	17%	6	29%	7	N/A				

***$p < .001$, **$p < .01$, *$p < .05$.

Comparison sample. Parents and adolescents confirmed on the K-SADS interview and the Conners questionnaire that their adolescent did not have any Axis I diagnosis other than a specific phobia, or any history or current complaints of problems in attention, behaviour, mood disturbances, or learning. Adolescents in the comparison sample were also excluded if they had scores below the 25th percentile on any of the standardised tests of arithmetic, reading, or an estimated IQ below 80.

Time perception measures

The time perception tasks from study 1 were utilised: the duration discrimination task, the frequency discrimination control task, and the duration estimation by method of reproduction task (using intervals of 400 ms, 2000 ms, and 6000 ms).

Results

Outliers. As in study 1, there were some individuals who displayed extreme performance on individual tasks but were within a normal range on others, specifically on tasks where reaction times were the dependent measure. These outliers were treated in the same manner as in study 1, that is, changing each deviant score to equal the next highest score in the distribution, plus one unit. This procedure was applied on the following measures: mean performance on the duration discrimination task ($n = 1$, ADHD) and scores on the duration estimation task (400 ms duration ($n = 1$; ADHD+RD)).

Group differences in duration and frequency discrimination. Group differences were tested using one-way analysis of variance for each dependent measure, and the descriptive statistics are summarised in Table 4. The groups differed in duration discrimination, but not frequency discrimination. Specifically, the adolescents with ADHD+RD were less able to discriminate among durations in the 400 ms range, compared to the adolescents with ADHD and age-matched comparisons ($p < .05$).

Group differences in duration estimation by reproduction. An analysis of variance for repeated measures across interval was conducted separately for the mean duration and standard deviation scores. For mean duration, the main effect for interval and the group × interval interaction were significant, but the main effect for group was not significant. Simple effects analysis revealed that the adolescents with ADHD+RD were significantly less precise in their reproduction of the 400 ms interval compared to the adolescents with ADHD and the comparison group ($p < .05$), but this was not the case for the 2000 ms and 6000 ms intervals. For the intra-individual

Table 4 Means (standard deviation) for frequency, duration discrimination and estimation tasks for ADHD adolescent and comparison groups (study 2)

	ADHD (1)	ADHD+RD (2)	Control group (3)	Post-hoc
Frequency and duration discrimination[a]				
Frequency (3000 Hz)	3019.5 (8.2)	3017.85 (8.08)	3016.84 (5.67)	n.s.
Duration (400 ms)	492.7 (36.4)	510.4 (47.6)	485.4 (29.2)	2 > 1, 3
Duration estimation by method of reproduction[b]				
400 ms: Mean	519.9 (177.5)	577.3 (198.4)	463.0 (72.2)	2 > 1, 3
: SD	259.2 (410.0)	365.1 (465.1)	101.2 (102.4)	2 > 1, 3
2000 ms: Mean	2166.9 (319.9)	2219.0 (397.6)	2040.8 (314.7)	n.s.
: SD	616.2 (409.8)	695.8 (343.9)	340.4 (173.6)	1, 2 > 3
6000 ms: Mean	5347.9 (643.2)	5249.1 (890.1)	5590.0 (571.5)	n.s.
: SD	1153.5 (523.3)	1281.7 (657.2)	626.4 (263.5)	1, 2 > 3

[a]Frequency discrimination: $F(2,94) = 1.26$; n.s.; Duration discrimination: $F(2,94) = 3.44$, $p < .05$.
[b]Estimation task reproductions: Main effect for group: $F(2, 94) = 0.02$, n.s.; Main effect for interval: $F(2, 188) = 3584.74$, $p < .0001$; Group × interval interaction: $F(4, 188) = 4.41$, $p < .01$. Estimation task variability: Main effect for group: $F(2, 94) = 23.83$, $p < .0001$; Main effect for interval: $F(2, 188) = 123.22$, $p < .0001$; Group × interval interaction: $F(4, 188) = 3.92$, $p < .01$.

variability (SD) of the reproduced intervals, the repeated-measures ANOVA revealed significant main effects for group, interval, and a significant group × interval interaction. Simple effects analysis indicated that the ADHD+RD group displayed significantly more variability than the ADHD and comparison group at the 400 ms interval ($p < .01$), and adolescents with ADHD and ADHD+RD displayed significantly more variability at the 2000 ms ($p < .001$) and 6000 ms ($p < .001$) intervals than the comparison group.

Group differences in working memory measures. An analysis of variance (ANOVA) was conducted with the Digit Span and Arithmetic Standard Scores in order to test differences between groups in working memory. Significant differences between groups were obtained on both the Digit Span ($F(2, 92) = 12.47$, $p < .0001$) and Arithmetic ($F(2, 91) = 14.76$, $p < .0001$) Standard Scores. The ADHD+RD ($M = 7.17$, $SD = 2.64$) group had significantly lower Digit Span scores than the control ($M = 10.66$, $SD = 2.93$) and ADHD groups ($M = 10.44$, $SD = 2.85$; $p < .001$). The same pattern was observed for the Arithmetic scores. That is, the ADHD+RD ($M = 6.96$, $SD = 2.95$) group had significantly lower Digit Span scores than the control ($M = 11.43$, $SD = 3.18$) and ADHD groups ($M = 10.06$, $SD = 3.15$; $p < .001$).

As some have argued that short-term memory and working memory are often used interchangeably when in fact they are separable constructs (Engle, 2002; Engle, Tuholski, Laughlin, & Conway, 1999), additional group difference testing was done with the Digit Span Forwards and Backwards subtests. Standard scores for the Digits Forward and Backward scores were derived (WISC-III PI; Kaplan, Fein, Kramer, Delis, & Morris, 1999). A repeated measures design was used to examine differences between groups on these two measures, with performance on the Digits Forward and Backwards serving as the within subjects factor. Only group was found to be significant, ($F(2, 91) = 14.78$, $p < .0001$). The ADHD+RD ($M = 7.43$, $SD = 2.27$) group performed worse on Digits Forward than the control ($M = 10.37$, $SD = 3.28$) and ADHD ($M = 10.21$; $SD = 2.95$) groups ($p < .0001$), and the ADHD+RD ($M = 7.74$, $SD = 2.51$) group performed significantly worse on Digits Backward than the control ($M = 11.02$, $SD = 2.40$) and ADHD ($M = 10.36$, $SD = 2.52$) groups ($p < .0001$).

Effects of ADHD subtype, gender, and other comorbid disorders. With respect to ADHD subtypes, 79% of participants met criteria for the Inattentive subtype in the adolescent sample. When an analysis of variance was conducted with subtype and performance on the time perception measures, no significant differences or trends were observed. Notably, one of the unique characteristics of this adolescent sample is the relatively high representation of female adolescents with ADHD and ADHD+RD. Therefore, gender was also considered as a variable of interest in these analyses, and no gender differences were found on any of the time perception measures.

The impact of comorbid disorders on the time perception measures was also examined, specifically, the presence of Oppositional Defiant Disorder (ODD), Conduct Disorder (CD), and Generalised Anxiety Disorder (GAD). When ODD and GAD were examined, no statistically significant effects were obtained. One significant difference did emerge with the presence of CD on the estimation task. Specifically, participants with CD reproduced a significantly longer estimation ($F(1, 95) = 16.27$, $p < .001$) and displayed significantly more variability ($F(1, 95) = 16.03$, $p < .001$) on the 400 ms interval of the estimation task than participants who did not have CD. Importantly, only five participants (four ADHD and one ADHD+RD) met criteria for CD in this sample. Taking into account the effect of CD, the analysis of variance was carried out by excluding these five participants. When this analysis was done, the previously reported group differences were maintained on the duration estimation task.

Relationships between time perception, intellectual, achievement, and behaviour rating measures. Correlational analyses were conducted to determine relationships between performance on the time perception measures, ADHD symptoms (from parent and teacher reports), and intellectual and academic functioning. Analyses were conducted separately for clinical (ADHD, ADHD+RD) and comparison groups to examine whether the relationship between these variables co-vary differently in these groups. The Pearson correlation co-efficients are presented in Table 5.

The relationships obtained between the time perception *and* intellectual and behaviour measures differed in the clinical and comparison groups. In fact, performance seemed to be completely dissociated between the clinical and comparison groups. The reasons why performance may be completely dissociated in the clinical and comparison groups are unknown, but we proceeded to interpret correlations separately for the clinical and comparison groups given this pattern of findings. In the comparison group, significant correlations were obtained between the intellectual and behaviour measures *and* the frequency discrimination task. In the clinical group, performance on the duration discrimination task was significantly correlated with all of the working memory measures (including the Freedom From Distractibility Index, Arithmetic and Digit Span standard scores, and Digit Span forwards and backwards standard scores). Also in the clinical groups, the mean reproduction at the 400 ms interval of the estimation task was significantly associated with estimated Full-scale IQ (both Vocabulary and Block Design subtests), the WISC-III Processing Speed Index, and teacher reports of inattentive and hyperactive/impulsive behaviour. No significant associations were obtained with the achievement measures, and no significant associations were found between the time perception measures and the 2000 ms and 6000 ms intervals of the estimation task. The pattern of associations in Table 5 suggests that associations between these constructs differ between clinical and control groups. Consequently, regression analyses were performed to examine predictors of time perception performance, and these analyses permitted examination of the hypothesised association between time perception and working memory (Ivry, 1996).

Regression analyses with the clinical groups on the duration discrimination and estimation tasks. Stepwise multiple regression analyses were performed with the duration discrimination and estimation tasks, as these constituted the time perception measures in this study. These analyses were done separately with the clinical (ADHD, ADHD+RD) and comparison control groups. The different pattern of associations between the clinical and control groups in Table 5 necessitated separate examinations of each group. The stepwise multiple regression procedure was selected in order to attempt to prioritise entry of the variables, as many of these cognitive measures are highly intercorrelated. Based on the correlation matrix presented in Table 5, predictors were selected based on their size of correlation (Tabachnick & Fidell, 1989). The results of these regression analyses are presented in Table 6.

Based on the correlations in Table 5, the working memory measures were examined as predictors of participants' performance on the duration

Table 5 Zero-order correlations between measures of time perception and intellectual and academic abilities in clinical (ADHD, ADHD+RD) and comparison adolescents (study 2)

	FREQ Threshold (3000 HZ)		DUR Threshold (400 ms)		Estimation task at 400 ms interval	
	Clinical	Control	Clinical	Control	Clinical	Control
WISC-III Scores						
Estimated Full-Scale IQ	.17	−.23	−.14	.09	−.35**	.15
Freedom From Distractibility Index	.12	−.45**	−.50***	.09	−.07	−.19
Processing Speed Index	.03	−.26	−.26	.00	−.28*	−.16
Arithmetic Standard Score	.11	−.34*	−.42***	.04	−.05	−.26
Digit Span Standard Score	.10	−.41**	−.46***	.12	−.07	−.05
Digit Span – Forwards Standard Score	.17	−.40**	−.43***	−.05	−.12	−.10
Digit Span– Backwards Standard Score	−.01	−.42**	−.33*	.05	.04	−.10
Behaviour/Diagnostic Measures						
Parent K-SADS-Inattention	−.01	.32*	−.05	.07	−.04	−.13
Parent K-SADS- Hyperactive/Impulsive	.05	.36*	−.02	.20	−.20	−.08
Parent Conners–Inattention	.08	−.05	.06	.18	−.06	−.08
Parent Conners-Hyperactive	.15	−.05	.03	.12	.03	−.16
Teacher Conners-Inattention	−.12	.20	.12	−.09	.27*	.09
Teacher Conners-Hyperactive/Impulsive	−.15	.23	.12	−.20	.34**	.07

***$p < .001$, **$p < .01$, *$p < .05$.

Table 6 Stepwise regression analyses using clinical (ADHD, ADHD+RD) adolescent sample (study 2)

	Standardised beta weight	*t*-value	Partial *r*
Criterion Variable: Duration Threshold			
Step 1: Age	−.03	−.24	−.03
Step 2: WRMT-R Word Identification SS	−.03	−.19	−.03
Step 3: Digits Forward WISC-III Standard Score	−.43	−3.47***	−.43
Step 4: Digits Backward WISC-III Standard Score	−.16	−1.08	−.15
Step 5: Arithmetic WISC-III Standard Score	−.27	−2.01*	−.27
Overall Regression $F = 12.07$***			
Multiple $R = .43$			
Multiple R-squared = .19			
Criterion Variable: 400 ms Reproduction Task			
Step 1: Age	.14	1.1	.15
Step 2: WISC-III Estimated Full-Scale IQ[1]	−.27	−2.12*	−.28
Step 3: WISC-III Processing Speed Index Score	−.18	−1.35	−.19
Step 4: Conners' Teacher Report – Hyperactive/Impulsive Scale	.27	2.09*	.28
Overall Regression $F = 5.98$**			
Multiple $R = .43$			
Multiple R-squared = .19			

[1]This estimate is a composite based on Vocabulary and Block Design subtest scores.
***$p < .001$, **$p < .01$, *$p < .05$.

discrimination task. Age was entered as the first predictor to control for age effects, followed by reading ability (as measured by the WRMT-R Word Identification subtest). Then, three working memory measures were entered, including the Digits Forward, Digits Backward, and Arithmetic Standard Scores (all WISC-III test scores). The Digits Forward and Backward scores were considered as separate predictors for two reasons. First, their correlations with performance on the duration discrimination task differed, suggesting that Digits Forward performance may be more strongly tied to performance on this time perception measure. Second, theoretically, these two tasks involve different cognitive processes – namely, the Digits Forward involves holding and maintaining information, while the Digits Backward involves holding and manipulating information. Only the Digits Forward and Arithmetic Standard Scores entered into the equation as significant predictors of performance on the duration discrimination task. Other multiple regression analyses were conducted with full-scale IQ and the parent and teacher behaviour ratings, but none of these measures entered as significant predictors of performance. When this same regression analysis was conducted with the control group, none of these variables entered as significant predictors of performance on the duration discrimination task.

Performance on the duration estimation task at the 400 ms interval was most strongly correlated with estimated WISC-III Full-Scale IQ, the WISC-III Processing Speed Index score, and the teacher report of inattention and hyperactivity/impulsivity, as displayed in Table 5. A stepwise regression was performed, entering age, estimated Full-Scale IQ, the Processing Speed Index, and the teacher report of hyperactivity/impulsivity in this sequence. Estimated Full-Scale IQ and teacher report of hyperactivity and impulsivity were found to be significant predictors of performance on the estimation task at the 400 ms interval. In another analysis, teacher report of hyperactivity/impulsivity was entered before estimated Full-Scale IQ, and both continued to be significant predictors. Teacher report of inattention did not enter as a significant predictor. When these same regression analyses were conducted with the control group, none of these variables entered as significant predictors of performance on the estimation (400 ms interval) task.

Discussion

The purpose of the present investigation was to determine whether children and adolescents with ADHD exhibited deficits in time perception as predicted by current theory (Barkley, 1997a, c). To do so, we used psychophysical tasks that require processing of temporal information with children (study 1) and with adolescents (study 2).

The present investigations yielded two major findings. With the stratification of ADHD on the basis of reading ability and the inclusion of a developmental contrast with children and adolescents, the present study provides evidence to suggest that children and adolescents with ADHD and ADHD+RD exhibit deficits in some aspects of time perception. Specifically, children with ADHD displayed less accurate performance on the duration discrimination task and displayed more intra-individual variability on the estimation task at 2000 ms and 6000 ms intervals, but no differences were obtained on the frequency discrimination control task. Children with ADHD+RD displayed less accurate performance on virtually all of the time perception measures, but not on the frequency discrimination control task. Adolescents with ADHD displayed significantly more intra-individual variability on the estimation task at the 2000 ms and 6000 ms intervals compared to comparison controls, but no differences with the ADHD group were obtained on the duration discrimination task as was reported in the sample of children (study 1). The ADHD+RD adolescent group displayed deficits across most of the time perception measures, but not on the frequency discrimination control task, as was found in study 1.

Second, different variables were found to predict performance on the two time perception tasks examined in the sample of adolescents. Short-term and working memory measures were found to be significant predictors of performance on the duration discrimination task. Then, estimated Full-Scale IQ and teacher reported hyperactive/impulsive behaviours were found to be significant predictors of performance on the duration estimation task at the 400 ms interval.

Time perception and ADHD

There is evidence in the present investigation to suggest that time-related deficits are associated with ADHD. Specifically, children with ADHD (study 1) exhibited impairments in duration discrimination compared to the comparison group. This finding is in line with other investigations which have reported deficits in time perception with individuals with ADHD (Barkley, 1997c; Barkley et al., 1997, 2001; Sonuga-Barke et al., 1998), and cerebellar deficits in ADHD (Castellanos, 2001; Castellanos et al., 1996, 2001). Also, both child and adolescent groups with ADHD displayed significantly more variability in performance than the comparison group on the estimation task. Importantly, this variability of performance on the estimation task has been found to be characteristic of patients with cerebellar or cortical lesions, who typically display timing deficits (Ivry, 1997). One possible explanation is that this variability is nonspecific to timing, and is a reflection of variability in attentional focus. Alternatively, the present findings raise the possibility that impairments in time perception and estimation of temporal task-parameters could account in part for the ubiquitous finding of extreme variability in response times in ADHD, across a variety of speeded response tasks (Leth-Steensen, Elbaz, & Douglas, 2000; Tannock, 1998).

An even more consistent set of findings was obtained with the ADHD+RD group. It was hypothesised that this group would display deficits like the ADHD group, but perhaps even more impairment based on the additional RD comorbidity. Our hypothesis, however, was only partially supported, as the ADHD and the ADHD+RD groups did not display consistent performance trends on the time perception measures. In addition, the ADHD+RD group of adolescents displayed significantly lower scores on working memory measures (Digit Span Forwards and Backwards) compared to both the ADHD and comparison groups. This research therefore highlights the importance of considering comorbid-reading difficulties in these samples. However, since we did not include a reading disability group or another clinical comparison group, we cannot determine whether the deficit in time perception is specific to ADHD or common to other neurodevelopmental disorders, such as reading disabilities. The latter possibility has been investigated in depth in the reading disability literature (Chiappe, Stringer, Siegel, & Stanovich, 2002; Farmer & Klein, 1995; Stringer & Stanovich, 2000; Tallal, 1980; Wolf, 2001), and deficits in timing are an important component of the double-deficit hypothesis of reading disability (Wolf, Bowers, & Biddle, 2000; Wolf & Bowers, 1999; Bowers & Wolf, 1993). One study has reported selective impairments in duration discrimination at intervals longer than those used in the present study in children with reading disabilities, but no differences were reported on a frequency discrimination task (Fawcett, Nicolson, & Dean, 1996). The inclusion of a reading-disabled group is essential in future investigations to determine shared and unique deficits in time perception. While time perception and timing-related deficits are not unique to either ADHD or RD, there are important theoretically based reasons to consider these two disorders together. Specifically, an important line of work has purported that ADHD and RD may share a similar genetic etiology (Willcutt et al., 2001), which highlights the importance of considering time perception deficits in both of these populations.

One critical difference between the two time perception measures used is the motor timing component in the estimation task. This difference has implications for providing an alternative explanation for the current findings. Inconsistent associations between time perception and motor timing performance has been described in the literature (Block, 1990), and empirical investigations of individuals with ADHD have provided evidence for impairments on both types of tasks (Rubia et al., 1999a, b, 2001; Smith, Taylor, Warner Rogers, Newman, & Rubia, 2002). In the current study, children with ADHD displayed impaired performance on the duration discrimination task, which is a more purely cognitive, not motor timing task, suggesting deficits in time perception, which is consistent with other work (Smith et al., 2002). Importantly, Smith et al. (2002) examined duration discrimination at a target interval of 1000 ms, which is considerably longer than the duration used in this study.

Alternative explanations of these findings (i.e., other than a specific deficit in time perception) are also possible and must be considered. For example, the pattern of findings on the time perception measures may have been due to non-specific problems in processing auditory stimuli, or difficulties with the response requirements used in the tasks. The task design allows us to rule out the possibility of a general perceptual deficit or difficulty processing auditory information, since both tasks involved the presentation of brief auditory tones (either as boundary markers for the specific intervals, or as stimuli for the frequency discrimination task), but the impairments were specific to the duration discrimination task. Also, since both tasks used a forced choice response procedure and neither required a speeded response, we can rule out the possibility of a general difficulty with the type of decision making that was required (i.e, first versus second stimulus) or slow response times.

Another possible explanation is that the psychophysical tasks used in the present study place demands on working memory and so the findings may reflect deficits in working memory that have been reported in ADHD (e.g., Barkley, 1997a; Mariani & Barkley, 1997). This is because the tasks require a comparison between two successive stimuli, separated by a brief interval. The presentation of the first stimulus would have to be maintained across the interstimulus interval as well as during the presentation of the second stimulus, at least until a decision is reached. Such an operation is consistent with the functions of working memory (e.g., Baddeley, Gathercole, & Papagano, 1998; Goldman-Rakic, 1995). This function of working memory may then explain the seemingly counterintuitive finding that working memory measures were significantly associated with the duration discrimination task at the 400 ms interval in the clinical adolescent sample. Specifically, the Digits Forward and Arithmetic Standard Scores were associated with performance on the duration discrimination task. Some investigators, such as Ivry (1996), have distinguished between short (< 2 seconds) and longer (> 2 seconds) durations; specifically, that shorter durations are linked to an internal timing mechanism, while longer durations may be related to functions of working memory. This distinction between short and long intervals has not held in the current empirical investigation, but there may be good reasons for the association. Working memory may inevitably play a role in tasks where judgements (frequency and duration discrimination task) or cognitive and motor coordination requirements must be integrated (duration estimation task). Given the task demands of making judgements or integrating cognitive and motor requirements would trail into longer intervals of time than the actual length of the stimuli, therefore, likely prompting functions of working memory. However, the working memory measures were not associated with performance on the estimation task, which is not inconsistent, as performances on discrimination and estimation tasks do not tend to co-vary together (Block, 1990). The results of study 2 with the adolescent sample do implicate the role of short-term and working memory in performance on the most purely cognitive time perception measure – the duration discrimination task, but not on performance on the estimation task at the equally short interval.

Interestingly, performance on the estimation task was most strongly associated with estimated Full-Scale IQ and teacher reports of hyperactivity/impulsivity in the adolescent clinical sample. The estimation task was different from the discrimination task in many ways, but most obviously because of the motor reproduction component. The link between estimated Full-Scale IQ and estimation performance highlights the cognitive requirements in this task, and in this case, the link is with general cognitive ability. The relationship obtained between the estimation task and estimated Full-Scale IQ is not explanatory in terms of implicating specific cognitive mechanisms. However, the dissociation between the variables associated with each of the time perception measures continues to be an issue of interest – namely, that working memory measures were significantly associated with the frequency and duration discrimination tasks, but not the estimation task. Teacher reports of inattention and hyperactivity/impulsivity also predicted performance on the estimation task, and two possible interpretations may be considered. Either the teacher observations capture difficulties in the timing or synchronisation of motoric behaviours, such as calling out in class or jumping out of a seat, *or* the more general types of motoric difficulties described in ADHD samples. Interestingly, it is the teacher reports, not the parent reports, that predicted performance on the reproduction task. It may be the case that motoric difficulties are more obvious to teachers than to parents, as it is in classroom settings that ADHD children and adolescents are expected to perform in structured environments for extended periods of time. This finding is consistent with the literature that has demonstrated motor timing (Rubia et al., 1999a, b, 2001) and motor coordination deficits in ADHD samples (Beyer, 1999; Piek, Pitcher, & Hay, 1999; Rubia et al., 1999a, b; Sagvolden & Sergeant, 1998; Steger et al., 2001).

An additional consideration is the nature of the two samples studied in this investigation. Namely, study 1 was conducted with children and study 2 was conducted with adolescents, introducing developmental considerations in the interpretation of the results. In fact, some of the differences obtained in the child sample were not replicated in the adolescent sample. For example, children with ADHD and ADHD+RD displayed weaker duration discrimination performance in study 1, but only the adolescents with ADHD+RD displayed this effect in the adolescent sample. Also, differences on the estimation task in the child sample were no longer evident in the adolescent sample at intervals of 2000 ms and 6000 ms. Given the positive direction of the results obtained, that is, that the adolescents displayed somewhat better performance on particular aspects of the time perception measures than children, these findings do suggest developmental influences on intact time perception abilities. With development, children become more capable and skilled at deploying resources and control in cognitive tasks (Zelazo & Frye, 1998; Zelazo, Carter, Reznick, & Frye, 1997), which may impact performance on tasks such as those examined in the present investigation.

By contrast to the current beliefs that perceptual and sensory processes are intact in ADHD (Barkley, 1998; Douglas, 1999; Ross, Hommer, Breiger, Varley, & Radant, 1994), the present findings suggest that some basic processes related to time perception are impaired in ADHD. Importantly, further consideration should be given to the relationship between time perception deficits and the highly comorbid disorders of ADHD and RD. These findings also suggest that aspects of time perception are related to short-term and working memory, and that deficits in these cognitive processes are separable from the motor control problems associated with ADHD.

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