ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Human Movement Science 21 (2002) 919–945

HUMAN MOVEMENT SCIENCE

www.elsevier.com/locate/humov

Timing and force control in boys with attention deficit hyperactivity disorder: Subtype differences and the effect of comorbid developmental coordination disorder

Thelma M. Pitcher, Jan P. Piek *, Nicholas C. Barrett

Research Centre for Applied Psychology, School of Psychology, Curtin University of Technology, G.P.O. Box U1987, Perth 6845, Australia

Abstract

This study examined the motor and performance outcomes of boys with subtypes of attention deficit hyperactivity disorder (ADHD) (DSM-IV, [American Psychiatric Association, Diagnostic and statistical manual of mental disorders, 4th ed., Washington, DC, 1994]). It also examined the differences between boys with a single diagnosis of ADHD versus those who have the dual categorisation of ADHD and developmental coordination disorder (DCD). The participants were 157 boys, aged 7.70–12.98 years recruited from a community sample. Parent report was used to classify 143 boys into either a comparison group or one of the three DSM-IV ADHD subtypes. Participants were given a battery of tests that included the Movement Assessment Battery for Children [Movement Assessment Battery for Children, Psychological Corporation/Harcourt Brace-Jovanovich, New York, 1992], the Wechsler Intelligence Scales for Children – Third Edition [Manual for the Wechsler Intelligence Scale for Children, Psychological Corporation, New York, 1992] and a finger tapping task targeting motor processing, preparation, and execution. Boys with subtypes that included inattentive symptomatology had significant difficulties with timing, force output and showed greater variability in motor outcomes. Boys with the comorbid condition (i.e., ADHD and DCD) had particular difficulty with force control. These outcomes identify a need for increased recognition of the clinical and research implications of the relationship between ADHD and motor dysfunction. This potentially impacts on assessment, intervention, theoretical modelling and the general interpretation of cognitive abilities research with children with ADHD.

* Corresponding author. Tel.: +618-9266-7990; fax: +618-9266-2464.
E-mail address: j.piek@curtin.edu.au (J.P. Piek).

0167-9457/02/$ - see front matter © 2002 Elsevier Science B.V. All rights reserved.
doi:10.1016/S0167-9457(02)00167-7

PsycINFO classification: 2330; 2820
Keywords: Attention deficit hyperactivity disorder; Reaction time; Movement time; Force; Developmental coordination disorder

1. Introduction

Children with attention deficit hyperactivity disorder (ADHD) experience a persistent condition that can lead to life long problems. Diagnosis of ADHD requires identification of a specific number of symptoms from an inventory of persistent inattentive and/or hyperactive–impulsive behaviours that are inconsistent with their developmental level and are maladaptive (American Psychiatric Association, 1994). Characteristically, these children may be unable to plan ahead or complete tasks and may demonstrate increased levels of activity and/or impulsivity. Three distinct subtypes are identified in the most recent formulation of ADHD, namely, ADHD-predominantly inattentive (ADHD-PI), ADHD-hyperactive–impulsive (ADHD-HI) and ADHD-combined (ADHD-C) (American Psychiatric Association, 1994). The diagnostic criteria needed to meet either of the single diagnostic subtypes requires a child to have either six of nine inattention symptoms (ADHD-PI) or six of nine hyperactive–impulsive symptoms (ADHD-HI) but not reach the specified number of symptoms for the alternate diagnosis. To meet the ADHD combined type diagnosis (ADHD-C), a child must meet the criteria for both the inattention and hyperactive/impulsive symptoms.

The link between ADHD and motor coordination difficulties such as developmental coordination disorder (DCD) is well founded (e.g., Barkley, DuPaul, & McMurray, 1990; Hartsough & Lambert, 1985; Piek, Pitcher, & Hay, 1999). However, research examining the underlying motor functions of children with DSM-IV ADHD subtypes is limited, and findings to date are inconsistent. Although the most recent formulation of ADHD emphasises three distinct subtypes, earlier work (e.g., Hartsough & Lambert, 1985) has focused primarily on children with hyperactivity/impulsivity and is therefore more informative of DSM-IV ADHD subtypes with this type of symptomatology. To date, research specifying the severity and range of movement difficulties experienced by children with subtypes that include inattention has not been comprehensively documented.

The information processing approach has been used to investigate the underlying motor difficulties of both children with ADHD (van der Meere, 1996) and those with dysfunctional motor coordination (e.g., Wilson & McKenzie, 1998). The 'input' stage of information processing involves perceptual processes such as the registration, integration and interpretation of sensory information (Wilson & McKenzie, 1998). Perceptual processes in particular appear to be disrupted in children with DCD (e.g., Coleman, Piek, & Livesey, 2001; Wilson & McKenzie, 1998). Central processes are responsible for the response-selection stage, which involves decisions on the response required. Motor, or output processes involve the organisation and initiation of the appropriate response or motor program. It is this stage that has received considerable attention in the ADHD literature.

Children with ADHD are often found to be slow, inaccurate performers (Jennings, van der Molen, Pelham, Debski, & Hoza, 1997; Oosterlaan & Sergeant, 1996; Scheres, Oosterlaan, & Sergeant, 2001; van der Meere, 1996; van der Meere & Sergeant, 1988) where delayed motor processing is considered a core deficit (see also Sergeant & van der Meere, 1988; van der Meere, Vreeling, & Sergeant, 1992). These findings have led to the development of a motor output deficit hypothesis (Sergeant & van der Meere, 1988; van der Meere, 1996; van der Meere et al., 1992). In particular, children with hyperactivity have demonstrated greater reaction time (RT) variability in performance on various psychometric tasks than control children (Douglas, 1972; Jennings et al., 1997; van der Meere & Sergeant, 1988). However, as discussed by Rubia, Oosterlaan, Sergeant, Brandeis, and van Leeuwen (1998), RT outcomes and their variability require contextual analysis of associated task demands (i.e., cognitive, sensory and motor related demands). Thus, it is possible that observed outcomes may be less related to specific motor deficits than to difficulties with executive functions (e.g., attentional, memory) that are taxed by the test construction. From an information processing perspective, attention (i.e., the rate of information processing within the working memory system (Schiffrin and Schneider, 1977, cited in Sergeant & van der Meere, 1990)) assists the process of stimuli recognition, response selection and response organisation as compatible memory traces are accessed, selected and assimilated, and incompatible activities are attenuated (Keele, 1973).

Using primed and delayed RT tasks, output stage processing difficulties were again implicated for children with ADHD (Leung & Connolly, 1997). Yet, interestingly, a choice RT paradigm follow-up study with the same sample, whilst finding significant differences in RT, Movement Time (MT) and their variability as a function of task complexity (i.e., number, and position, of keys within the movement sequence), found no significant difference in motor organisation or motor execution (Leung & Connolly, 1998). However, this result may have been influenced by low power due to small group sizes and the authors agreed that cross-validation was necessary (Leung & Connolly, 1998). A factor restricting the applicability of these findings to DSM-IV ADHD is the omission of children without symptoms of hyperactivity–impulsivity (i.e., ADHD-PI). This factor arose due to the authors' utilisation of ICD-10 criteria. Indeed, investigation of subtype variance with respect to RT is limited.

Simple finger tapping tests (e.g., number of taps completed within a specified time interval) have often been used within a battery of neuropsychological tests for children with ADHD in order to gauge motor speed (e.g., Seidman et al., 1995; Seidman, Faraone, Biederman, Weber, & Oulette, 1997). Slower tapping speed has been linked to inattentive symptomatology in community samples although some participants had comorbid hyperactive–impulsive and disruptive behaviours (McGee, Williams, & Silva, 1985, 1987). Stevens, Stover, and Backus (1970) also report slower response rates and an inability to speed up when instructed to or when provided with an incentive. However, others report no significantly different performance to that of the controls (e.g., Gordon & Kantor, 1979; Seidman et al., 1995). Seidman and colleagues (e.g., Seidman et al., 1995; Seidman et al., 1997) failed to find any significant motor speed difference in children with varying comorbid combinations of learning difficulties, ADHD (DSM-III-R) and family history ADHD as compared to control children. These simpler tests of fine motor skills (i.e., simple tapping speed) do not seem to be as affected as the more complex motor sequences (Breen, 1989; Grodzinsky & Diamond, 1992; Mariani & Barkley, 1997).

Given the relationship between timing and force to the production of movement, there is surprisingly little in the ADHD literature on this aspect of functioning, with two exceptions. Pereira, Eliasson, and Forssberg (2000), using a grip-force technique, found that boys with ADHD (DSM-III-R) and motor performance difficulties displayed greater variability in force output and impaired sensory motor control than control children (Pereira et al., 2000). Boys with ADHD and no motor difficulties were found to have inconsistent force output more similar to the ADHD/motor impaired group than the control group. However, the grip-force task did discriminate the loci of dysfunction from "sensory information processing, the storage and retrieval of the memory representation, or the programming of the motor commands" (Pereira et al., 2000, p. 551). A study by Steger et al. (2001) examined neuromotor and attentional deficits in a group of 11 year old children with ADHD (DSM-III-R). Force was continuously monitored during both unilateral and bilateral RT tasks that required an "opposing pressure of thumb and index finger (precision grip)" response to the visual stimuli (Steger et al., 2001, p. 174). Children with ADHD were found to take longer to reach peak force (PF) and had more variability in their RT to force onset (Steger et al., 2001).

The aim of the current study was to utilise the information processing approach to derive understanding about the timing and force variables disrupted in each of the three ADHD subtypes. A sequential tapping task was used to analyse the timing of movement and its variability when task complexity was manipulated by requiring the previewed, accentuation of force on none, one or more taps within a five-tap sequence. Increasing the complexity of the task increases the cognitive load (Piek, Glencross, Barrett, & Love, 1993; Piek & Skinner, 1999). Earlier studies investigating timing in children with ADHD have often relied on tasks that have minimal motor related procedures and were often more visuo-spatially oriented (e.g., the visual search task of Sergeant & Scholten (1985a)). Leung and Connolly (1998) argued that "different processes are examined" in tasks that manipulate aspects such as event rate (e.g., van der Meere et al., 1992), whereas tasks that manipulate the sequence complexity are more reflective of the "organization and execution of serial movement" (p. 605). The task used in the current study was developed specifically to examine the organization and execution of movement sequences (e.g., Refer to Garcia-Colera & Semjen, 1988; Keele, Ivry, & Pokorny, 1987; Klapp & Wyatt, 1976; Piek & Glencross, 1993; Piek et al., 1993; Semjen & Garcia-Colera, 1986; Semjen, Garcia-Colera, & Requin, 1984; Wing, Keele, & Margolin, 1984), and has been successfully used on children with DCD who were shown to have timing related impairment (Piek & Skinner, 1999). The technique enables the measurement of RT, inter-tap interval (ITI) relating to overall movement speed, and PF.

The participant pool was distinguished in two distinct ways to address two separate issues. The first analysis involved examining four groups of boys, a comparison group and each of the three subtypes of ADHD as defined by the DSM-IV. It was hypothesised that boys in the ADHD groups would have longer RTs for each tapping force condition than boys in the comparison group (e.g., Lorys, Hynd, & Lahey, 1990; Oosterlaan & Sergeant, 1996; Ullman, Barkley, & Brown, 1978; Zahn, Kruesi, & Rapoport, 1991). They would also show significantly different PF output for each tapping force condition than the boys in the comparison group (e.g., Pereira et al., 2000), and would have significantly longer ITIs than the comparison group within the complex force (i.e., accentuation) conditions (e.g., Sergeant & Scholten, 1985a; Sheppard, Bradshaw, Georgiou, Bradshaw, & Lee, 2000; van der Meere et al., 1992). Finally, it was expected that each of the ADHD subtypes would have significantly greater timing and force variability as demonstrated by their mean RT, mean PF and mean ITI when compared to the comparison group (e.g., Leung & Connolly, 1994; Pereira et al., 2000; Schachar, Tannock, & Logan, 1993; Sergeant & Scholten, 1985a).

The second approach involved the comparison of boys with a single diagnosis of ADHD, with those who have a dual diagnosis of ADHD and DCD. A third, control, group was also included. This was designed to determine the comparative degree of difficulty for children with a single compared with a dual diagnosis, and to determine whether deficits for a single or dual diagnosis also differ in terms of the processes disrupted. It was expected that boys with comorbid ADHD/DCD would have significantly poorer performance on each experimental measure than either the ADHD only or control groups. Given that a disruption in input processes has been identified for children with DCD (e.g., Wilson & McKenzie, 1998), and output processes have been linked to children with ADHD (e.g., Sergeant & van der Meere, 1988), it would be expected that different processes would be identified for children with a single versus a dual diagnosis. This provides insight into the suitability of the definitional criteria detailed within the DSM-IV ADHD section with respect to the lack of formal recognition of the potential for comorbid DCD (American Psychiatric Association, 1994).

2. Method

2.1. Participants

The sample for the current study was a community sample derived from main stream primary schools, across a broad spectrum of socio-economic localities, within the Perth metropolitan area.

2.1.1. Subtype allocation

One hundred and forty three boys were allocated to one of four groups according to parent/guardian response to the Australian disruptive behaviours scale (ADBS) (Levy & Hay, 1991) identifying the presence or relative absence of hyperactivity/impulsivity or inattentive symptoms. Boys classified in the ADHD-PI ($n = 50$) group were required to have at least six of nine inattentive symptoms but less than six

Table 1
Means, standard deviations and range for age, VIQ and number of DSM-IV ADHD symptoms

		Age[a]	VIQ	DSM-IV Symptoms[b]	
				Inattentive	Hyperactive/ impulsive
Comparison	*M*	10.32	108.54	0.15	0.13
	SD	1.31	18.29	0.59	0.41
	Range	7.70–12.86	70–141	0–3	0–2
ADHD-PI	*M*	10.04	101.68	7.50	2.12
	SD	1.21	19.72	1.23	1.85
	Range	7.80–12.96	59–137	6–9	0–5
ADHD-HI	*M*	9.88	99.50	2.87	6.81
	SD	1.18	19.69	1.50	1.05
	Range	7.90–12.46	54–133	1–5	6–9
ADHD-C	*M*	10.17	98.63	8.16	7.82
	SD	1.34	18.98	1.08	1.04
	Range	7.97–12.98	65–133	6–9	6–9

[a] Age in years.
[b] Total number of DSM-IV ADHD symptoms rated as present on the ADBS – out of a possible 9.

hyperactive/impulsive symptoms. Forty percent of the ADHD-PI group had been previously diagnosed. Boys in the ADHD-HI ($n = 16$) group had at least six of nine hyperactive/impulsive symptoms but fewer than six inattentive symptoms (37.5% had received a previous diagnosis). Boys in the ADHD-C ($n = 38$) group had at least six of nine symptoms within both the inattentive category and the hyperactive/impulsive category (66% had received a previous diagnosis). The smaller number in the ADHD-HI group was an anticipated outcome as children with ADHD-HI are generally more prevalent in a younger age range (Lahey et al., 1994) than that considered ideal for the current study (7–12 years). Information obtained post-group allocation as reported within the Conners' Parent Rating Scale (CPRS-R:L:Conners, 1997) provided evidence in support of the ADHD groupings derived from the ADBS. Participants allocated to the comparison group ($n = 39$) were required to have minimal ADHD symptomatology (<3 ADHD symptoms), minimal birth complications and no serious developmental or mental difficulties as reported by a screening questionnaire. Group means, standard deviations and range for age, verbal intelligence (VIQ) and number of DSM-IV ADHD Symptoms are shown in Table 1. Groups were equivalent in terms of SES as measured by mothers' and fathers' highest level of education.

2.1.2. Allocation by diagnosis

For this stage, group membership involved the categorisation of the ADHD and comparison participants into groups based on their presence or absence of a 'DCD' classification. The performance criteria for 'DCD' category membership were established based on the participant's Movement Assessment Battery for Children (MABC) total impairment score (i.e., $\leqslant$ 15th percentile).

Table 2
Means, standard deviations and range for age, VIQ, number of DSM-IV ADHD symptoms and ADHD symptomatology continuum score for ADHD/DCD, ADHD-U and comparison groups

		Age[a]	VIQ	DSM-IV Symptoms[b]	
				Inattentive	Hyperactive/ impulsive
Comparison	*M*	10.16	111.10	0.13	0.13
($n = 31$)	SD	1.37	17.98	0.56	0.43
	Range	7.7–12.9	70–141	0–3	0–2
ADHD-U	*M*	9.91	103.06	7.00	5.18
($n = 49$)	SD	1.28	17.89	2.35	3.25
	Range	7.8–12.98	59–133	1–9	0–9
ADHD/DCD	*M*	10.20	97.71	7.05	4.69
($n = 55$)	SD	1.22	20.32	2.03	2.97
	Range	7.8–12.5	54–137	1–9	0–9

[a] Age in years.
[b] Total number of DSM-IV ADHD symptoms rated as present on the ADBS – out of a possible 9.

The first group included all boys who met the criteria for ADHD categorisation (see above for full details) and a 'DCD' categorisation (i.e., ADHD/DCD). The ADHD/DCD group was comprised of 55 participants. A second group consisted of all participants with an ADHD diagnosis (unspecified subtype) (ADHD-U) but no 'DCD' categorisation. The comparison group was comprised of all participants without either ADHD or DCD ($n = 31$). A DCD group was not formed due to low numbers (i.e., only eight participants from the original comparison group met the DCD criteria). The means, standard deviations and range for age, prorated WISC-III VIQ, and number of DSM-IV ADHD symptoms are displayed in Table 2. Age was found to be statistically nonsignificant, $F(2, 132) < 1$; partial $\eta^2 = 0.01$. However, a statistically significant difference was found for VIQ, $F(2, 132) = 4.96$, $p < 0.025$; partial $\eta^2 = 0.07$. Post hoc analysis revealed that the ADHD/DCD group had significantly lower VIQ than the comparison group, $p < 0.05$.

Both inattentive symptomatology, $F(2, 132) = 134.97$, $p < 0.025$; partial $\eta^2 = 0.67$, and hyperactive/impulsive symptomatology, $F(2, 132) = 45.28$, $p < 0.025$; partial $\eta^2 = 0.41$, were found to be statistically significant. Post hoc analysis indicated that both the ADHD/DCD and ADHD-U groups had significantly more inattentive and hyperactive/impulsive symptomatology than did the comparison group ($p < 0.05$) but that they did not differ between themselves ($p > 0.05$).

2.2. Apparatus

2.2.1. The Australian disruptive behaviours scale (ADBS)

The shortened form of the ADBS (Levy & Hay, 1991) is an 18 item parent report questionnaire that reflects DSM-IV criteria for ADHD (i.e., nine inattentive symptoms and nine hyperactive/impulsive symptoms). The rater indicates the applicability of each item for their child either now or within the last six months on a 0 (not at all) to 3 (very much/very often) scale. Ratings of 0 or 1 are interpreted as symptom absent and ratings of 2 or 3 are interpreted as symptom present. This method of establishing symptom presence is consistent with the procedures adopted in other studies (e.g., Lahey et al., 1998; Pelham, Gnagy, Greenslade, & Milich, 1992) and is a valid method of identifying children with subtypes of ADHD (refer to Levy, McStephen, & Hay, 2001). Parental ratings of behaviour using the ADBS have been found to be a conservative indicator of symptom presence (Levy, Hay, McLaughlin, Wood, & Waldman, 1996). Studies using DSM-III-R ADHD criteria have reported kappa coefficients of 0.561 to 0.648 and an alpha coefficient of 0.86 (Levy, Hay, McStephen, Wood, & Waldman, 1997).

2.2.2. The movement assessment battery for children (MABC)

The MABC (Henderson & Sugden, 1992) is a revised version of the test of motor impairment (TOMI) (Stott, Moyes, & Henderson, 1984), and is a standardised, two part, structured, motor ability assessment consisting of a parent/teacher report checklist and an individually administered performance test. The standardised performance test was used in the current study and consists of four age bands (4–6, 7–8, 9–10 and 11–12 years) that incorporate the performance of eight different tasks, rated on a 0–5 scale. A total impairment score is derived from the compiled scores and may then be interpreted against the age-related peer performance as established in test standardisation studies in United States. Higher test scores indicate greater motor impairment. Children with total impairment scores in the 5th and lower percentiles are considered to have performed at a level "indicative of a definite motor problem" that requires intervention (Henderson & Sugden, 1992, p. 108). Children with scores between the 5th and up to the 15th percentile demonstrate a 'borderline' degree of difficulty (Henderson & Sugden, 1992).

The percentages of agreement between a test-retest study for the MABC revealed a range between 73% and 97% concordance in the total impairment score and similarly in each of the three performance groupings (Henderson & Sugden, 1992). A recent study has reported the MABC to significantly correlate ($r = 0.62$) with a German test of coordination in children (i.e., Physical Coordination Test for Children: Kiphard and Schilling, 1974) (Smits-Engelsman, Henderson, & Michels, 1998).

2.2.3. Verbal intelligence quotient

A short form of the Wechsler Intelligence Scale for Children – III (WISC-III) (i.e., the similarities and vocabulary subtests; Wechsler, 1992) was used to assess verbal intelligence quotient (VIQ) in order to ensure comparative abilities between groups. These two subtests were chosen because as a dyad they have high reliability coefficients (vocabulary $r = 0.87$, similarities $r = 0.81$) and good validity (Sattler, 1988; Wechsler, 1992).

2.2.4. The tapping apparatus

This computer linked apparatus consisted of a single 1.5 cm diameter tapping key upon which the participant executed each tap with the index finger of their dominant hand. The tapping key was connected to a strain gauge within a metal earthing plate affixed to the table top. The strain gauge was wired into an Apple Centris 650 computer via an amplifier and an analogue and digital input card (National Instruments Lab NB). Touching the surface of the tapping key triggered the electronic circuit, enabling the onset and conclusion of each tap to be recorded. Depression of the key activated the strain gauge leading to the electronic amplification of the information and recording of the PF of the tap.

A graphical representation of the tapping sequence for each condition was displayed at participant eye level. A Seiko digital metronome (DM-20), with an accuracy rating to within 3% of the required beats per minute, was used to assist participants during a practice phase to modify their tapping speed to test requirements. A green light-emitting diode (LED) was used to signify the requirement to commence tapping. At the completion of each five-tap sequence, the outcome was graphically displayed on the computer monitor providing the experimenter with immediate feedback about the participant's performance. Labview 3.0.1 software for Macintosh computers was used to manage the tapping sequences and record each participant's results in separate data files for each tap condition.

2.3. Procedure

Ethical guidelines of the National Health and Medical Research Council of Australia were followed. The participants were recruited from 35 primary schools in the metropolitan area of Perth, Western Australia. Consenting parents/guardians were forwarded a questionnaire containing the ADBS and demographic items. The questionnaire was used to screen participants and allocate group membership. Parents/guardians were notified upon completion of the study of any potentially problematic test or questionnaire outcome. In order to minimise the effects of ADHD related medication on test outcomes, participants were asked to abstain from all doses on their scheduled day of testing and testing was coordinated, where possible, with any usually occurring temporary withdrawals (e.g., school holidays). Consequently, all medicated participants had, at minimum, a period of abstinence of approximately 15 h prior to being tested. Although this length of abstinence did not officially meet the 'drug free' status according to the pharmacokinetic data for medications with lengthier half-lives (e.g., dexamphetamine – 10.25 h) (Pharmaceutical Society of Australia, 2000), the strategy served to effectively minimise, as opposed to negate, the effects of medications for the majority of participants.

Research assistants who were blind to the participant's ADHD status administered the VIQ and tapping test in a standardised manner at mutually convenient times. These tests were components of a broader test battery that was administered in a counter balanced design in two sessions and included the WISC-III Performance IQ (Wechsler, 1992) and the Purdue Peg Board (Tiffin, 1968). Given the age of the participants and nature of ADHD symptomatology, each participant was advised that they could take a brief break during the testing if they grew tired.

A randomly selected number of participants from each group were videotaped in order to assess 'attention to task' using the child observation component of the observing pupils and teachers in classrooms (OPTIC) system (Houghton, Wheldall, Jukes, & Sharpe, 1990). These assessments revealed a significant inter-rater reliability of the 'on-task' behaviour (i.e., appropriate task oriented behaviour) at $r = 0.98$, $p < 0.001$ (off-task ratings, $r = 0.95$, $p < 0.001$) and no significant differences in the mean level of on-task, $F(3, 52) = 2.24$, $p > 0.05$, or off-task, $F(3, 52) = 2.24$, $p > 0.05$, behaviour.

The tapping task was administrated at the University laboratory according to a standardised set of instructions. The task required the production of 20 five-tap sequences within three experimental conditions administered in a counter-balanced design. The participant was seated at a desk with his forearm resting comfortably on the table top and the index finger of his dominant hand extended over the tapping key. Prior to each condition, the experimenter demonstrated the required sequence on the table top and allowed the participant to practice his technique to the sound of a precise metronome set to an ITI of 300 ms. The experimenters monitored each participant's technique to ensure that their action was generated only by movement of the index finger. Three essential movement sequence elements are emphasised within this task, namely, a speedy response to the start stimulus, and accurate reproduction of the timing and force requirements.

The force conditions were graphically represented (e.g., short block = soft tap; tall block = stressed tap) and displayed, as required, in front of the participant at eye level. The no force change (NFC) condition required five evenly forced taps. The force change at 3rd tap (FC3) condition required four evenly stressed taps and a stressed 3rd tap. The force change maintained (FCM) condition required a stressed 3rd, 4th and 5th tap. A sequence commenced with the experimenter saying 'Ready' and the participant resting his index finger lightly on the tapping key. He was required to commence tapping as soon as he saw the green LED illuminate following a random foreperiod of 1000–2200 ms. The experimenter provided the participant with verbal feedback regarding the conformity of his speed and accuracy to the required tapping sequence. Five practice trials were immediately followed by twenty experimental trials. An example of the elements of a FC3 sequence is shown in Fig. 1.

Three essential elements may be noted within the initiation and execution of each five-tap sequence: (a) the RT to respond to the start signal, (b) the temporal reproduction of the ITI (i.e., 300 ms between taps), and (c) reproduction of the sequence force elements.

2.4. Data analysis

Within each of the three force conditions the following variables were recorded:

Reaction time (RT): The time that the participant's finger was in contact with the key following the initial response signal.

Peak force (PF): The peak output voltage for the force exerted while the finger was in contact with the key.

Inter-tap interval (ITI): The interval that includes the contact interval and the non-contact interval immediately preceding it.

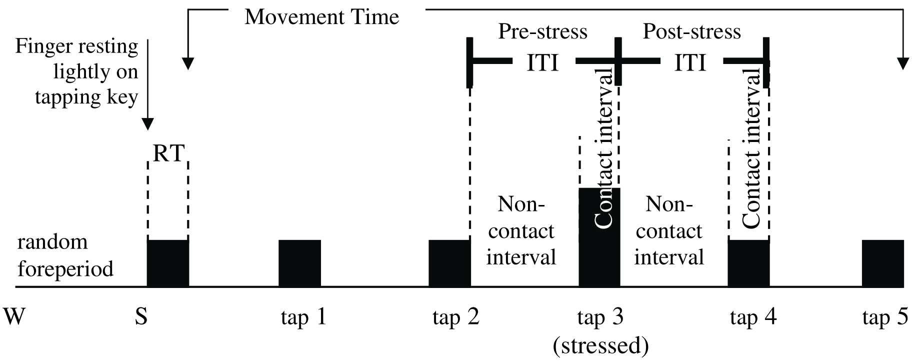

Fig. 1. The movement sequence for a response trial in which participants stress tap 3 (W = verbal warning prompt, S = green LED response signal, RT = reaction time, i.e, lift of finger from key after S; ITI = inter-tap interval). Note: Each tap within the sequence derives both a noncontact interval and a contact interval.

Variability: The coefficient of variation, as calculated by dividing the standard deviation of the distribution by the median of the distribution (Diekoff, 1992), was determined for each of the above three variables.

Statistical significance was assessed using a mixed design with two repeated measures factors of Force (three conditions) and Tap (five tap locations) examined at each level of the between groups factor (Group) for all dependent variables with the exceptions of RT (Group × Force only).

Given that the primary aim of the research was to determine the effect of the independent variable 'Group' on each of the dependent variables, main effects and interactions that did not involve the 'Group' variable (e.g., Force by Tap) were not analysed for their simple effects. These interactions indicated the adherence of the participants to task requirements and demonstrated a consistency with both the outcomes of previous studies and an indication of appropriate task completion (e.g., Piek & Glencross, 1993; Piek et al., 1993; Piek & Skinner, 1999). Logarithmic transformations were performed on all dependent variables in order to reduce the variability and general positive skew of the data.

3. ADHD subtype comparisons

3.1. Results

3.1.1. Reaction time

Fig. 2 shows the group mean logarithmic RTs plotted as a function of force condition. The 4 (Group) × 3 (Force) mixed design ANOVA for the RT data found both a statistically nonsignificant two-way interaction between Group and Force, $F(6,272) < 1$, and main effect for Force, $F(2,272) = 2.38$, $p = 0.094$. A statistically

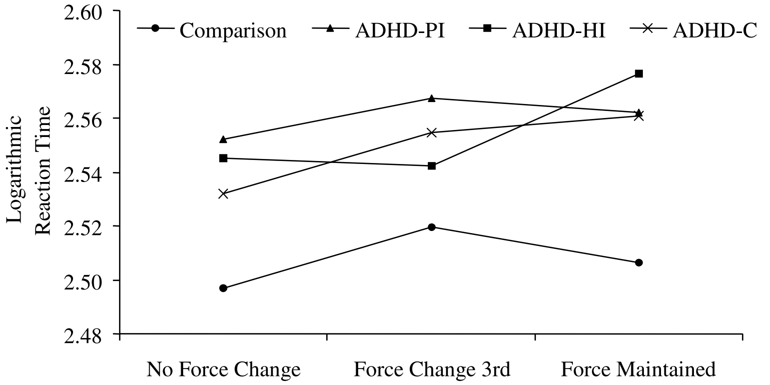

Fig. 2. Logarithmic RT means for each group plotted as a function of force condition.

significant main effect was found for Group, $F(3,136) = 2.89$, $p = 0.038$. This was followed by planned contrasts across the marginal means for the Group factor. The ADHD-PI and ADHD-C groups were both found to have significantly slower RTs when contrasted with the comparison group ($p < 0.05$). The contrast between the comparison group and the ADHD-HI group was statistically nonsignificant ($p > 0.05$).

3.1.2. Peak force

Fig. 3 displays the mean logarithmic PF for each group in each condition per tap location. The univariate outcomes of the 4 (Group) × 3 (Force) × 5 (Tap) mixed design ANOVA for PF are shown in Table 3. Statistically significant main effects were found for Force, Tap, and as predicted, Group. Given that the main effect for Group did not depend on either Force or Tap, planned contrasts were used to compare the marginal means for each group. Both the ADHD-PI and ADHD-C

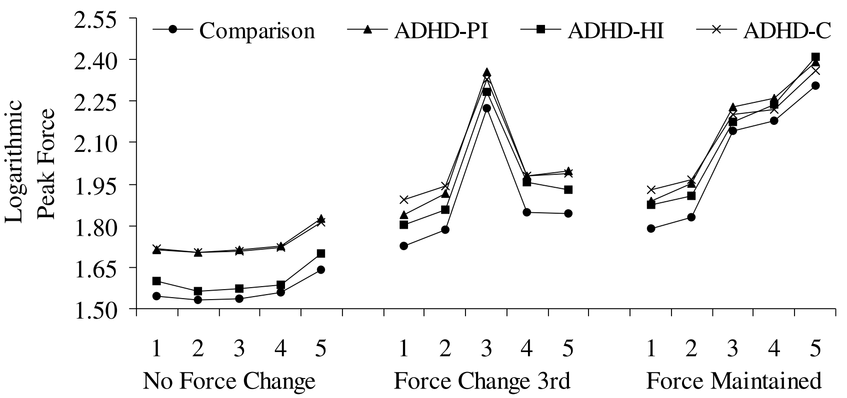

Fig. 3. Logarithmic PF means for each group plotted as a function of force condition and tap location.

Table 3
Statistical significance, effect size and power for univariate tests of logarithmic PF across groups

	F	df	P	Partial η^2	Power
Force × Tap × Group	0.61	10.98, 493.98	0.824	0.013	0.337
Force × Tap	250.73	3.66, 493.98	0.000	0.650	0.999
Force × Group	1.23	5.67, 255.16	0.291	0.027	0.467
Tap × Group	1.10	6.96, 313.20	0.361	0.024	0.473
Force	292.85	1.89, 255.16	0.000	0.684	0.999
Tap	336.92	2.32, 313.20	0.000	0.714	0.999
Group	4.66	3, 135	0.004	0.094	0.886

groups were found to have significantly higher PF than the comparison group, $p < 0.05$. That is, the ADHD-PI and ADHD-C groups exerted statistically significantly higher PF levels during the movement sequences than did the comparison group. The contrast between the comparison group and the ADHD-HI group was statistically nonsignificant, $p > 0.05$.

3.1.3. Inter-tap interval

Fig. 4 displays the mean logarithmic ITIs for each group in each condition per tap location. The three-way interaction between Force, Tap and Group was statistically significant (see Table 4). The two-way interactions for Force with Group and for Tap

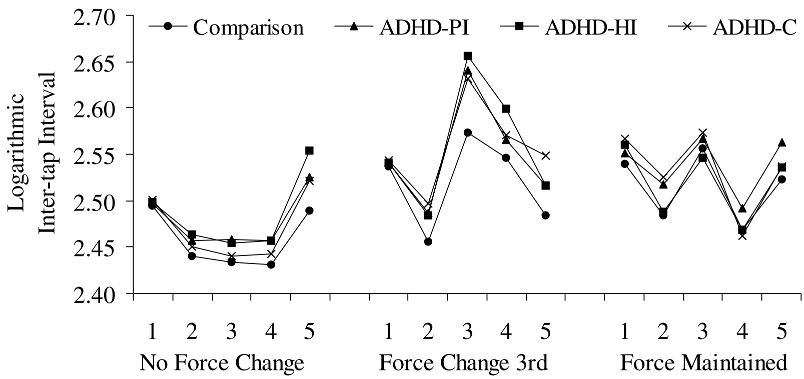

Fig. 4. Logarithmic ITI means for each group plotted as a function of force condition and tap location.

Table 4
Statistical significance, effect size and power for univariate tests of ITI across groups

	F	df	P	Partial η^2	Power
Force × Tap × Group	1.78	17.21, 757.41	0.025	0.039	0.958
Force × Tap	66.53	5.74, 757.41	0.000	0.335	0.999
Force × Group	1.78	6, 264	0.104	0.039	0.665
Tap × Group	0.72	8.91, 391.99	0.688	0.016	0.357
Force	112.93	2, 264	0.000	0.461	0.999
Tap	39.08	2.97, 391.99	0.000	0.228	0.999
Group	3.90	3, 132	0.010	0.081	0.818

with Group were statistically nonsignificant. However, the two-way interaction between Force and Tap was statistically significant. It was this two way interaction which depended on the group. These outcomes were not evaluated for their simple effects as they did not include the group factor.

Significant main effects were found for Force, Tap and Group. The main effect for Group was followed by planned contrasts on the marginal means. Both the ADHD-PI and ADHD-C groups were found to have significantly longer mean logarithmic ITIs than the comparison group, $p < 0.05$. That is, both the ADHD-PI group and the ADHD-C group took a significantly longer amount of time between successive taps. The contrast between the comparison group and the ADHD-HI group was statistically nonsignificant, $p > 0.05$.

3.1.4. Coefficient of variation (C of V)

For RT, only the two-way interaction between Force and Group was statistically significant, $F(6, 272) = 2.76$, $p = 0.013$, with a moderate effect. Analysis of the simple effects were evaluated at the Bonferroni modified alpha level of 0.0125, and revealed no significant simple effects for Group across each level of Force.

For PF, moderate effect sizes were found for both the Force × Group, $F(5.72, 248) = 2.98$, $p = 0.009$, and the Force × Tap, $F(7, 909) = 7.88$, $p = 0.000$, interactions. Statistically significant main effects were found for Force, $F(1.91, 248) = 22.57$, $p = 0.000$, Tap, $F(3.46, 450) = 4.69$, $p = 0.002$, and Group, $F(3, 130) = 8.39$, $p = 0.000$. The simple effect for Group within the two-way interaction between Force and Group revealed statistically significant effects for both the NFC condition and the FCM condition. In the NFC condition, both the ADHD-PI and ADHD-C groups had statistically significantly greater PF variability than the comparison group, $p < 0.05$. The ADHD-HI group and the comparison group contrast was statistically nonsignificant, $p > 0.05$. The planned contrast for the FCM condition also indicated that both the ADHD-PI and ADHD-C groups had significantly greater PF variability than the comparison group, $p < 0.05$. The ADHD-HI contrast was again statistically nonsignificant, $p > 0.05$.

For ITI, only the Force × Tap interaction was statistically significant, $F(6.61, 886) = 8.49$, $p = 0.000$. However, main effects were found for Force, $F(2, 268) = 13.10$, $p = 0.000$, Tap, $F(3.06, 410) = 65.92$, $p = 0.000$, and Group, $F(3, 134) = 8.49$, $p = 0.000$. Planned contrasts to investigate the marginal means for the Group main effect revealed that both the ADHD-PI and ADHD-C groups had significantly greater ITI variability than did the comparison group, $p < 0.05$. The ADHD-HI and comparison group contrast was statistically nonsignificant, $p > 0.05$.

3.2. Discussion

As found in previous studies (e.g., Lorys et al., 1990; Oosterlaan & Sergeant, 1996; Ullman et al., 1978; Zahn et al., 1991), RT significantly differentiated the groups. However, against prediction, only the ADHD-PI and ADHD-C groups, that is, those boys with inattentive symptomatology, had significantly longer RTs than the comparison group. The ADHD-HI group did not differ from the comparison group. Whilst the results are consistent with previous research that has shown no difference in RT for children with ADD/H and ADD/WO (e.g., Hynd et al., 1989; Lorys et al., 1990), the prediction for the ADHD-HI group seems to have been less well formulated. On face value it suggests that the current study's experimental design has targeted performance characteristics within the ADHD groups that are more sensitive to inattention than to hyperactivity–impulsivity. An immediate response may be to assume that the response latency was specifically due to inattentive (i.e., off task) behaviour. However, this explanation is not supported given that the random sample of participants who were videotaped during their test administration demonstrated no significant differences in the levels of on-task behaviour.

Complex RT (CRT) tasks, where there is an increased task complexity, have shown that the children with ADHD-C perform more poorly than control children (e.g., Leung & Connolly, 1998). Longer simple RTs (SRT) for children with hyperactivity disorder (i.e., ADHD-C) have also been reported (e.g., Ullman et al., 1978) although inconsistencies have been noted (see Rosenthal & Allen, 1978). The finger tapping task within the current study targeted both SRT (i.e., no force condition) and CRTs (i.e., the force accentuation conditions). However, the complexity of the task within the current study did not lead to increased response latency, and despite the main effect for Group, these results suggest that complexity, as operationalised within the current study, did not influence the RT outcome. This finding is consistent with participants in all groups being able to distribute the planning of the tapping sequence. Piek et al. (1993) found that in a normal population, certain features of the task are planned later in the sequence. If this ability was impaired in ADHD children, one would expect their initial RT to be longer.

Increased RT or response speed variability has previously been observed in studies of inhibitory deficits (e.g., Oosterlaan & Sergeant, 1996), children with ADHD and their responses to complex stimuli (e.g., Oosterlaan, Logan, & Sergeant, 1998), increased task complexity (e.g., Leung & Connolly, 1994) and warned simple, choice and cross-modal RT tasks (Zahn et al., 1991). However, nonsignificant findings have also been reported (Leung & Connolly, 1997; van der Meere et al., 1992). Within the current study, against prediction, the ADHD groups did not demonstrate greater RT variability. Whilst the overall effect for RT variability for the experimental groups and for the three force conditions within the current study was nonsignificant, the ADHD-HI group had significantly greater RT variability in the condition where force was stressed at the 3rd, 4th and 5th taps. Increased variability reflects the difficulty of the system when adopting the strategy of distributed planning, that is, planning the movement on-line once the movement has begun (Semjen et al., 1984). It appears to be the preparation for distributed planning which is impaired in this group.

It was expected that boys in the ADHD groups would show significantly different PF output for each tapping force condition and demonstrate significantly greater PF variability than boys in the comparison group (e.g., Pereira et al., 2000). As predicted, PF output was found to significantly differentiate the groups. However, against prediction, the outcome of the planned contrasts revealed that only the ADHD-PI and ADHD-C (i.e., those boys with inattentive symptomatology) had differed from the comparison group. The ADHD-HI group did not differ to the comparison group. The result indicates that the ADHD-PI and ADHD-C groups, on average, hit the key with greater force than the comparison group. The effect the ADHD-PI and ADHD-C groups was not specific to the particular movement condition or place of the key strike within the movement sequence as there were no interactions with either force condition or tap location. Overall, as would be predicted due to the experimental design, the average PF output varied in the interaction between the three force conditions and the tap location. This demonstrated that the participants completed the task according to task specifications.

Previous studies have found that children with ADHD have significantly longer movement times and demonstrate significantly greater movement time variability than comparison groups (e.g., Sergeant & Scholten, 1985a; Sheppard et al., 2000; van der Meere et al., 1992). This was also found in the current study, as significant group differences were found for the ITI, with a moderate effect. As with our findings for RT and PF, only the ADHD-PI and ADHD-C groups were found to have slower ITIs compared with the comparison group. This result is interesting in the context of RT variability suggesting that the groups that did not experience difficulty in planning had impaired ITI during the upcoming sequence. The ADHD-HI group was not found to significantly differ to the comparison group in terms of their time taken between successive taps or in the amount of variability of their ITI. The group that had difficulty in initiating the response, however, was then able to execute the sequence effectively. This outcome supports the previous findings that have found a link between slower tapping speed and inattentive symptomatology in community samples (McGee et al., 1985, 1987).

The above outcomes were obtained irrespective of the particular force condition being completed. As would be predicted, there was a significant interaction between the force condition and tap location (e.g., Piek & Glencross, 1993; Piek et al., 1993). Furthermore, the interactive effects of force condition and tap location did not depend on group. This result was in contrast with the prediction that group differences would be observed in the simple versus the complex sequences. The hypothesis was based on the suggestion that simpler tests of fine motor skills (i.e., simple tapping speed) do not seem to be as affected as the more complex motor sequences (Breen, 1989; Grodzinsky & Diamond, 1992; Mariani & Barkley, 1997; Sheppard et al., 2000). However, the ADHD-PI and ADHD-C groups demonstrated a more generalised slower movement. This may reflect the nature of the task where some form of distributed planning is required. The general slowing may indicate problems specifically with implementing the distributed planning.

Previous findings for general tapping speed with children with ADHD appear to be inconsistent. Rosenthal and Allen (1978) and others have classed the performance of children with hyperactivity as "slower, less consistent, and less persistent across trials" than normal participants (p. 702). Some authors report slower response rates and an inability to speed up when instructed to or when provided with an incentive (e.g., Stevens et al., 1970) and others report no significantly different performance to that of the controls (e.g., Gordon & Kantor, 1979; Seidman et al., 1995). Boys with ADHD (i.e., ADHD-C) have often been characterised as slower movers (e.g., Carte, Nigg, & Hinshaw, 1996; Sergeant & Scholten, 1985a,b). The role of inattention in the movement difficulties of children with ADHD-C has been disputed in preference to an activation deficit hypothesis where consistent motor slowness is evident (Kalverboer, 1993). However, the results of the current study have indicated that the role of inattention may be more relevant to the outcome for these groups given that both the ADHD-PI and ADHD-C share this behavioural characteristic. The ADHD-HI group, whom one would assume would share the same behavioural characteristic of activation dysfunction within the energetical systems approach, did not demonstrate slower performance.

A relevant omission from the discussion above and also from the literature discussing motor control within children with ADHD is any reference to the underlying level of motor dysfunction of participants. Given the high level of reported motor dysfunction within children with ADHD (e.g., Piek et al., 1999), it is likely that the outcomes from research in a range of domains may be influenced by poor motor abilities (e.g., any task requiring a physical response to stimuli). This suggestion raises some doubts as to the generalisability and interpretation of results for children with ADHD for studies that have not controlled for the underlying presence of motor dysfunction. The following section examines motor control issues for children with ADHD with or without comorbid DCD.

4. ADHD comparisons with or without comorbid DCD

For these comparisons, the same variables were recorded but the criteria for group allocation was different. In this analysis, participants were allocated into one of three groups according to the presence or absence of ADHD and/or DCD.

4.1. Results

The groups significantly differed in terms of their VIQ, $F(2,132) = 4.96$, $p < 0.025$. Specifically, the ADHD/DCD group was found to have significantly lower VIQ than the comparison group, $p < 0.05$. No other group differences were observed. VIQ was assessed for its suitability as a covariate. It was found to have weak and statistically nonsignificant correlations with the dependent variables and was therefore not included.

Data from one boy within the ADHD-U group and two boys within the ADHD/DCD groups were lost due to incomplete data sets. Logarithmic transformations were performed on all dependent variables in order to reduce the variability and general positive skew of the data.

4.1.1. Reaction time

Fig. 5 shows the group mean logarithmic RTs plotted as a function of force condition. The ANOVA for RT found that the two-way interaction between Group and Force, $F(4,258) < 1$, and the main effect for Force, $F(2,258) = 2.74$, $p = 0.066$, were statistically nonsignificant. A significant main effect was found for Group,

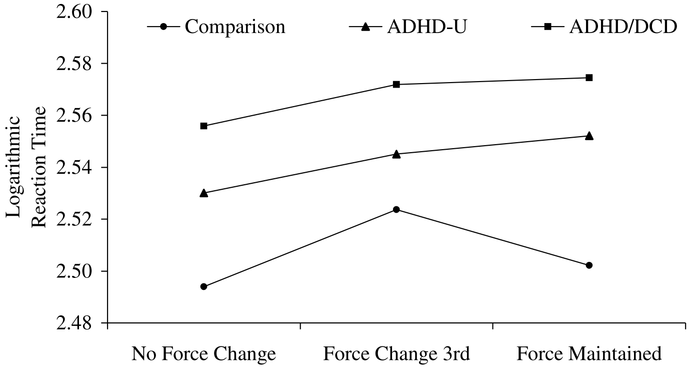

Fig. 5. Logarithmic RT means for each group plotted as a function of force condition.

$F(2, 129) = 4.65$, $p = 0.011$, which was followed up by planned contrasts across the marginal means at a modified Bonferroni corrected alpha level of 0.03. The contrast between the ADHD-U group and comparison group was statistically nonsignificant indicating that the groups did not differ in terms of their RTs. The contrast between the ADHD/DCD group and the comparison group, however, was statistically significant. The ADHD/DCD group had significantly longer RTs across the three conditions than the comparison group. An additional contrast between the ADHD/DCD group and the ADHD-U group was not significant.

4.1.2. Peak force

Two univariate outliers were removed from the data set. Violation of the homogeneity of covariance matrices (i.e., Box's M) necessitated a Greenhouse-Geisser adjustment. Fig. 6 displays the mean logarithmic PF for each group in each condition per tap location.

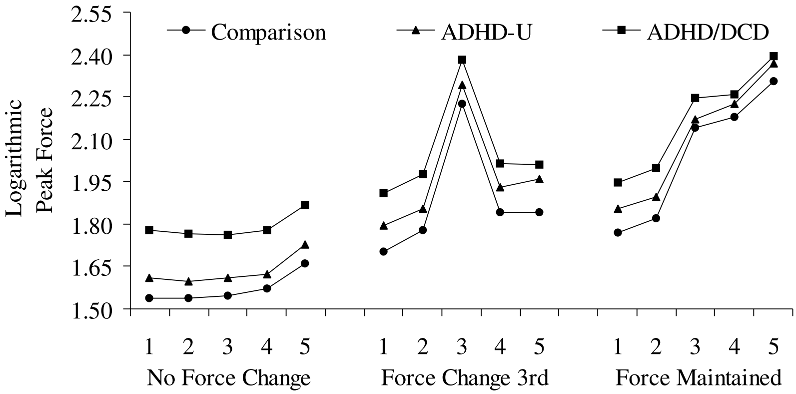

Fig. 6. Logarithmic PF means for each group plotted as a function of force condition and tap location.

The univariate outcomes of the 3 (Group) × 3 (Force) × 5 (Tap) mixed design ANOVA for PF are shown in Table 5. The two-way interaction between Force and Tap was found to be statistically significant. This interaction demonstrated a large effect size and indicated that the changes in force across the five tap locations depended on the force condition. This result is consistent with the participants' performing the task as instructed.

Significant main effects were found for Force, Tap, and Group. Given that the main effect for Group did not depend on either Force or Tap, group performance was examined using planned contrasts across the marginal means for the group factor at a modified Bonferroni corrected alpha level of 0.03. The ADHD-U group contrast with the comparison group did not reach statistical significance, $p > 0.03$. However, statistically significant outcomes were obtained for the contrasts between the ADHD/DCD group and the comparison group, in addition to the contrast between ADHD/DCD and the ADHD-U group, $p < 0.03$. This indicated that the ADHD/DCD group had significantly higher PF output than either the comparison group or the ADHD-U group.

4.1.3. Inter-tap interval

Two univariate outliers were removed from the data set. Violation of the homogeneity of covariance matrices (i.e., Box's M) necessitated an adjustment to the per comparison alpha level, which was set at 0.025. Fig. 7 displays the mean logarithmic ITIs for each group in each condition per tap location.

Again, the two-way interaction between Force and Tap was statistically significant with large effect size (see Table 6). Significant main effects were found for Force, Tap and Group. The main effect for Group was followed by planned contrasts across the marginal means for the group factor at the modified Bonferroni corrected alpha level of 0.03. Both the ADHD-U and the ADHD/DCD groups were found to have significantly longer mean logarithmic ITIs than the comparison group. That is, both of these groups took a significantly longer amount of time between successive taps than did the comparison group. No significant difference in terms of ITI was found between the ADHD/DCD and ADHD-U groups, $p > 0.03$.

Table 5
Statistical significance, effect size and power for univariate tests of logarithmic PF across groups

	F	df	P	Partial η^2	Power
Force × Tap × Group	0.453	7.41, 470.60	0.877	0.007	0.205
Force × Tap	269.56	3.71, 470.60	0.000	0.680	0.999
Force × Group	1.57	3.77, 239.08	0.186	0.024	0.466
Tap × Group	2.12	4.64, 294.44	0.068	0.032	0.673
Force	310.15	1.88, 239.08	0.000	0.709	0.999
Tap	398.36	2.32, 294.44	0.000	0.758	0.999
Group	10.27	2, 127	0.000	0.139	0.985

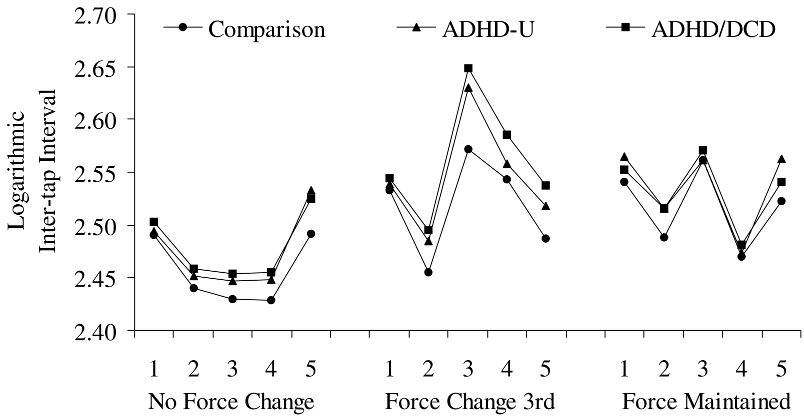

Fig. 7. Logarithmic ITI means for each group plotted as a function of force condition and tap location.

Table 6
Statistical significance, effect size and power for univariate tests of ITI across groups

	F	df	P	Partial η^2	Power
Force × Tap × Group	1.17	11.23, 712.99	0.306	0.018	0.656
Force × Tap	62.66	5.61, 712.99	0.000	0.330	0.999
Force × Group	1.69	4, 254	0.153	0.026	0.514
Tap × Group	0.71	5.94, 377.35	0.643	0.011	0.280
Force	126.48	2, 254	0.000	0.499	0.999
Tap	41.27	2.97, 377.35	0.000	0.245	0.999
Group	4.86	2, 127	0.009	0.071	0.793

4.1.4. Coefficient of variation (C of V)

No significant main effects or interactions were found for the 3 × 3 ANOVA examining C of V for RT. All effect sizes were trivial to small.

For PF, three univariate outliers were removed from the data set. Moderate effect sizes were found for the statistically significant outcomes for both the two-way interactions of Force × Group, $F(3.86, 243) = 3.21$, $p = 0.015$, and Force × Tap, $F(6.94, 874) = 7.86$, $p = 0.000$. Significant main effects were found for Force, $F(1.93, 243) = 23.75$, $p = 0.000$, Tap, $F(3.47, 437) = 5.54$, $p = 0.000$, and Group, $F(2, 126) = 10.72$, $p = 0.000$. The two-way interaction between Force and Group was further investigated and analysed for its simple effects for Group, collapsed across tap location, at a modified alpha level of 0.017. A significant effect was found for the NFC condition, with a large effect size. Planned contrasts indicated that the comparison group had significantly less PF variability than either the ADHD/DCD group or the ADHD-U group. The contrast between the ADHD/DCD group and the ADHD-U group was nonsignificant. A significant simple effect for Group was also found for the FCM condition. The planned contrasts for FCM indicated that, as for NFC, the comparison group had significantly less PF variability than either the ADHD/DCD group or the ADHD-U group. The contrast between the

ADHD/DCD group and the ADHD-U group was nonsignificant. The simple effect for FC3 was statistically nonsignificant.

The data set for the C of V for ITI revealed two univariate outliers that were removed. Violation of the homogeneity of covariance matrices (i.e., Box's M) necessitated an adjustment of the per comparison alpha level to 0.025. The two-way interaction between Force and Tap was statistically significant, $F(6.5, 825) = 8.35$, $p = 0.000$, with a moderate effect size. Significant main effects were found for Force, $F(2, 254) = 11.43$, $p = 0.000$, Tap, $F(3.08, 391) = 68.59$, $p = 0.000$, and Group, $F(2, 127) = 8.19$, $p = 0.000$. The strength of the relationship as indexed by partial η^2 for Tap was strong. The effect sizes for both Force and Group were within the moderate to strong range. The outcome of planned comparisons revealed that both the ADHD-U and ADHD/DCD groups had significantly greater ITI variability than did the comparison group, $p < 0.03$. The ADHD/DCD and ADHD-U contrast was nonsignificant, $p > 0.03$.

4.2. Discussion

The above analyses investigated the specific timing and force control issues for children with comorbid ADHD and DCD difficulties as compared with those participants with intact motor function. In summary, boys with the dual diagnosis of ADHD and DCD were found to have longer RTs and ITIs, greater PF output and higher levels of ITI and PF variability than the comparison group. The boys with a single diagnosis of ADHD differed from the comparison group in only their ITIs and the variability of their PF and ITI scores. Interestingly, the ADHD/DCD group had significantly higher levels of PF output than the ADHD-U group. This outcome suggests that the results for the boys with a dual diagnosis may be more associated with motor dysfunction than with their ADHD status. However, greater PF output for children with DCD on this particular tapping task has not been supported (Piek & Skinner, 1999) suggesting that this outcome may be more reflective of the interaction of force with underlying timing dysfunction (i.e., late firing of the antagonist burst or multiple agonist firings). Similarity in outcome between the ADHD/DCD and ADHD-U groups for the other measures suggests that speed of movement and variability may be more associated with ADHD symptomatology. Further research of the comorbid condition of ADHD/DCD is warranted and, to account for the unique influence of inattentive symptomatology, it is recommended that this occur with subtype specific ADHD participant samples.

These results establish that boys with a dual diagnosis of ADHD and DCD experience a more dysfunctional profile in terms of their RT and PF, but not movement time as measured by ITI. The result identifying an overall greater force output than either the ADHD-U or comparison groups and higher levels of PF output variability are in line with the research of Pereira et al. (2000). Using a grip-force technique, they found that boys with ADHD and motor performance difficulties (i.e., ADHD-C/DCD) had greater variability in force output and impaired sensory motor control than control children (Pereira et al., 2000). The boys with ADHD and no motor difficulties in their study displayed inconsistent force output more similar to the combined group than the control group (Pereira et al., 2000). In the current study, the ADHD boys with no motor difficulties also displayed greater PF variability but no greater PF output than the comparison group, and significantly less PF output than the ADHD/DCD group. These results would suggest that the aspect of variability is common to the shared ADHD status of the boys whereas the greater force output, may be more associated with the motor dysfunction experienced by the ADHD/DCD boys.

Evaluation of these results against previous research is difficult given that research into the relationship between force and timing with children with ADHD and in particular, their comorbid relationship with DCD, has received surprisingly little attention. There is some evidence to support the result for the response latencies for the ADHD/DCD group from studies within the DAMP diagnostic system that have found prolonged complex RTs to visual stimuli (Hellgren, Gillberg, Gillberg, & Enerskog, 1993). Hellgren et al. (1993) also provided some support for the failure to find a significant difference in overall movement sequence completion times. In a simple finger tapping speed test, their DAMP group did not vary from the comparison group. However, direct comparison is again limited by the diagnostic inconsistencies.

5. General discussion

This paper investigated timing and force dysfunction within boys with ADHD from two perspectives. The first perspective, ADHD subtype analysis, may be viewed as the typical approach to the investigation of cognitive and timing abilities for children with inattentive or hyperactive/impulsive symptoms. The outcome from the current study indicated that the ADHD-PI and ADHD-C subtypes experience significant underlying timing and force dysfunction as compared to the comparison boys. On face value, this outcome suggested a potent role for the subtypes' shared symptomatology, namely, inattention. However, is this the entire story? The second perspective, dual diagnosis analysis, sought to integrate the plethora of past research emphasising the link between motor incoordination and ADHD into an examination of the relevance of the first perspective outcomes. In general, summarising the outcomes of the two perspectives provides the following conclusions:

1. Boys with a single diagnosis of ADHD and those with a dual diagnosis of ADHD and DCD took significantly longer between successive taps than the comparison group, and had higher level of ITI and PF variability. Thus, speed of movement and variability may be more associated with ADHD symptomatology.
2. Boys with a dual diagnosis of ADHD and DCD had significantly higher levels of PF output and slower RTs. Thus, force output and initial reaction may be more associated with motor dysfunction, or the interaction between ADHD and DCD.

Boys with the comorbid condition demonstrate a profile of distinct timing and force dysfunction when compared with the performance of the comparison group.

These outcomes reinforce concerns about the validity of results from nonmotor related studies of children with ADHD that fail to specify and control for differences in underlying motor ability of the groups. The results of previous studies that have identified motor response organisation difficulties (e.g., Carte et al., 1996) or motor output difficulties (e.g., van der Meere, van Baal, & Sergeant, 1989) may require replication in ADHD groups both with and without motor dysfunction. The study by van der Meere, Wekking, and Sergeant (1991) investigating sustained attention and pervasive hyperactivity is an example of a study that has taken motor ability into account. It may be that some of the inconsistencies within the literature are reflective of the influence of motor dysfunction. Further research will determine the utility of such distinctions and whether distinct underlying processes are disrupted for each of the comorbid conditions.

In total, these findings may potentially offer some explanation of the observed inconsistencies in cognitive research with children with ADHD. At minimum, past research must be interpreted within the context of the possibility that motor dysfunction, such as DCD, was also present in the experimental sample. This is especially pertinent to outcome studies that have examined performance in tasks where information processing or motor activity is a component of task completion. Future research must adequately account for the potential experimental confound of underlying motor disability in children with ADHD.

Acknowledgements

This research was principally supported by a scholarship from The Women's Service Guild (WSG) of WA Trust and a private research grant provided by Mr Ian and Mrs Jean Hutcheson to the first author. We wish to thank the participants, their parents and the participating schools for their support of this research. Also thanks to Motohide Miyahara, Peter Wilson and Natalie Gasson for their valuable comments on this paper.

References

American Psychiatric Association (1994). *Diagnostic and statistical manual of mental disorders* (4th ed). Washington, DC: Author.

Barkley, R. A., DuPaul, G. J., & McMurray, M. B. (1990). Comprehensive evaluation of attention deficit disorder with and without hyperactivity as defined by research criteria. *Journal of Consulting and Clinical Psychology, 58*, 775–789.

Breen, M. J. (1989). Cognitive and behavioral differences in ADHD boys and girls. *Journal of Child Psychology and Psychiatry, 30*, 711–716.

Carte, E. T., Nigg, J. T., & Hinshaw, S. P. (1996). Neuropsychological functioning, motor speed, and language processing in boys with and without ADHD. *Journal of Abnormal Child Psychology, 24*, 481–499.

Coleman, R., Piek, J. P., & Livesey, D. (2001). A longitudinal study of motor ability and kinaesthetic acuity in young children at risk of developmental coordination disorder. *Human Movement Science, 20*, 95–110.

Conners, C. K. (1997). *Conners' rating scales – revised: Technical manual*. North Tonawanda, NY: Multi-Health Systems.

Diekoff, G. (1992). *Statistics for the social and behavioural sciences: Univariate, bivariate and multivariate*. Dubuque, IA: Wm. C. Brown.

Douglas, V. I. (1972). Stop, look and listen: The problem of sustained attention and impulse control in hyperactive and normal children. *Canadian Journal of Behavioral Science, 4*, 259–282.

Garcia-Colera, A., & Semjen, A. (1988). Distributed planning of movement sequences. *Journal of Motor Behavior, 20*, 341–367.

Gordon, N. G., & Kantor, D. R. (1979). Effects of clinical dosage of methylphenidate on two-flash thresholds and perceptual motor performance in hyperactive children. *Perceptual and Motor Skills, 48*, 721–722.

Grodzinsky, G., & Diamond, R. (1992). Frontal lobe functioning in boys with attention deficit hyperactivity disorder. *Developmental Neuropsychology, 8*, 427–445.

Hartsough, C. S., & Lambert, N. M. (1985). Medical factors in hyperactive and normal children: Prenatal, development, and health history findings. *American Journal of Orthopsychiatry, 55*, 190–210.

Hellgren, L., Gillberg, C., Gillberg, I. C., & Enerskog, I. (1993). Children with deficits in attention, motor control and perception (DAMP) almost grown up: General health at age 16. *Developmental Medicine and Child Neurology, 35*, 881–892.

Henderson, S. E., & Sugden, D. A. (1992). *Movement assessment battery for children*. New York: Psychological Corporation/Harcourt Brace-Jovanovich.

Houghton, S., Wheldall, K., Jukes, R., & Sharpe, A. (1990). The effects of limited private reprimands and increased private praise on classroom behaviour in four British secondary school classes. *British Journal of Educational Psychology, 60*, 255–265.

Hynd, G. W., Nieves, N., Conner, R., Stone, P., Town, P., Becker, M. G., Lahey, B. B., & Lorys, A. R. (1989). Attention deficit disorder with and without hyperactivity: Reaction time and speed of cognitive processing. *Journal of Learning Disabilities, 22*, 573–579.

Jennings, J. R., van der Molen, M. W., Pelham, W., Debski, K. B., & Hoza, B. (1997). Inhibition in boys with attention deficit hyperactivity disorder as indexed by heart rate change. *Developmental Psychology, 33*, 308–318.

Kalverboer, A. F. (1993). Neurobehavioural relationships in children: New facts, new fictions. *Early Human Development, 34*, 169–177.

Keele, S. W. (1973). Mechanisms of attention. In E. C. Carterette, & M. P. Friedman (Eds.), *Handbook of Perception* (Vol. 9, pp. 1–68). New York: Academic Press.

Keele, S. W., Ivry, R., & Pokorny, R. (1987). Force control and its relation to timing. *Journal of Motor Behavior, 19*, 96–114.

Klapp, S. T., & Wyatt, E. P. (1976). Motor programming within a sequence of responses. *Journal of Motor Behavior, 8*, 19–26.

Lahey, B. B., Applegate, B., McBurnett, K., Biederman, J., Greenhill, L., Hynd, G. W., Barkley, R. A., Newcorn, J., Jensen, P., Richters, J., Garfinkel, B., Kerdyk, L., Frick, P. J., Ollendick, T., Perez, D., Hart, E. L., Waldman, I., & Shaffer, D. (1994). DSM-IV field trials for attention deficit hyperactivity disorder in children and adolescents. *American Journal of Psychiatry, 151*, 1673–1685.

Lahey, B. B., Pelham, W. E., Stein, M. A., Loney, J., Trapani, C., Nugent, K., Kipp, H., Schmidt, E., Lee, S., Cale, M., Gold, E., Hartung, C. M., Willcutt, E., & Baumann, B. (1998). Validity of DSM-IV attention-deficit/hyperactivity disorder for younger children. *Journal of the American Academy of Child and Adolescent Psychiatry, 37*, 695–702.

Leung, P. W., & Connolly, K. (1997). Test of two views of impulsivity in hyperactive and conduct disordered children. *Developmental Medicine and Child Neurology, 39*, 574–582.

Leung, P. W. L., & Connolly, K. J. (1994). Attentional difficulties in hyperactive and conduct-disordered children: A processing deficit. *Journal of Child Psychology & Psychiatry, 7*, 1229–1245.

Leung, P. W. L., & Connolly, K. J. (1998). Do hyperactive children have motor organization and/or execution deficits. *Developmental Medicine and Child Neurology, 40*, 600–607.

Levy, F., & Hay, D. (1991). *The Australian twin disruptive behaviour rating scale*. Melbourne, Vic: La Trobe University: La Trobe Twin Study.

Levy, F., Hay, D., McLaughlin, M., Wood, C., & Waldman, I. (1996). Twin-sibling differences in parental reports of ADHD, speech, reading and behaviour problems. *Journal of Child Psychology and Psychiatry, 37*, 569–578.

Levy, F., Hay, D., McStephen, M., Wood, C., & Waldman, I. (1997). Attention-deficit hyperactivity disorder: A category or a continuum? Genetic analysis of a large-scale twin study. *Journal of the American Academy of Child and Adolescent Psychiatry, 36*, 1–8.

Levy, F., McStephen, M., & Hay, D. A. (2001). The diagnostic genetics of ADHD symptoms and subtypes. In F. Levy & D. A. Hay (Eds.), *Attention, genes and ADHD* (pp. 35–57). Sydney, NSW: Macmillan.

Lorys, A. R., Hynd, G. W., & Lahey, B. B. (1990). Do neurocognitive measures differentiate attention deficit disorder (ADD) with and without hyperactivity? *Archives of Clinical Neuropsychology, 5*, 119–135.

Mariani, M. A., & Barkley, R. A. (1997). Neuropsychological and academic functioning in preschool boys with attention deficit hyperactivity disorder. *Developmental Neuropsychology, 13*, 111–129.

McGee, R., Williams, S. M., & Silva, P. A. (1985). Factor structure and correlates of ratings of inattention, hyperactivity, and antisocial behavior in a large sample of 9-yr-old children from the general population. *Journal of Consulting and Clinical Psychology, 53*, 480–490.

McGee, R., Williams, S. M., & Silva, P. A. (1987). Comparison of girls and boys with teacher-identified problems of attention. *Journal of the American Academy of Child & Adolescent Psychiatry, 26*, 711–717.

Oosterlaan, J., Logan, G. D., & Sergeant, J. A. (1998). Response inhibition in AD/HD, CD, comorbid AD/HD + CD, anxious, and control children: A meta-analysis of studies with the Stop task. *Journal of Child Psychology and Psychiatry, 39*, 411–425.

Oosterlaan, J., & Sergeant, J. (1996). Inhibition in ADHD, aggressive, and anxious children: A biologically based model of child psychopathology. *Journal of Abnormal Child Psychology, 24*, 19–36.

Pelham, W. E., Gnagy, E. M., Greenslade, K. E., & Milich, R. (1992). Teacher ratings of DSM-III–R symptoms for the disruptive behavior disorders. *Journal of the American Academy of Child and Adolescent Psychiatry, 31*, 210–218.

Pereira, H. S., Eliasson, A.-C., & Forssberg, H. (2000). Detrimental neural control of precision grip lifts in children with ADHD. *Developmental Medicine and Child Neurology, 42*, 545–553.

Pharmaceutical Society of Australia. (2000). Pharmacokinetic data, Australian Pharmaceutical Formulary and Handbook (17th ed.). Parkville, Vic: Author.

Piek, J. P., & Glencross, D. J. (1993). *The planning of force changes during a sequential finger-tapping task* (Unpublished manuscript). Perth, Western Australia: Curtin University of Technology.

Piek, J. P., Glencross, D. J., Barrett, N. C., & Love, G. L. (1993). The effect of temporal and force changes on the patterning of sequential movements. *Psychological Research, 55*, 116–123.

Piek, J. P., Pitcher, T. M., & Hay, D. A. (1999). Motor coordination and kinaesthesis in boys with attention deficit hyperactivity disorder. *Developmental Medicine and Child Neurology, 41*, 159–165.

Piek, J. P., & Skinner, R. A. (1999). Timing and force control during a sequential tapping task in children with and without motor coordination problems. *Journal of the International Neuropsychological Society, 5*, 320–329.

Rosenthal, R. H., & Allen, T. W. (1978). An examination of attention, arousal, and learning dysfunction of hyperkinetic children. *Psychological Bulletin, 85*, 689–715.

Rubia, K., Oosterlaan, J., Sergeant, J. A., Brandeis, D., & van Leeuwen, T. (1998). Inhibitory dysfunction in hyperactive boys. *Behavioural Brain Research, 94*, 25–32.

Sattler, J. M. (1988). *Assessment of children* (3rd ed.). San Diego, CA: Author.

Schachar, R., Tannock, R., & Logan, G. D. (1993). Inhibitory control, impulsiveness, and attention deficit hyperactivity disorder. *Clinical Psychology Review, 13*, 721–739.

Scheres, A., Oosterlaan, J., & Sergeant, J. (2001). Response execution and inhibition in children with AD/HD and other disruptive disorder: The role of behavioural activation. *Journal of Child Psychology & Psychiatry, 42*, 347–357.

Seidman, L. J., Biederman, J., Faraone, S. V., Milberger, S., Norman, D., Seiverd, K., Benedict, K., Guite, J., Mick, E., & Kiely, K. (1995). Effects of family history and comorbidity on the neuropsychological performance of children with ADHD: Preliminary findings. *Journal of the American Academy of Child and Adolescent Psychiatry, 34*, 1015–1025.

Seidman, L. J., Faraone, S. V., Biederman, J., Weber, W., & Oulette, C. (1997). Toward defining a neuropsychology of attention deficit–hyperactivity disorder: Performance of children and adolescents from a large clinically referred sample. *Journal of Consulting and Clinical Psychology, 65*, 150–160.

Semjen, A., & Garcia-Colera, A. (1986). Planning and timing of finger-tapping sequences with a stressed element. *Journal of Motor Behavior, 18*, 287–322.

Semjen, A., Garcia-Colera, A., & Requin, J. (1984). On controlling force and time in rhythmic movement sequences: The effect of stress location. In J. G. L. Allen (Ed.), *Timing and time perception* (Vol. 423, pp. 168–182). New York: Annals of the New York Academy of Sciences.

Sergeant, J. A., & Scholten, C. A. (1985a). On data limitations in hyperactivity. *Journal of Child Psychology & Psychiatry, 26*, 111–124.

Sergeant, J. A., & Scholten, C. A. (1985b). On resource strategy limitations in hyperactivity: Cognitive impulsivity reconsidered. *Journal of Child Psychology & Psychiatry, 26*, 97–109.

Sergeant, J. A., & van der Meere, J. (1988). What happens when the hyperactive child commits an error? *Psychiatry Research, 24*, 157–164.

Sergeant, J. A., & van der Meere, J. (1990). Additive factor method applied to psychopathology with special reference to childhood hyperactivity. *Acta Psychologica, 74*, 277–296.

Sheppard, D. M., Bradshaw, J. L., Georgiou, N., Bradshaw, J. A., & Lee, P. (2000). Movement sequencing in children with Tourette's Syndrome and Attention Deficit Hyperactivity Disorder. *Movement Disorders, 15*, 1184–1193.

Smits-Engelsman, B. C. M., Henderson, S. E., & Michels, C. G. J. (1998). The assessment of children with Developmental Coordination Disorder in the Netherlands: The relationship between the Movement Assessment Battery for Children and the Körperkoodinations Test für Kinder. *Human Movement Science, 17*, 699–709.

Steger, J., Imhof, K., Coutts, E., Gundelfinger, R., Steinhausen, H.-C., & Brandeis, D. (2001). Attentional and neuromotor deficits in ADHD. *Developmental Medicine & Child Neurology, 43*, 172–179.

Stevens, D. A., Stover, C. E., & Backus, J. T. (1970). The hyperkinetic child: Effect of incentives on the speed of rapid tapping. *Journal of Consulting and Clinical Psychology, 34*, 56–59.

Stott, D. H., Moyes, F. A., & Henderson, S. E. (1984). *The test of motor impairment*. San Antonio, TX: The Psychological Corporation.

Tiffin, J. (1968). *Purdue pegboard: Examiner manual*. Chicago: Science Research Associates.

Ullman, D. G., Barkley, R. A., & Brown, H. W. (1978). The behavioral symptoms of hyperkinetic children who successfully responded to stimulant drug treatment. *American Journal of Orthopsychiatry, 48*, 425–437.

van der Meere, J. (1996). The role of attention. In S. Sandberg (Ed.), *Monographs in child and adolescent psychiatry: Hyperactivity disorders of childhood* (pp. 111–148). Cambridge, UK: Cambridge University Press.

van der Meere, J., & Sergeant, J. (1988). Acquisition of attention skill in pervasively hyperactive children. *Journal of Child Psychology and Psychiatry, 29*, 301–310.

van der Meere, J., van Baal, M., & Sergeant, J. (1989). The additive factor method: A differential diagnostic tool in hyperactivity and learning disability. *Journal of Abnormal Child Psychology, 17*, 409–422.

van der Meere, J., Vreeling, H. J., & Sergeant, J. (1992). A motor presetting study in hyperactive, learning disabled and control children. *Journal of Child Psychology and Psychiatry, 33*, 1347–1354.

van der Meere, J., Wekking, E., & Sergeant, J. (1991). Sustained attention and pervasive hyperactivity. *Journal of Child Psychology and Psychiatry, 32*, 275–284.

Wechsler, D. (1992). *Manual for the Wechsler intelligence scale for children* (3rd ed.). New York: The Psychological Corporation.

Wilson, P. H., & McKenzie, B. E. (1998). Information processing deficits associated with developmental coordination disorder: A meta-analysis of research findings. *Journal of Child Psychology and Psychiatry, 39*, 829–840.

Wing, A. M., Keele, S., & Margolin, D. (1984). Motor disorder and the timing of repetitive movements. In: J. Gibbon, & L. Allan (Eds.), *Timing and time perception* (Vol. 423, pp. 183–192). New York: Annals of the New York Academy of Science.

Zahn, T. P., Kruesi, M. J. P., & Rapoport, J. L. (1991). Reaction time indices of attention deficit in boys with disruptive behavior disorders. *Journal of Abnormal Child Psychology, 19*, 233–252.