The Dynamics of Bimanual Coordination in Attention Deficit Hyperactivity Disorder

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I declare that this thesis contains no material which has been accepted for a degree or diploma by the University or any other institution, except by way of background information and duty acknowledged in the thesis, and to the best of my knowledge and belief no material previously published or written by another person except where due acknowledgement is made in the text of the thesis.

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Bruno A. Cayoun

20 June 2008

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Abstract

The present research examined how the inhibitory dysfunction observed in Attention Deficit Hyperactivity Disorder (ADHD) affects bimanual coordination in three experiments with unmedicated boys (aged 8 to 15) with ADHD-C (with and without Developmental Coordination Disorder (DCD)) and matched controls. Experiment 1 (N = 31, Mean age = 11 years : 9 months) explored the dynamics of bimanual circling using both free-hand movements using circle templates and constrained movements using cranks. Impairment in temporal stability was mostly attributable to difficulties in controlling the spatial component of the task, which was more pronounced in children with comorbid DCD. Experiment 2 (N = 32, Mean age = 12 years : 1 month) used a Stop-re-engagement paradigm (Change task) with a continuous (hand-circling) task to investigate whether inhibitory deficits at the central level of processing and/or allocation of effort in ADHD affect movement coordination. The ADHD and ADHD/DCD groups showed a lack of inhibitory control, as measured by Switch reaction time. However, these children also displayed slower and more variable speed of execution and the apparent inhibitory deficit was more associated with the re-engagement component of the task. Experiment 3 (N = 32, Mean age = 12 years : 1 month) used the Change Task, as traditionally delivered by computer, to investigate the source of the poor response re-engagement. Results showed a slow mode of information processing in ADHD groups rather than a deficit in the processes necessary to inhibit a prepotent

response. Processing speed was most impaired in children with ADHD/DCD, indicating that difficulties in cognitive flexibility and motor coordination were the main deficits. The overall results are a better fit for the hypothesis that ADHD involves a deficit in the regulation of energetic states. It was concluded that children with ADHD without DCD do not suffer from bimanual coordination impairment and that it is a necessity for future bimanual coordination studies to control for the presence of comorbid DCD in ADHD samples.

Chapter 1

Introduction

1.1. Description of ADHD

1.1.1. Prevalence

Attention deficit hyperactivity disorder (ADHD) is a severe ~~"d~~evelopmental disorder of self-control" (Barkley, 1995, p. 17). Children with ADHD, especially those who do not respond well to treatment, are unpopular at school and have difficulties establishing and maintaining friendships. The parents, teachers and peers of children with this condition usually report feeling stressed and frustrated because of the child's uninhibited or disruptive behaviour (Carlson, Lahey, & Neeper, 1984; Erhardt, & Hinshaw, 1994).

ADHD is the current label for one of the most controversial, prevalent and intensively studied syndromes in child psychology and psychiatry, conservatively estimated to occur in 3% to 6% of children from diverse cultures (Tannock, 1998). Australian studies have shown prevalence rates ranging between 2.3% and 6% depending on the methodology used (Glow, 1980). It has been estimated that about 50% of all referrals to behavioural paediatricians, paediatric neurologists, and neuropsychologists are related to ADHD (Shaywitz, Fletcher, & Shaywitz, 1997). Follow-up studies suggest that from 30% to 60% of these children continue to show

impairments associated with ADHD symptoms into adulthood (Weiss & Hechtman, 1993). Global spending for treatment from 1993 to 2003 rose ninefold, adjusting for inflation, reaching $2.4 billion in 2003 in the United States alone (Scheffler, Hinshaw, Modrek, & Levine, 2007).

1.1.2. Aetiology

Despite the importance of its prevalence, the aetiology of ADHD is essentially unknown as there is evidence that numerous factors are involved (including genetic, neurophysiological, cognitive, familial and environmental), and a combination of these factors is likely to contribute to the symptoms (Baron, 2007; National Health and Medical Research Council [NHMRC], 1997). Moreover, studies examining the appropriateness of diagnosis suggest that primary clinicians do not appropriately diagnose (but do not over-diagnose) children with ADHD, and there is uncertainty regarding which therapy is effective in a primary care context (Wolraich, 1999).

1.1.3. Typology

The *Diagnostic and Statistical Manual of Mental Disorders – 4th Edition* (DSM-IV, American Psychiatric Association, 1994) classifies ADHD into two symptom domains: poor sustained attention and poor impulse control associated with excessive motor restlessness. The syndrome is divided into

three subtypes: Predominantly inattentive (ADHD-PI), predominantly hyperactive-impulsive (ADHD-HI), and combined type (ADHD-C), where sufficient symptoms from the two other domains are present. Only ADHD-C meets the *International Classification of Disorders-10th Edition* (ICD-10, WHO, 1992) criteria for the Hyperkinetic syndrome.

It has been proposed that ADHD-HI is rarer and is believed to be a precursor of ADHD-C — ADHD-HI occurs generally in preschool children whereas ADHD-C tends to occur more in school-aged children (Barkley, 1997). According to the DSM-IV, the ADHD-PI type is mainly concerned with deficits in selective and sustained attention, speed of information processing and memory retrieval, it often displays some anxiety and learning difficulties, and may display mood disorders. Because ADHD-PI differs from other subtypes in the symptoms, outcomes, associated conditions, family histories, and response to treatments, several authors argue that ADHD-PI constitutes a different disorder than the other subtypes (e.g., Barkley, 1997; Johansen, Aase, Meyer, & Sagvolden, 2002; Piek, Pitcher, & Hay, 1999). The ADHD-HI type involves persistent and maladaptive symptoms of hyperactivity and impulsivity, but does not meet the criteria for ADHD-PI. According to the DSM-IV, symptoms for each subtype must have been noticed prior the age of seven, reach a degree that is maladaptive, be inconsistent with developmental level, and must have lasted for at least six months.

Nonetheless, the DSM-IV and ICD-10 classifications are not universally accepted. As will be discussed later, there are increasing concerns about the use of the DSM-IV criteria for diagnosing children with ADHD (Baron, 2007). Moreover, the categorical stance taken by the ICD-10 and the DSM-IV taxonomies appears increasingly challenged as authors argue for a continuum view of ADHD. For example, a large taxometric Australian study on 2996 children, aged 6 to 17 years, recently investigated whether the latent structure of ADHD is best understood as categorical or dimensional (Haslam, Williams, Prior, Haslam, Graetz, et al., 2006). The authors stressed that "ADHD is best modelled as a continuum among both children and adolescents, and no discrete dysfunction can therefore be assumed to cause it." (p. 639). They proposed that a diagnostic threshold should be decided on practical specifications, such as the level of impairment and need for treatment.

1.2. Attention in ADHD

The conventional view is that the main deficit in ADHD is one of sustained attention and impulse control (e.g., APA, 1980, 1987; Barkley, 1981; Douglas, 1972, 1983; Seidel & Joschko, 1990). ADHD has been associated with minimal brain damage, which was reflected in the use of the Continuous Performance Task (described later), originally constructed "for brain damage" (Rosvold, Mirsky, Sarason, Bransome, & Beck, 1956).

However, the findings have been inconsistent and are highly dependent on the definitions, stimuli, and tasks used to assess this dimension of attention (Hinshaw, 1994).

1.2.1. Functions of attention

Traditional research in the area of attention has seldom attempted to integrate the entire range of empirical data within a common theoretical framework (Neumann, 1996). Reviews of the literature on attention show a lack of consensus regarding both the terminology and the functions of attention. Despite William James' (1890/1950) remark that "Everyone knows what attention is" (p. 404), Summers and Ford (1995) have argued that the phenomenon is poorly understood, and stress that a single concise definition of attention is not viable. Over a century ago, James defined attention as:

> … the taking possession by the mind, in clear and vivid form, of one out of what seems several simultaneous possible objects or trains of thoughts. Focalisation, concentration of consciousness is of its essence. It implies withdrawal from some things in order to deal effectively with others. (p. 403-404).

This definition is now recognised to cover only the *selective* dimension of attention. The last three decades of research have provided evidence that, as for the concept of memory, attention is not a unitary entity or mechanism. It

consists of, at the very least, *selective, switchable* and *divisible* dimensions, and all models seem to agree that attentional resources are limited, and that this limitation is flexible and under conscious control (Summers & Ford, 1995).

In effect, the ability to make effective decisions necessitates the integration of various attentional components. At the very least, effective attention requires an optimal balance of alertness, mood and cognitive flexibility (Pliszka, Carlson, & Swanson, 1999). Even in an environment of distractions and through phases of low interest or mounting fatigue, the capacity to do what is intended requires sustained attention (Mazoyer, Zago, Mellet, Bricogne, Etard, et al., 2001). In addition, the ability to search memory, link current sensation to the immediate context and connect this experience to past memories, is a quintessential attentional task (Davis, 2004).

It has been shown that unless irrelevant stimuli in the immediate environment are very salient or embedded within the laboratory task, ADHD children do not seem to experience a deficit in the selective dimension of attention (Berger & Posner, 2000; Milich & Lorch, 1994; Sergeant & Sholten, 1985). In addition, the overall attentional capacity does not appear significantly different in ADHD and control children (Alvarez Del Pino, 1996; Schachar & Logan, 1990a; Taylor, 1995; Vaughn, 1997). Zentall (1985) has argued:

> If attention deficits were the primary variable that led to referral and identification, then hyperactivity would be expected in task settings where attentional demands were greatest. However, the evidence indicates that attention problems often occur when such demands are low, for example, in non-task settings, during performance of very easy, boring tasks, and during tasks with delays, but not during demanding discrimination and attentional tasks (pp. 336-337).

Zentall also pointed out that behavioural changes in ADHD are moderated by the discriminative properties of stimuli within settings (i.e., stimulation or novelty) that interact with the difficulty level of the task.

However, studies continue to demonstrate a deficit in sustained attention. For instance, Heaton et al. (2001) explored the utility of the Test of Everyday Attention for Children as a measure of attentional impairments in 63 children with ADHD and 23 non-ADHD clinical control children. The results showed that ADHD children performed worse than the controls in sustained attention and attentional control, but no group differences were found for selective attention. Others have incorporated the repeated finding of dopamine deficiency necessary for sustained attention in terms of dysfunctional reinforcement and extinction processes (e.g., Johansen et al., 2002). In a recent study (N = 56), Aase and Sagvolden (2006) found that sustained attention was significantly poorer in ADHD children than in their matched controls when reinforcers were infrequent, but the group differences did not occur when reinforcers were given frequently.

1.2.2. Main models of attention

Traditionally, one of the most common views is that attention involves a deployment of cognitive resources. As will be discussed later, some etiological models of ADHD adhere to this notion (e.g., Sergeant, 1998, 2000). Kahneman‘s (1973) Resource Theory assumes that individuals possess a limited pool of attention resources, a generalised, undifferentiated and unspecialised central capacity, which can be flexibly divided according to present needs. As consistently observed, early attempts to perform a complex task require conscious control and all the available resources at hand, with subsequent practice leading to automatic processing, allowing the remaining (unused) resources to be used for a concurrent task (e.g., Fitts, 1964).

Thus, resource-allocation models assume a central fixed quantity of cognitive energy that can be allocated to concurrent tasks in a graded manner. When the attentional demand for one of the tasks increases, the performance on the other decreases. In other words, one task interferes with the other. This performance trade-off has been extensively demonstrated (Posner & Boies, 1971), and is central to recent research investigating the performance of attentional components in ADHD (e.g., Oosterlaan & Sergeant, 1998) and in the coordination of the limbs (e.g., Summers, Byblow, Bysouth-Young, & Semjen, 1998; Temprado, Zanone, Monno, & Laurent, 1999).

Despite Kahneman's (1973) assertion that "interference is non-specific, and it depends only on the demand of both tasks" (p. 11), research using the dual-task paradigm has shown that not all mental processes create, or are subject to, interference when paired with other simultaneous processes. In a number of cases, more interference occurs between similar tasks (e.g., two auditory tasks) than between dissimilar tasks (e.g., a visual task paired with an auditory task) (Allport, Antonis, & Reynolds, 1972). These observations have led to the view that if interference is task-specific, then specific types of tasks may be taxing attentional energy from separate structures, or resource pools of attention (McLeod, 1977). This view was formalised by the multiprocessors and multiple-resources models of attention (Allport et al., 1972; McLeod, 1977; Wickens, 1984) which posit a set of independent channels, processors, or resource pools, working in parallel.

Allport and colleagues (e.g., Allport et al., 1972) repeatedly observed that the dual-task performance decrement depends on the extent to which concurrent tasks access the same structures (resource pool or processors). Interference has also been shown between the cerebral hemispheres and a different resource pool for each hemisphere has been hypothesised (Friedman & Polson, 1981).

Whereas some researchers have argued that the data may be better explained in terms of a single pool of attentional resource (Heuer, 1996;

Navon, 1984), others suggest that the data are best explained by a more general viewpoint which identifies resources with particular mental processes or peripheral effectors. The so-called ~~"~~expanded multiple resource theory" (EMRT, Phillips & Boles, 2004) proposes that each perceptual process depends on its own attentional resource. For example, whereas conventional multiple-resource models would assume that any two visual tasks should employ the same resource pool, EMRT proposes that different visual processes (e.g., spatial positional and visual lexical) draw on different pools (Boles, 2006).

1.3. Neuroanatomy of attention

1.3.1. A three-component model

At many levels, attention requires the coordination of cortical and subcortical functioning (Bennett & Hacker, 2005; Weddell, 2004). Posner and Raichle (1997) proposed a model of attention based on neuroimaging studies, represented in Figure 1, which they applied to ADHD. The model posits that attention processes may be attributed to serve three major functions: orienting to sensory (especially visual) stimuli, establishing and maintaining alertness, and executing control of goal-directed behaviour (including intention, planning, analysis, target and error detection, conflict resolution, and inhibition of automatic responses). Within this framework, ADHD is thought to involve deficits in the executive control network and

the vigilance/alertness network, neuroanatomically related to the midline frontal cortex (cingulate and SMA), basal ganglia (especially caudate), anterior prefrontal cortex, and anterior right parietal cortex (Swanson et al., 1998).

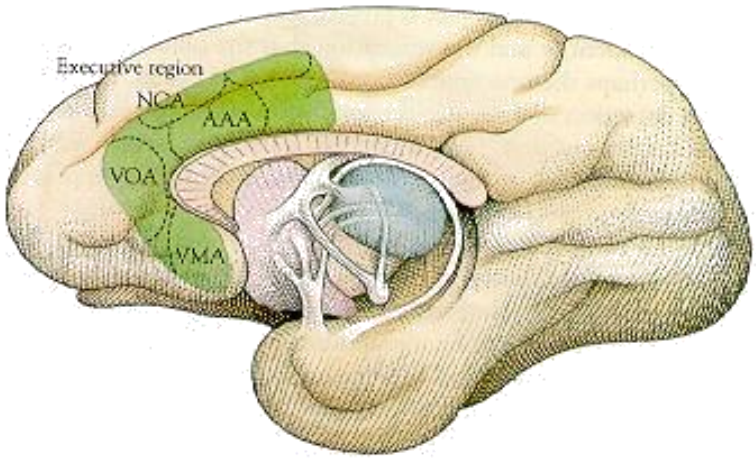

Figure 1. The anterior cingulate gyrus of the monkey brain contains executive areas that have been shown to execute particular functions: Attention (AAA), pain (NCA), emotional vocalisation (VOA), and autonomic responses (VMA) (from Posner & Raichle, 1997).

Recently, Liston et al. (2006) provided direct evidence that dendritic remodelling in the prefrontal cortex underlies functional deficits in attentional control. Their results also indicated that chronic stress induces contrasting morphologic effects in the lateral orbital frontal cortex and

anterior cingulate cortex, which in turn predict the severity of stress-related impairments in attention-shifting. Although ADHD has not been directly associated with stress, repeated peer rejection and negative feedback from parents and teachers often result in high stress and low self-esteem in these children (Johnston, Pelham, & Murphy, 1985).

1.3.2. Orienting network

When excited, the orienting network produces a burst of energy enabled by a noradrenalin surge, which enables the orientation of attention to a situation for immediate response (Posner & Raichle, 1997). The diffuse localisation of noradrenalin neurons facilitates this broad impact on behaviour and is thought to be essential for survival in an unpredictable and threatening environment (Posner & Raichle, 1997). Visual orientation is localised in the dorsal visual areas, although the spatial localisation of events essential to orientation mainly involves the parietal lobe (Fuster, 1997).

1.3.3. Vigilance network

The most critical structures for maintaining alertness include the reticular activating system. According to previous research (e.g., Aston-Jones, Rajkowski & Cohen, 1999), this system, beginning in the brain stem, is primarily activated by noradrenalin arousing from the Locus Coeruleus located in the area of the Pons. The Locus Coeruleus sends diffuse projections throughout the cortex and cerebellum, extending to the limbic

system and down the spinal cord. These projections regulate both tonic (baseline) level of arousal and phasic (episodic) or event-activated arousal. Tonic arousal is associated with sustained attention (e.g., helps us stay awake while driving at night despite fatigue). Phasic arousal is activated when a sudden response is required (e.g., quickly slam on the brakes and swerve while driving). The tonic mode may produce a state of high behavioural flexibility or scanning attentiveness. These observations are important for the investigation of clinical disorders such as ADHD. For example, Sergeant (1998, 2000) has argued that tonic changes are central to the main deficit in ADHD.

1.3.4 Executive control network

The so-called "executive system" is a theorised cognitive system which controls and manages other cognitive operations. It is thought to be involved in processes such as planning complex cognitive behaviors, cognitive flexibility, abstract thinking, rule acquisition, selection of relevant sensory information, personality expression, and initiation of appropriate actions and inhibition of inappropriate actions, including moderating appropriate social behaviour (Barkley, 1997; Burgess & Simons, 2005; Mazoyer, et al., 2001). As mentioned earlier, the cognitive aspects of executive functions are primarily located in the prefrontal cortex, divided into the lateral, orbitofrontal and medial prefrontal areas of the frontal lobes.

The prefrontal cortex has a high number of interconnections both between the brainstem's reticular activating system and the limbic system (Kandel, Schwartz, & Jessell, 2000). As a result, centers in the prefrontal cortex depend greatly on high levels of alertness and emotional connections with deeper brain structures related to the control of pleasure, pain, anger, aggression, fear (fight-flight-freeze responses) and basic sexual responses (Miller & Cohen, 2001; Liston, Miller, Goldwater, Radley, Rocher, et al., 2006). In addition, skills of comparison and understanding of eventual outcomes produced in the prefrontal cortex control the ability to delay immediate gratification for a better or more rewarding long term gratification, which, as will be discussed later, is impaired in ADHD (Aase & Sagvolden, 2006; Johansen et al., 2002).

There is evidence that the cognitive components of executive functions are principally situated in the prefrontal cortex, where spatial organisation occurs more dorsally, verbal memory and organisation are localised more internally, the ability to interpret visual experience is processed in the posterior visual cortex, and sustained attention is mostly managed in the cingulate gyrus (Burgess & Simons, 2005; Fuster, 2002; Posner & Raichle, 1997). The anterior cingulate participates in many aspects of executive functions and working memory (Baddeley, 1998), and retains information in a state of alertness (Banich, 2004). It also plays an important role in sustaining versus changing expectations and shifting set,

and the working instructions of what to do or anticipate next (Fuster, 1997; Posner & Raichle, 1997).

However, the executive system has been traditionally difficult to define, mainly due to what has been called a lack of ―process-behaviour correspondence" (Burgess, Alderman, Forbes, Costello, Coates, et al., 2006). In short, there is no single behaviour which can in itself be tied to executive function, or indeed executive dysfunction (Burgess, Alderman, Evans, Emslie, & Wilson, 1998). For example, whereas it is quite obvious that reading impaired patients have difficulty reading, it is not so obvious as to exactly what executive impaired individuals might be unable to do.

This is largely due to the nature of the executive system itself. It is mainly concerned with the dynamic, ―online", co-ordination of cognitive resources and hence its effect can only be observed by measuring other cognitive processes. Moreover, it does not always fully engage except in real-world situations (Burgess et al., 1998). Consequently, a number of popular tests of executive functions traditionally used to assign impairment in ADHD have been severely criticised (Burgess et al., 1998; 2006). This may account for some of the discrepencies in ADHD research, since the majority of studies investigating the causes of ADHD have used measures of executive functioning in the laboratory context.

1.4. Summary of Chapter 1

Between 2.3% and 6% of children in Australia are diagnosed with ADHD, which is essentially a pervasive disorder of self-control. Diagnosis is a difficult task because aetiological factors are numerous and the criteria on which clinicians rely are continuously disputed. This also makes research complicated and slow. One difficulty is the difference of sampling between European research, in which ADHD-C tends to be the main subtype chosen for inclusion, and research in the United States and Australia, where all subtypes tend to be perceived as belonging to a single disorder. Another difficulty is the categorical systems proposed by the DSM-IV and ICD-10, which are heavily criticised by a number of clinicians and researchers who argue that ADHD is best modelled on a continuum across the community.

Models which conceptualise attention in terms of a general resource pool or multiple processors have been useful in guiding ADHD research. Partly due to technological advancements, a large body of research tends to also investigate attentional deficits by examining the neural substrates of attention. One of the most influential neurocognitive models of attention is that of Posner and Raichle (1997), conceptualised in terms of three interactive neural networks: the alerting, vigilance and executive networks. As will be discussed in the next chapter, the vigilance and executive networks may be compromised in ADHD.

Chapter 2

ADHD and Response Inhibition

2.1. Measuring response inhibition in ADHD

2.1.1. The Continuous Performance Test

As aforementioned, earlier laboratory assessment of ADHD fits its early conceptualisation as an attentional deficit. For instance, the Continuous Performance Test (CPT; Rosvold, et al., 1956) measures sustained attention and impulsivity. It has been used effectively to differentiate children with ADHD from non-clinical children (e.g., Douglas, 1983).

The test involves the presentation of a series of stimuli, generally letters, which appear successively on a computer screen. The child is required to press a key only when a specific stimulus follows another. For example, in a string of letters (starting from the left), AAARPAARAAAAPTAAPAAASAAAP, the instructions may be to respond only when the letter P follows the letter A. If the child fails to press the key when the letter P follows the letter A, it is recorded as an error of omission, reflecting inattention. If a response occurs when P does not follow A, it is an error of commission, reflecting impulsivity.

There are several versions of the CPT. Some have been successfully marketed for clinical use since they permit standardised and computerised administration and are supplemented with user-friendly interpretive reports

(e.g., Test of Variables of Attention [TOVA], Greenberg & Kindschi, 1996).

2.1.2. The Go/No-Go Task

The Go/No-Go Task is a motor inhibition task that requires responding to a go signal and refraining from responding to a no-go signal. Discrete trials are presented in a preset sequence so the no-go signal is given in a fixed order in relation to go trials and is not dependent upon the go response. ADHD participants have been shown to make the go response on no-go trials and commit consistently more no-go responses than children without ADHD (e.g., Brophy, Taylor & Hughes, 2002; Shue & Douglas, 1992).

2.1.3. The Stop-Signal Task

The Stop-Signal task (Logan & Cowan, 1984) is currently considered the most direct and precise measure of the processes required in inhibiting a response (Sergeant, 2000). Typically, it involves the presentation of two stimuli, generally two letters (e.g., X and O), which appear successively at equal temporal intervals on a computer screen. The task consists of two components, a go response and a stop response. During the go trials, participants are required to press an X key when X appears on the screen, or an O key when O appears on the screen. For the stop trials, a tone (stop signal) is presented at given times during letter presentation, signalling to withhold the intended response. Usually, stop signals are presented at

various intervals following the occurrence of the stimulus and before the participant‘s expected response. The closer the stop signal is presented to the ―point of no return” (i.e. temporally very close to the subsequent stimulus presentation), the more difficult it is to inhibit the response. This gives an accurate measure of the time required to inhibit responses. As opposed to the go/no-go task, where children are told to respond to one stimulus on go trials but to make no response to another stimulus on no-go trials , this task requires suppression of a response that is already in the process of being executed. On this task, children with ADHD have been successfully distinguished from controls (e.g., Sergeant, 2000).

2.1.4. The Change Task

The Change Task is an extension of the Stop-Signal task which permits an evaluation of cognitive flexibility, as reflected by the ability to suppress a response and subsequently initiate an alternative response; ―response re-engagement” (e.g., Schachar, Tannock, Marriott, & Logan, 1995). On this task, ADHD children have shown less ability to inhibit a response, slower inhibitory processing, and slower response re-engagement than controls (Tannock, Schachar, & Logan, 1995). However, this has not been universally established. Oosterlaan and Sergeant (1998) observed that while reaction time was slower for ADHD children than controls on the Stop-Signal task, no difference was found in change reaction time. Some of the

discrepancies may be accounted for by differences in sample selection procedures. Schachar et al. (1995) assigned children to ―home-only ADHD", ―school-only ADHD" and ―pervasive-ADHD" groups using DSM-III-R criteria, whereas Oosterlaan and Sergeant (1998) did not differentiate these three categories and assigned selected a single ADHD group in which all children scored at or above the 95th percentile on two standard measures of inattention and one measure of over-reactivity.

2.2. Inhibitory dysfunction as primary deficit

2.2.1. Neurobehavioural observations

Numerous authors have argued that the unique deficit in ADHD is a decreased ability to regulate motor output or inhibit a response, reflected in difficulties in keeping future goals and consequences in mind (e.g., Banaschewski, Besmens, Zieger, & Rothenberger, 2001; Taylor, 1995; van der Meere, van Baal, & Sergeant, 1989). This view has emerged after the recurring observation that children with ADHD show deficits in executive functions associated with motor inhibition (Pennington & Ozonoff, 1996). These deficits are highlighted by several consistent symptoms, including difficulty with motor preparation, timing and adjustment, and difficulties inhibiting, controlling, and coordinating overt motor movements according to situational demands (Asarnow, 1998; Barkley, 1997; Quay, 1988,

Sagvolden & Sergeant, 1998).

Inhibitory dysfunction models suggest that ADHD stems from developmental/genetic abnormalities in dopaminergic (and possibly noradrenergic) pathways originating in brain stem nuclei that act to regulate a cortico-striato-thalamo-cortical network (e.g., Barkley, 1997). This network is believed to be critical for the proper maintenance of prefrontal executive functions and the regulation of behavioural responses (McCracken, 1991). The prefrontal cortex (particularly Broadmann areas 9 and 46) is also known to be involved in sustained and phasic attention to environmental events (Stuss & Benson, 1986)—although Berger and Posner (2000) extend the network involved in sustaining attention to the superior region of the pre-motor cortex (i.e. Broadmann area 6). Researchers have proposed that dysfunction in this system leads to problems in self-control and goal-directed behaviour, involving abnormal functioning in arousal, behavioural inhibition, and attentional processes (NHMRC, 1997).

2.2.2. Barkley's theory of ADHD

One of the most comprehensive models of ADHD has been proposed by Barkley (1997) and appears in Figure 2.1. The model proposes that people with ADHD-HI and ADHD-C (but not ADHD-PI) suffer a deficiency in inhibitory processing that causes secondary deficits observed in neuropsychological functions, including working memory, self-regulation of

affect and motivation, internalisation of speech, and behavioural analysis and synthesis. In short, the problem is one of executive control.

Within the information-processing framework, executive processes are known to be involved in the management of the constant stream of sensory information competing for access to the processes controlling action and decisions about the appropriateness and timing of action (Denckla, 1996). Barkley (1999) proposed that behavioural inhibition lies particularly within the orbital-frontal regions of the prefrontal cortex. The literature provides evidence for dysfunction of the frontostriatal networks (which control attention and response organisation) that may be of genetic origin, consistent with current inhibition deficit models of ADHD (Tannock, 1998).

Pennington and Ozonoff (1996) have argued that ~~–s~~ince an underlying inhibition deficit provides a straightforward explanation of ADHD, we can make a fairly strong case for a primary executive function deficit" (p. 80). The view that the deficit in the ability to inhibit responses is the core deficit in ADHD is supported by numerous studies (e.g., Cepeda, Cepeda & Kramer, 2000; Schachar et al., 1995; Schachar, Mota, Logan, Tannock, & Klim, 2000; Smith, Taylor, Brammer, Toone, & Rubia, 2006). However, others report data that do not fit well inhibition deficit models and propose other explanations for many of the findings.

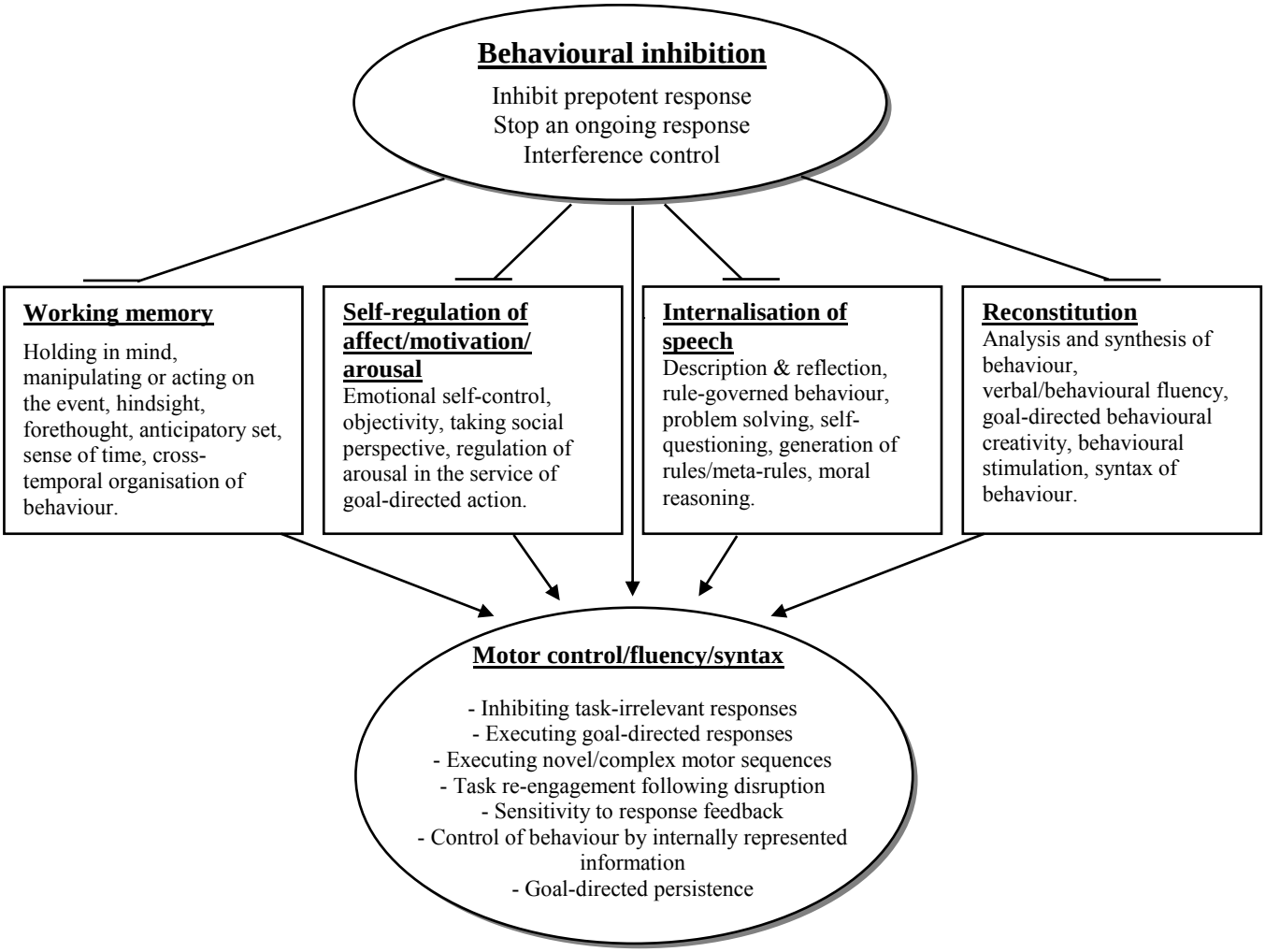

Figure 2.1. A schematic configuration of a conceptual model that links behavioural inhibition with the performance of the four executive functions that bring motor control, fluency and syntax under internally represented information (from Barkley, 1997).

2.2.3. Evidence against disinhibition models

A number of recent studies have shown no evidence of response-inhibition impairment in ADHD. For example, Shaw, Grayson and Lewis (2005) compared the inhibitory capacity of 6 to 14 years old boys with and without ADHD (N = 32) on four measures: two commercially available games, the computerised version of the *Conners' Continual Performance Test II* (CPT-II), and a more game-like analogue of the CPT-II, more appealing and presumably more reinforcing than the conventional CPT-II used for formal assessment. The performance of participants with ADHD on commercially available games was equivalent to that of control participants and was significantly better on the more game-like version of the CPT II. This finding provides further evidence for the role of reinforcement in inhibitory performance of children with ADHD (Johansen et al., 2002; Sagvolden & Sergeant, 1998) and is consistent with observations that the performance of children with ADHD is poorer when tasks are uninteresting and is improved when the discriminatory properties of stimuli are novel and stimulating (Zentall, 1985).

Moreover, Lawrence et al. (2002) examined behavioural inhibition and other executive functions in children with ADHD and matched controls (N = 114) during two real-life activities, two video games (one mostly requiring motor skill and hand-eye coordination, the other necessitating prepotent response inhibition) and an outing to a zoo (following instruction

swiftly, not deviating from instructed paths, etc, while preventing varying degrees interference from distracters, such animal noises). In the laboratory context, children with ADHD demonstrated poorer working memory and motor control than the controls but did not show impairment in behavioural inhibition. However, their inhibitory capacity was significantly poorer than that of controls in the zoo context whereas working memory was not impaired. The authors proposed that ADHD involves problems in sustained interference control, whereby inhibition is impaired when it needs to be sustained but it may not be impaired when prolonged inhibition is not required. The results did not support the hierarchical structure assumed by Barkley‘s (1997) inhibitory model, whereby deficits in behavioural inhibition give rise to secondary impairment in four other executive functions (see Figure 2.1). These studies showed that the context in which the data are collected is of considerable importance.

Another recent study investigated the relationship between executive functions and symptoms of ADHD in 43 children aged 7-11, diagnosed with ADHD-C or ADHD-PI (Jonsdottir, Bouma, Sergeant, & Scherder, 2006). The results showed a lack of relationship between executive functions, as measured by neuropsychological tests, and ADHD symptoms. However, executive functions were associated with comorbid symptoms of depression and autism, whereas inattention was associated with language disorders, showing the importance of screening for comorbidity in ADHD research. In agreement with Jonsdottir et al.‘s (2006) unsupportive stance for

disinhibition models, Piek, Dyck, Francis, and Conwell's (2007) study (N = 195) failed to show deficits in working memory, set-shifting and processing speed in ADHD relative to controls. However, impairment in processing speed was found in a Developmental Coordination Disorder group.

Wolfe and Riccio (2005) also found that the theoretical model of inhibition did not represent a good fit of the data. In their discriminant analysis (N = 93), none of the executive processes of set shifting, interference, inhibition, and planning, separated the groups (ADHD-C, ADHD-PI, no diagnosis, and other clinical). Differences emerged for interference, but only when girls were excluded from the analysis and no control for IQ was made. Given correlational and predictive discriminant analysis results, further analyses were conducted to investigate the contribution of the measures selected for the domains. The theoretical model did not represent a good fit of the data. A three-factor model indicated the best representation suggesting that inhibition and attention were not separable. There were no group differences with their revised measurement model for inhibition/attention, working memory and planning. Taken together, results indicated that measures originally selected to tap executive function may not be clean measures of inhibition, working memory, planning, or attention processes. In addition, recently proposed theories overlap and conceptualise the multiple constructs involved in ADHD with a variety of methodologies, further contributing to difficulties in interpreting results and measurement issues.

2.3. Disinhibition as dysfunctional energetic states

2.3.1. Dysfunction in effort/activation systems

Another etiological hypothesis is that ADHD involves a deficit in the energetic maintenance and allocation of attentional resources causing inhibitory systems dysfunction (e.g., Sergeant, 2000; Sergeant & Scholten, 1985; Sergeant & van der Meere, 1990). This view has been formalised by Sergeant, Oosterlaann, and van der Meere (1999) using Sanders' (1983) cognitive-energetic model, represented in Figure 2.2.

The model implies that the efficiency of information processing depends on both cognitive processing factors (encoding, central processing, and response organisation) and energetic state factors (effort, arousal, and activation). A third level involves a management or evaluation mechanism associated with planning, monitoring, and detecting and correcting errors. Sergeant associates this level with the concept of executive function, which is central to Barkley's (1997) model.

Berger and Posner (2000) have also argued that Sergeant et al.'s (1999) activation pool, thought to involve the control of mental effort, could also be part of the executive control network. Given the evidence that damage to some of these three attention networks produces similar symptoms regardless of what caused the damage (e.g., developmental abnormalities, stroke, etc), the authors propose that the various models of ADHD are best conceptualised under the umbrella of pathologies of

attentional networks.

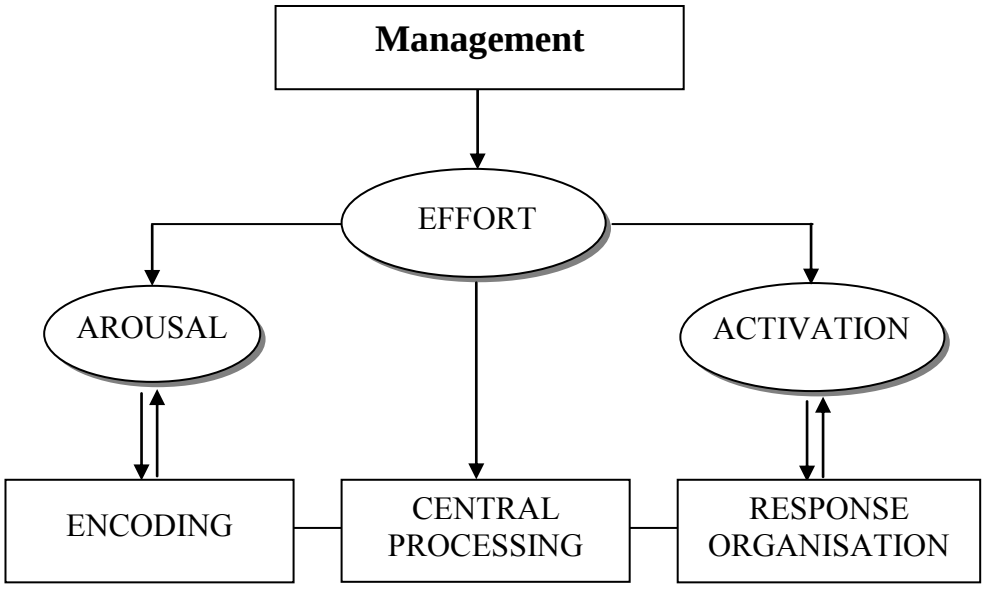

Figure 2.2. The cognitive-energetic model (from Sergeant, Oosterlaan, & van der Meere, 1999). The "Management" box contains typical executive functions. The three ellipses represent the three energetic pools. Effort influences both arousal and activation. The three lower boxes represent the stages of information processing with which these pools are associated.

Sergeant and van der Meere (1990) proposed that ADHD involves deficits of processing in motor organisation but not with encoding or central processing at the first level of the model. At the second level, the primary deficits are associated with the activation pool, and the deficits in inhibitory processes found in ADHD are considered to be the consequence of this

energetic deficit. Accordingly, Sergeant (2000) stresses that claims that ADHD is a prefrontal deficit and is solely explainable by disinhibition (e.g., Barkley, 1997, 1999) are inappropriate since the activation pool appears necessary for inhibition of motor response to occur and is therefore crucial in explaining behavioural disinhibition in ADHD.

According to Sergeant et al. (1999), there is a deficit in response inhibition at the third level. However, several studies found no evidence for deficit in response inhibition but reported large differences in response execution and variability in the speed of responding (e.g., Scheres, Oosterlaan, & Sergeant, 2001). In addition, a meta-analysis of eight studies which used the Stop task to discriminate between children with ADHD, Conduct Disorder and comorbid ADHD + Conduct Disorder, indicated that none of the studies were able to find a deficit in inhibition that is specific to ADHD (Oosterlaan, Logan, & Sergeant, 1998). Based on this overlap of symptoms, the authors suggested that the inhibitory-deficit explanation is not unique to ADHD and that it exists in associated disorders such as Oppositional Defiant Disorder and Conduct Disorder.

2.3.2. Evidence from brain imaging research

Rubia et al. (1999) investigated the neural responses of adolescents with ADHD (age 12-18) to two different executive tasks using fMRI and found contrasting results. One task required the inhibition of a planned motor

response, while the other required the timing of motor responses to a sensory cue. ADHD participants showed smaller responses in the right medial prefrontal cortex than controls during both tasks. They also showed selective decreased responses in the right inferior prefrontal cortex and left caudate to the response inhibition task. The authors concluded that ADHD involves ~~a~~ task-unspecific deficit in higher-order attentional regulation of the motor output", and that ~~l~~lower than normal activation of the right inferior prefrontal cortex and caudate nucleus during the stop task may be responsible for poor inhibitory control in ADHD" (p. 895). This subnormal activation of prefrontal systems lends support to effort/activation systems models.

Further evidence supporting these models is highlighted in Johansen et al. (2002) and Sagvolden and Sergeant's (1998) reviews. The authors report no evidence of brain abnormality in ADHD and argue that the symptoms may be secondary to an underlying deficit in reinforcement processes that are particularly apparent when the timing of stimulus presentation is experimentally manipulated. For instance, using the Go/No-Go task, Boerger and van der Meere (2000) could not find differences in response inhibition between ADHD and control children. On the other hand, they did observe between-group differences with respect to motor activation and effort allocation in a condition whereby stimuli were presented at a slow rate, but not when stimuli were presented at a fast rate. They concluded that a slow presentation rate of stimuli decreases the activation state efficiency in

ADHD children, that is, decreased effort. This finding was replicated by Scheres et al. (2001).

2.3.3. Dual-task studies

Hollingworth, McAuliffe and Knowlton‘s (2001) dual-task study measuring the temporal allocation of visual attention in adults with ADHD further supports the above observations. Their results showed that the ADHD group could use automatic (reflexive) attention to detect items in close temporal proximity, but had difficulties allocating controlled attention to multiple stimuli separated by several hundred milliseconds.

An earlier study by Carlson, Pelham, Swanson, and Wagner (1991) analysed the effect of Methylphenidate (MPH) on ADHD children‘s arithmetic performance using a dual-task paradigm. Participants completed arithmetic problems presented on a computer screen. On half the trials, a foot press was required to terminate a computer-generated tone presented 2 sec before, 1 sec before, 1 sec after, or 2 sec after arithmetic problem presentation. The results showed that MPH decreased ADHD children‘s RTs to tone probes (compared with placebo). Interestingly, MPH also increased answers to arithmetic problems when the two tasks did not overlap in time, but not when simultaneous processing was required (i.e. when the probe was presented 2 sec after arithmetic problems). When dual-task processing increased attention demands, MPH still improved accuracy

on the primary (arithmetic) task relative to placebo, but at the expense of speed of performance on the secondary (RT) task. The authors proposed that MPH treatment of ADHD might result in reallocation of existing attention resources from a secondary to the primary task. A speculative extension of this explanation is that MPH provided the means to apply sufficient control to preserve performance in the task given priority (primary task). Sergeant (2000) also points out that drugs appear to influence both energetic and computational factors in the cognitive-energetic model.

2.3.4. Evidence against the dysfunctional energetic states regulation model

The notion of dysfunctional energetic state regulation in ADHD was investigated by Schachar, Logan, Wachsmuth and Chajczyk (1988), who could not find a difference between children with ADHD and controls in their ability to activate and maintain preparation for an unexpected stimulus. To explain the difficulty in rapidly reorienting attention to a secondary task in ADHD (e.g., Alvarez Del Pino, 1996), Schachar and Logan (1990b) hypothesised a longer psychological refractory period (Telford, 1931) displayed by a difficulty in inhibiting a response, which they observed using the Stop Signal Task.

Strandburg et al. (1996) studied the brain activity associated with visual information processing in ADHD children using event-related potentials (ERPs) recorded during two versions of the Continuous

Performance Task (CPT). They measured ERPs before, during and after continuous processing, and found that ADHD children made more errors and had longer RTs than controls on both the single- and dual-target CPT. As shown by ERPs, ADHD participants did not differ in their level of preparedness or their ability to mobilise resources for target identification and categorisation, but had a reduced involvement in post-decisional processing. A decrease in performance at a later stage of processing does not agree with etiologic models of ADHD which suggest a dysfunction in energetic mechanisms (e.g., Sergeant et al., 1999).

2.4. Limitations in ADHD research

2.4.1. Methodological difficulties

It must be noted that the numerous discrepancies in findings may reflect methodological problems. These include, but are not limited to, the use of small sample sizes, the high level of heterogeneity in ADHD samples and the failure to control for comorbidity confounds, maturational and gender effects, and family history.

Differences in task manipulations must also be taken into account. For example, a possible methodological problem when using button-press methods to measure inhibitory control has been noted. Simpson and Riggs (2006) reported that too short exposure to the stimulus does not attract inhibitory demands. They argue that studies which omit the importance of

timing in the presentation of stimuli are not likely to capture an accurate representation of inhibitory capacity, especially in young children.

The issue of context is also highlighted by investigators. Brophy et al. (2002) stressed the importance of combining experimental and observational approaches when assessing problems in executive control. Similarly, the results from Lawrence et al. (2002) indicate that behavioural inhibition in ADHD is dependent on context and the authors stress the importance of ecological validity.

The effect of context is also reflected by the differences between parents‘ and teachers‘ ratings of child behaviour and the experimental data collected in the laboratory. For example, in a study examining the differences in academic and executive functions among children with ADHD-PI and ADHD-C (N = 40), Riccio, Homack, Jarratt, and Wolfe (2006) found that parents rated the ADHD-C group as being less able than ADHD-PI to inhibit their behaviour in daily life. However, when using formal measures of the executive function domains of set shifting, interference, inhibition, and planning, no group differences emerged after controlling for differences in IQ. Miyahara, Piek and Barrett (2006) also pointed out that subjective measures such as parents‘ and teachers‘ ratings vary greatly according to the assessor‘s personality and mental health, and the school setting which the child attends (e.g., mainstream versus segregated special class).

Motivation has also been repeatedly reported as an important extraneous variable in experimental trials. A number of authors pointed out that typical experimental tasks are uninteresting or boring for children and do not represent the child‘s behaviour in daily life (Brown, 1999, Shaw et al., 2005; Zentall, 1985).

2.4.2. Definitional and typological disagreements

The use of inconsistent selection criteria across studies in defining ADHD is yet another limitation and the object of continual disagreement (Barkley, 1997; Sergeant, Piek, & Oosterlaan, 2006). For example, European researchers tend to select experimental samples from the Combined-Type subgroup, since it meets the ICD-10 criteria for the hyperkinetic syndrome, whereas North American and Australian researchers have used the two other subgroups extensively. Some international differences are well illustrated by Tannock‘s (1998) comprehensive review. For example, clinicians and researchers in Europe diagnose ADHD (i.e., Hyperkinetic Disorder) only when comorbid symptoms with other psychopathologies are absent, which is consequently perceived as a rather rare condition. In contrast, the North American approach is to conceptualise ADHD as a heterogeneous developmental disorder (see also Sergeant & Steinhausen, 1992). Consequently, major difficulties in ADHD research are the high frequencies of overlapping symptoms and comorbidity with Conduct, Oppositional

Defiant, Depressive, and Anxiety disorders.

A recent special issue of Neuropsychology Review dedicated to a re-evaluation of definition, diagnosis and treatment of ADHD reflects a number of inconsistencies in various research domains. Stefanatos and Baron‘s (2007) review strongly challenges the validity of the DSM-IV criteria for the diagnosis of ADHD. Baron (2007) also stresses that comorbidity is a critical issue and that ―elinicians cannot, or at least should not, operate in a research vacuum regarding the science of ADHD. To do so may only result in misdiagnosis, under or over-estimation of true incidence, and inappropriate therapeutic recommendations.” (p. 3).

As mentioned earlier, the construct of a central executive underlying cognitive functions has been insufficiently defined and some models relying on such construct have often been heavily criticised. For example, Garavan, Ross, Li, and Stein (2000) used fMRI to elucidate the central executive construct in normal populations. They designed an attention-switching task to isolate one elementary executive function; the allocation of attention resources within working memory. The frequency with which attention was switched between items in working memory was varied across different trials, while storage and rehearsal demands were held constant. fMRI revealed widespread areas, both frontal and posterior, that differentially activated as a function of a trial‘s executive demands. Together, the data suggested that the executive function that enables the switching of attention

seems to be neuroanatomically distributed, rather than being located in a specific and unique cortical area.

Another issue is the implication of working memory deficits in Barkley's (1997) model of dysfunctional inhibition. Although Barkley's model predicts that children with ADHD-C present working memory deficits caused by central impairments in behavioural inhibition, Vaughn (1997) found no such deficit in the ADHD-C group relative to controls. On the other hand, the ADHD-PI group showed significantly lower intelligence test scores than the ADHD-C and control groups, and remained the poorest even after covarying for the Verbal Comprehension Index. Accordingly, the author suggested that there is questionable validity for incorporating working memory deficits into a unifying theory of ADHD and for excluding children with ADHD-PI from it, as suggested by Barkley and colleagues.

To investigate the empirical evidence for deficits in working memory processes in children and adolescents with ADHD, Martinussen, Hayden, Hogg-Johnson, and Tannock (2005) used exploratory meta-analytic procedures. Twenty-six empirical research studies published from 1997 to December, 2003 were included. Working memory measures were categorised according to modality (verbal, spatial) and type of processing required (storage versus storage/manipulation). The results showed that children with ADHD exhibited deficits in multiple components of working memory that were independent of comorbidity with language learning

disorders and weaknesses in general intellectual ability. Overall effect sizes for spatial storage (effect size = 0.85) and spatial central executive working memory (effect size = 1.06) were greater than those obtained for verbal storage (effect size = 0.47) and verbal central executive working memory (effect size = 0.43). The authors concluded that there is sufficient evidence to support recent theoretical models implicating working memory processes in ADHD.

The relationship between working memory and response inhibition in ADHD (N = 65), high-functioning autism (N = 66), Tourette syndrome (N = 24) and normally developing children (N = 82) was recently investigated (Verte, Geurts, Roeyers, Oosterlaan, & Sergeant, 2006). The relationship between working memory and inhibition was similar between all groups, even after controlling for differences in processing speed. The authors reported that more symptoms of hyperactivity/impulsivity were related to a poorer inhibitory process and greater response variability, whereas more symptoms of autism were related to a poorer working memory process.

Other studies have shown that at least some components of working memory, such as the ~~–s~~ense of time" component, assumed to be impaired in Barkley's (1997) model, may not need to be included. It has been demonstrated that hyperactive children can perceive time just as well as controls but are impaired in timing their motor output (e.g., Rubia, Taylor, & Taylor, 1999).

Generally, while the average performance of children with ADHD is generally only slightly below that of controls, their performance over time, across tasks, and in different situations, shows large variability (Mash & Wolfe, 1999; van der Meere & Sergeant, 1987).

2.5. Summary of Chapter 2

Objective measurements used to assess ADHD have evolved from tests of sustained attention to sophisticated measures of behavioural inhibition. Although researchers are still divided as to what components of information processing are most impaired in ADHD, most include measures of the so-called executive functions. Among executive functions, inhibitory processes seem to be impaired and what causes disinhibition has been debated for over a decade.

There are two broad types of etiological models for ADHD. One approach proposes that a deficient inhibitory processing causes secondary impairments in working memory emotional self-regulation, internalisation of speech and behavioural analysis and synthesis (Barkley, 1997). The other advances that behavioural inhibition must first rely on the ability to activate and regulate energetic states. Accordingly, ADHD may be caused by a deficit in the energetic maintenance and allocation of attentional resources, causing difficulties in inhibiting or interrupting an undesired response (Sergeant, 2000). The results from etiological investigations are equivocal,

partly due to high comorbidity in selected samples, large variability within ADHD children‘s performance, methodological differences and typological disagreements about the disorder.

Chapter 3

Motor Coordination in ADHD

3.1. General observations

3.1.1. Prevalence

It is estimated that up to 52% of ADHD children present some type of motor dysfunction (Barkley, 1990). This is not surprising since ―most of the brain deals with motor function" (Georgopoulos, 1995, p. 507). There is a general acceptance among researchers that neuropsychological difficulties and motor difficulties—including motor coordination, motor planning and sequencing, rhythmicity and timing—are clinically interrelated in ADHD (Gillberg & Gillberg, 1988; Landgren, Petterson, Kjellman, & Gillberg, 1996; Piek, Pitcher, & Hay, 1999; Sagvolden & Sergeant, 2000).

3.1.2. Timing and motor factors

Time reproduction deficits in children and adolescents with ADHD and their non-affected siblings was recently investigated by Rommelse, Oosterlaan, Buitelaar, Faraone and Sergeant (2007), to clarify whether these deficits are familial and could therefore serve as a candidate endophenotype. The study included 226 children with ADHD, 188 non-affected siblings, and 162 controls ages 5 to 19. Children performed a visual and auditory time reproduction task. They reproduced interval lengths of 4, 8, 12, 16, and 20

seconds. Results showed that children with ADHD and their non-affected siblings were less precise than controls, particularly when task difficulty was systematically increased. Time reproduction skills were familial. Time reproduction deficits were more pronounced in younger children with ADHD than in older children. Children with ADHD could be clearly differentiated from control children until the age of 9, after which these differences were still present but attenuated. Differences between non-affected siblings and controls were constant across the age range studied. Deficits were unaffected whether the modality was visual or auditory. Accordingly, the authors proposed that time reproduction may serve as a candidate endophenotype for ADHD, predominantly in younger children with (a genetic risk for) ADHD.

Meel, Oosterlaan, Heslenfeld, & Sergeant (2007) attempted to clarify whether poor performance of children with ADHD on motor timing tasks reflects a true deficit in the temporal organization of motor output or is due to a lack of intrinsic motivation. Eighteen children with ADHD (age 8–12) were compared with 18 age- and gender-matched controls with respect to timing precision, timing variability, and the frequency of extreme under- and overestimations during a 1-second interval production task. Monetary reward, response cost, and no reward were implemented to manipulate motivation. The results showed that children with ADHD produced significantly more inaccurate and more variable time intervals and exhibited a larger number of extreme over- and underestimations than control

children. Although all children performed significantly better when monetary incentives were applied, group differences remained significant. In this study, the authors found no evidence for a motivational deficit as an explanation for impaired performance on a time production task in ADHD. Rather, their results provided clear support for a generic motor timing deficit, which they attribute to a dysfunctional fronto-striato-cerebellar network involved in temporal aspects of motor preparation.

However, a more recent study investigated the impact of reinforcement valence and magnitude on response timing in 25 children with ADHD (Luman, Oosterlaan, & Sergeant, 2008). Ten children met the DSM-IV criteria for ADHD-C, twelve were diagnosed with ADHD-PI and three were diagnosed with ADHD-HI. Children were required to estimate a 1-second interval, and both the median response time (response tendency) and the intrasubject-variability (response stability) were investigated. In addition, heart rate and skin conductance were measured to examine the autonomic responses to reinforcement. Feedback-only trials were compared to low response cost trials (response cost for incorrect responses), low reward trials (reward for correct responses), and high response cost and high reward trials. In feedback-only trials, children with ADHD underestimated more severely the interval and responded more variably than the controls. Unlike the controls, children with ADHD were unaffected by the reinforcement conditions in terms of time underestimations. However, the variability of responding decreased under conditions of reinforcement to a

larger extent in children with ADHD than the controls. There were no indications that children with ADHD were abnormally affected by the valence or magnitude of reinforcement. In addition, skin conductance responses increased when feedback was coupled with reinforcement in all children but this effect was larger in children with ADHD than in the controls. The authors proposed the possibility that children with ADHD suffer from a diminished awareness of the significance of feedback in the feedback-only condition. They suggest that children with ADHD suffer from motivation problems when reinforcement was not available, at least when variability in responding was measured, and that underestimations of time may reflect more stable deficits in ADHD.

In summary, motor timing deficits previously identified in ADHD seem to be affected by motivational factors. Moreover, motor timing deficits seem to be attenuated with age. This may be clarified by comparing motor timing in children and adults with ADHD in future studies.

3.1.3. Fine versus gross motor skills

A study by Piek et al. (1999) demonstrated that the severity of inattentive symptomathology was a significant predictor of motor coordination difficulties. Their results also revealed that ADHD-PI might exhibit poorer fine motor skill while ADHD-C may involve poorer gross motor skills—although the authors mention that the relatively low power of their analyses

casts some uncertainty on the findings. Caution is particularly recommended regarding the attribution of fine versus gross motor skill problems to various subgroups, as previous research has shown that children with ADHD-C frequently exhibit fine motor deficits (Denkla & Rudel, 1978; Shaywitz & Shaywitz, 1984). Moreover, since the study revealed that 20 of the 32 participants (62.5% of the overall ADHD sample) had motor difficulties, the authors stressed that objective assessment of motor performance in all children with ADHD should be conducted as standard clinical practice.

3.1.4. Bimanual coordination dynamics in ADHD

To the author‘s knowledge, only one previous study investigated the dynamics of bimanual coordination in ADHD (Klimkeit, Sheppard, Lee, & Bradshaw, 2004). The authors examined bimanual coordination in 12 boys (8-14 years of age) diagnosed with ADHD-C on a crank task. The children were required to perform simultaneous symmetrical and asymmetrical circular hand movements paced at 1 and 2 Hz by an auditory metronome. Compared with controls, the children with ADHD showed greater variability in coordination and velocity during both symmetrical and asymmetrical patterns. With symmetrical patterns, children with ADHD also showed less ability to coordinate the hands. The authors concluded that ADHD involves a problem of bimanual coordination that may be neuroanatomically associated with the finding of decreased activation in the

basal ganglia, cerebellum, and the rostral body of the corpus callosum (Castellanos et al., 1996). However, a major limitation acknowledged by the authors is that eight out of the 12 participants with ADHD had comorbid conditions. Given the criticism of such mixed samples in the literature, the conclusions drawn from the results must be accordingly tentative. For example, three out of the 12 ADHD participants had Oppositional Defiant Disorder, a condition which has been shown to display as much deficit in response inhibition as ADHD (Oosterlaan et al., 1998).

3.1.5. Lack of "online" measurements

The lack of such dynamic or ~~–o~~nline" measures limits our understanding of the extent to which the deficit in motor inhibition in ADHD affects task performances which require continuous movements. Standard assessments of motor ability (e.g., the *Movement Assessment Battery for Children*, Henderson & Sugden, 1992) provide a general estimation of motor performance in terms of generic tasks, but they cannot permit a direct evaluation of the various components of these tasks and the differential neural constraints they may exert in ADHD children. Consequently, the few studies devoted to the investigation of motor coordination in ADHD tended to measure the outcome of a motor task and were not particularly intended to examine the processes taking place during the task (e.g., Livesey, Keen, Rouse, & White, 2006; Piek et al., 2004). However, environmental and

biomechanical constraints on movements are also important to the understanding of movement coordination. This seems to be especially the case in children with ADHD, who have been shown to adapt their skills according to dynamic factors such as reinforcement (Aase & Sagvolen, 2006), and the specific features of stimuli (Shaw et al., 2005; Zentall, 1985). These constraints may be central to the understanding of motor task difficulties in ADHD.

Moreover, motor control training has an important role as a secondary intervention in ADHD multimodal treatment (Banaschewski et al., 2001; Barkley, 1990). Since it is not clear that all tasks implemented in this training are best suited to address the motor-coordination difficulties in ADHD, gaining a better understanding of these constraints could increase the quality of treatment. For example, given the motor timing difficulty in ADHD (e.g., Barkley, 1997; Sagvolden & Sergeant, 1998), tasks that mainly involve more temporal than spatial constraints may be less achievable and would therefore require adaptation on the part of treatment providers. The measurements of online performance capable of capturing spatial and temporal task components are central to the Dynamical Systems approach to the study of human motor control.

3.2. Bimanual Coordination Dynamics

3.2.1 The Dynamical Systems approach

The spatial and temporal constraints on interlimb coordination have been extensively investigated for over two decades by researchers using the Dynamical Systems approach (e.g., Kelso, 1981). This approach ~~a~~aims to mathematically model the stability and loss of stability (phase transition) evident in the formation of patterns in movement systems" (Summers, 1998, p. 391). This line of research has proven to be fruitful in broadening our understanding of the dynamics involved in motor system activity and has an important bearing on the existing models of skill learning and rehabilitation of motor functions in individuals with coordination impairment (e.g., Morris, Collier, Matyas, Summers, & Iansek, 1998).

A dynamical system can be simply defined as ~~a~~ more-or-less self-contained set of elements that interact over time in complex, often non-linear [but meaningful] ways" (Vallacher & Nowak, 1994, p. 2). Following a heterarchical principle, information processing is described in terms of complex non-linear dynamical systems operating simultaneously across the dynamics of the central nervous system, the dynamics of the effector, and the dynamics of the environment (Schmidt & Fitzpatrick, 1996).

While the traditional approach assumes that specific factors should be isolated from one another in order to measure their independent contributions to a phenomenon of interest, the Dynamical Systems approach

stresses the importance of feedback among the relevant factors (components of a system), and the system's tendency to become self-organised according to the patterns of such feedback (Franklin & Schroeck, 1994). Given that variation in any factor is associated nonlinearly to the behaviour of the whole system, even a minor change in a factor can promote dramatic change in the system.

As will be discussed below with regards to the bimanual movement system (Kelso, 1981), a spontaneous phase transition is due to the periodic evolution, or _limit cycle attractor', whereby a small additional environmental/task constraint (e.g., a small increase in movement frequency) can transform dramatically an otherwise stable pattern of behaviour. However, some systems evolve over time towards a steady state (e.g., the winding down of a pendulum) and have fixed-point attractors (i.e., the convergence of all the system's elements to a fixed set of values); some are attracted into quasiperiodic behaviour in which the system oscillates over time but never returns exactly to the same state, and other systems evolve in a chaotic fashion without apparent regularity and are extremely sensitive to initial conditions (e.g., as depicted by the spontaneous changes in weather patterns) (Newtson, 1994). Since any dynamical system requires its components to have ~~a~~n interplay of forces and mutual influence such that the system tends towards equilibrium of steady states" (Schmidt & Fitzpatrick, 1996, p. 197), theorists from various scientific disciplines assert that dynamic principles are also a fundamental feature of human behaviour

as a whole (e.g., Capra, 1996; Kelso, 1995; Latané & Nowak, 1994; Sheldrake, 1994).

Dynamical principles can easily be observed in interlimb coordination research (e.g., Kelso & Schöner, 1988), which suggests that the motor system behaves fundamentally in a manner similar to all natural complex systems. Numerous studies have shown a preferred synchronisation, or coupling, of the limbs, in a variety of bimanual tasks, including circle-drawing (Stucchi & Viviani, 1993), index fingers oscillation (Kelso, 1981, 1995) and pronation/supination movements with joysticks (Temprado et al., 1999).

3.2.2. Dynamics in circling patterns

During a typical circle-drawing task, for example, symmetrical patterns produced in the horizontal plane involve one hand circling clockwise and the other anticlockwise, with 0° difference between hands (0° relative phase), whereas asymmetrical patterns involve both hands circling clockwise or anticlockwise with a 180° relative phase. These modes of coordination are usually defined according to the pattern of muscle activation. Because symmetrical patterns involve mirror movements in homologous muscle coupling whereas asymmetrical circling requires simultaneous activation of the antagonist muscles, which is more difficult and less stable than symmetrical circling, symmetrical patterns have been

identified as the in-phase mode and asymmetrical patterns as the anti-phase mode of coordination (e.g., Hiraga, Summers, & Temprado, 2004; Semjen, Summers, & Cattaert, 1995; Swinnen, Jardin, & Meulenbroek, 1996; Swinnen, Jardin, Meulenbroek, Dounskaia, & HofkensVanDenBrandt, 1997).

In addition, when oscillation frequency of bimanual patterns increases beyond a critical value, an unavoidable switch ("phase transition") from anti-phase to in-phase occurs spontaneously (Monno, Temprado, Zanone, & Laurent, 2002). The phase transition that highlights hand coupling in bimanual tasks has been explained in terms of the 'taking over' by preferred coordination tendencies (intrinsic dynamics) inherent in all physical and biological systems, in order to reach a stable state (Haken, Kelso, & Bunz, 1985). Hence, movement patterns that occur spontaneously are considered intrinsic to the system (Kelso & Schöner, 1988). The in-phase mode is a coordination state to which movements are spontaneously attracted and is therefore considered an intrinsically stable coordination state (Kelso, 1984; Summers, Semjen, Carson, & Thomas, 1995). This phenomenon forms the basis for the notion of self-organised patterns put forward by the Dynamical Systems approach in motor control research (e.g., Kelso, 1995; Scholz & Kelso, 1989; Treffner & Turvey, 1995).

3.2.3. The circling task

In a bimanual circling task, participants are asked to perform blocks of trials of symmetrical and asymmetrical circling patterns with both hands simultaneously (e.g., Summers et al., 1995). The circling movement is often paced by a metronome (generally an auditory tone) at a frequency that is either constant throughout a trial (e.g., 1 Hz), or scaled so that it increases in steps across a trial (e.g., from 1 to 3 Hz).

Bimanual circling tasks have provided several spatial and temporal measures that are central to the understanding of coordination dynamics. _Relative phase', also referred to as _lead-lag', is a measure of the relationship between the positions of each hand in their respective cycle, _uniformity' of relative phase is a measure of variability of the lead-lag, and —aspect ratio' quantifies the degree of circularity of the movement. Relative phase offers an index of spatiotemporal accuracy whereas uniformity of relative phase is an indicator of the (spatiotemporal) stability between the hands. Aspect ratio provides an index of circularity of trajectory (spatial performance) whereby a score of 1 represents a perfect circle and 0 a straight line.

Circle-drawing tasks have revealed two stable states: in-phase and anti-phase, as represented in Figure 3.1. As mentioned earlier, it has been observed that increasing the frequency of anti-phase circling to a given critical value leads to a spontaneous transition from anti-phase to in-phase

coordination mode, with the non dominant hand being „pulled back" by the attraction of the dominant hand (Semjen et al., 1995)—although phase transitions occur less frequently in circling tasks than in other bimanual tasks such as finger flexing (Kay, Saltzman, & Kelso, 1991) or finger wagging (Scholz & Kelso, 1990).

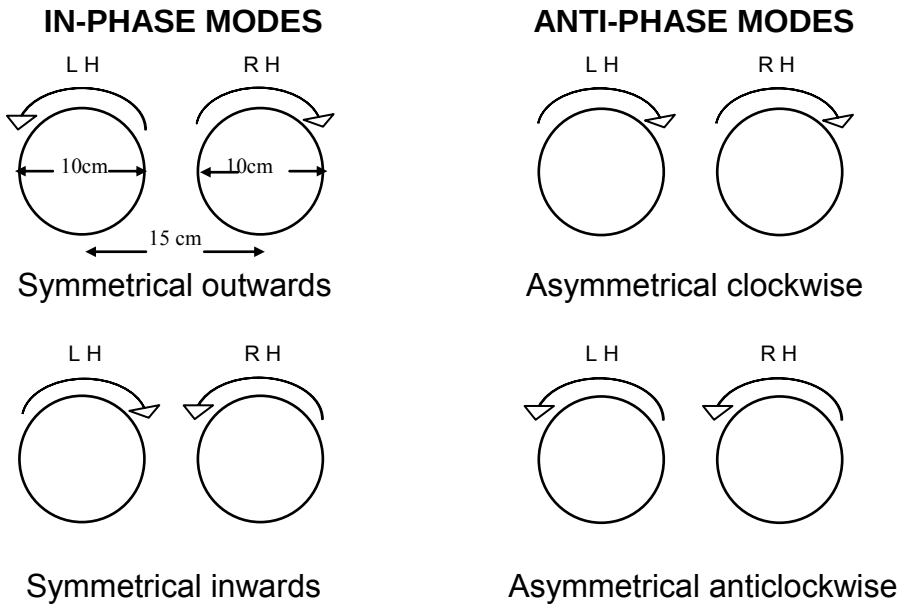

Figure 3.1. Schematic of the two in-phase and two anti-phase modes of bimanual coordination (LH = left hand; RH = right hand), adapted from Carson, Thomas, Summers, Walter, & Semjen, 1997, p. 668).

In contrast with previous observations that spatial and temporal task parameters of bimanual circling may be coupled (e.g., Temprado et al.,

1999; Wuyts et al., 1996), Hiraga, Summers and Temprado's (2004) study of bimanual circling in normal adults showed that focusing on coordinating the timing between the hands improved temporal performance but did not enhance or worsen spatial performance. Hence, attention enabled the dissociation of spatial and temporal components of the task. Subsequently, the authors showed that spatial-temporal decoupling is possible following the manipulation of attentional focus (Hiraga, Summers & Temprado, 2005). To date, the coupling of spatial and temporal task parameters during bimanual circling has not been investigated in clinical groups.

3.3. Bimanual Coordination in Clinical Samples

3.3.1. Neuroanatomy of bimanual tasks

Overall, current evidence suggests that the proper execution of a goal-directed bimanual task depends on the cooperation of widely distributed cortical association areas rather than being constrained within a single cortical locus. As an interconnected ensemble, these areas form a large region including the supplementary motor area (SMA) that may be functioning as a unifying structure (see Wiesendanger, Wichi, & Rouiller, 1994 for a review).

There is also some evidence that the rostral parts of the SMA play an important role in aspects of functional bimanual tasks which involve tight temporal coordination between different motor actions of both hands (Obhi,

Haggard, Taylor, & Pascual-Leone, 2002). Disorders involving bimanual coordination impairment have often been described with lesions in the cerebellum, frontal association cortex, lateral pre-motor cortex, and frequently in parietal association cortex (e.g., Diedrichsen, J., 2006; Leonard, Milner, & Jones, 1988; Seitz, et al., 2004). The rostral body of the corpus callosum has also been implicated with ADHD (Baumgardner, et al., 1996; Berquin, et al., 1998; Giedd, et al., 1994).

3.3.2 Coordination mode in clinical groups

It has been argued that the dynamics of spontaneous, in-phase, bimanual patterns may be more dependent on autonomous segmental and spinal networks (e.g., Carson, 1995). Out-of-phase patterns (e.g., 90° relative phase), however, are more complex and therefore goal-directed, relying on cortical monitoring (Byblow et al., 2000). Accordingly, Bogaerts and Swinnen (2001) proposed that the specification of different movement directions (away from the intrinsic ones) requires the recruitment of inhibitory networks to prevent phase transition to preferred coordination patterns. There is evidence that the stabilisation of more complex bimanual patterns necessitates intentional and skilful monitoring of the limbs (Monno et al., 2002), which is often impaired in clinical samples.

Typically, all types of lesions affecting bimanual coordination involve the following features: anti-phase movements are more seriously

disturbed than easier in-phase movements, and natural, everyday skills (that have become relatively automated) are better preserved than new or ~~"a~~bstract" bimanual skills (Wiesendanger et al., 1994). Moreover, the in-phase coordination mode tends to emerge in exaggerated form as a result of disorders such as developmental abnormalities, while the anti-phase mode appears more affected as a result of brain pathology (Bogaerts & Swinnen, 2001; Swinnen et al., 1997).

Given the propositions that (a) the primary deficits of ADHD may be associated with the activation pool, identified with the basal ganglia and corpus striatum (Sergeant et al., 1999), and (b) involve deficits in networks related to the midline frontal cortex (cingulate and SMA), basal ganglia (especially caudate), anterior prefrontal cortex, and anterior right parietal cortex (Swanson et al., 1998), it is not surprising that brain pathologies involved with these areas also display inhibition difficulties.

For example, Byblow, Summers, and Thomas (2000) examined the spontaneous and intentional dynamics of bimanual coordination in individuals with Parkinson's disease (PD), a degenerative condition involving dopamine deficiency in the basal ganglia. Participants were required to produce rhythmic pronation and supination movements at various rates in both in-phase and anti-phase coordination modes and to switch intentionally from in-phase to anti-phase and anti-phase to in-phase, and resist spontaneously transitions from anti-phase to in-phase. Compared

with controls, PD participants exhibited spontaneous transitions from anti phase to in-phase coordination at lower movement rates and had higher asynchrony between hands, though their relative phase tended to remain as stable as the relative phase performed by the controls.

A bimanual coordination study with chronic schizophrenic patients confirmed that brain dysfunction seems to increase the differences in the ability to perform in-phase and anti-phase coordination modes (Bellgrove et al., 2001). This is consistent with the repeated observation that schizophrenia sufferers display motor inhibition deficits associated with activities of prefrontal cortex and related networks (e.g., Badcock, Michie, Johnson, & Combrinck, 2002; Katsanis, Kortenkamp, Iacono, & Grove, 1997).

3.3.3. A cognitive account

According to the cognitive-energetic model, dysfunctions in motor output processing might be caused by a weakness to modulate the behavioural state (effort/activation) which mainly involves the brain‘s motor control and coordinating structures (Banaschewski et al., 2001; Sergeant et al., 1998; Sergeant & van der Meere, 1988, 1990). Bogaerts and Swinnen (2001) have argued that at higher (planning) levels, coordination deficits in motor-disordered patients may arise as the result of a decrease in available mental resources, because more resources are needed in monitoring the basic

aspects of motor performance as a result of less optimal movement control.

3.3.4. Motor Inhibition

A number of studies (e.g., Temprado et al., 1999) have shown that even at relatively high movement rates, when the required movement pattern corresponds to a stable state of the system (e.g., in-phase), little mental effort is required to maintain the correct pattern. In contrast, when a movement pattern does not correspond to a stable state of the system (e.g., 30° relative phase), some inhibitory functions are continuously required to maintain the pattern and resist spontaneous phase transition. Given that inhibitory control has been shown to be reduced in ADHD (Barkley, 1999), individuals with this disorder would be expected to show difficulties maintaining less stable (e.g., anti-phase) patterns and increased reliance on intrinsically stable coordination states, such as in-phase patterns.

However, the evidence that inhibition at higher cortical levels translates into motor inhibition at the effector level is currently not convincing (Sergeant, 1998). A recent study compared attentional versus motor inhibition in adults with ADHD (Carr, Nigg, & Henderson, 2006). The authors used the attentional blink paradigm to measure attentional inhibition and an antisaccade (eye movement) task to investigate motor inhibition. Antisaccade results showed longer latencies and increased anticipatory saccades in ADHD. In the attentional blink task, the ADHD

groups made more errors but did not show evidence of abnormal blink. The results suggested deficits in motor inhibition but not in attentional inhibition in the ADHD groups. The effect was more pronounced in ADHD-C than in ADHD-PI. Nonetheless, it is not clear whether the mechanism underlying inhibition of saccadic eye movement also subserves the control of hand coordination.

To investigate motor inhibition in ADHD, most recent studies have used the Stop Task (e.g., Lijffijt, Kenemans, Verbaten, & van Engeland, 2005), which consists of discrete responses rather than continuous motion. To the author‘s knowledge, motor inhibition in ADHD has not been investigated during a continuous motor task, such as circling patterns. The difference in the ability of ADHD children to inhibit a discrete prepotent response and an ongoing action is currently unknown. Yet, the inability to inhibit continuous actions has been reported as the hallmark of ADHD. As identified in recent publications, ~~th~~e field is in urgent needs of methodological improvements and innovations…and [should] demonstrate that effects converge across different measures of the same ability" (Stefanatos & Baron, 2007, p.22).

3.4. Summary of Chapter 3

About half the children with ADHD also display impairment in motor coordination. Standard measurements tools have shown that children with ADHD-C can display deficits in both gross and fine motor skills and

children with ADHD-PI tend to exhibit poorer fine motor skill. However, there is a paucity of studies examining the dynamics of motor performance in ADHD, and only one known to this author devoted to bimanual coordination dynamics. Measurements from the Dynamical Systems approach provide ―online" data, that is, the continuous stream of data reflecting motor behaviour during a whole movement sequence. Compared with relying solely on the outcome of a movement (e.g., whether throwing a ball leads to hitting a target or not), dynamical measures permit a direct evaluation of spatial and temporal aspects of a motor task and are particularly advantageous during continual movements.

Most authors agree that motor control deficit in ADHD is related to neuropsychological impairment. Measuring whether inhibition at higher cortical levels translates into motor inhibition at the effector level in ADHD would be valuable since this correspondence has not been established. Moreover, most studies measuring motor inhibition in ADHD used the Stop Task paradigm, which requires discrete responses. The ability to inhibit a response during continuous motion, such as a circling pattern, has not been studied.

Chapter 4

Experiment 1

4.1. Aims and rationale

The general aim of the present research was to obtain a better understanding of the impaired motor control in ADHD by systematically measuring the spatial and temporal aspects of bimanual coordination, using both measurements of movement dynamics and traditional tools from the Information Processing approach. The uniqueness of this research was its focus on decomposing motor control difficulties *during* task performance rather than relying on measurements of overall success and failure with motor tasks. Thus, it aimed to provide another dimension to ADHD research, as it is currently unclear whether inhibitory dysfunction at a higher level of motor organisation pervades the entire motor system during various coordination tasks.

Moreover, since motor control training has an important role in ADHD multimodal treatment, better understanding of whether inhibitory deficits are limited to discrete motor responses or extend to continuous motor tasks could potentially increase the quality of treatment. It is also possible that children with ADHD, compared to children with other motor problems (e.g., Developmental Coordination Disorder), may benefit

differentially across tasks which involve variable amounts of temporal and spatial constraints.

As mentioned earlier, there is a paucity of studies that have investigated motor coordination in ADHD. Even fewer have investigated the dynamics of bimanual movement in this population. Although the Klimkeit et al.'s (2004) study provided valuable information about ADHD children's performance on bimanual movements, as mentioned in Chapter 3, other important components of bimanual circling patterns have not been examined. For instance, when the movements are constrained by cranks, as in the Klimkeit et al.'s (2004) study, the hands are spatially constrained (i.e., locked in a perfect circle), greatly minimising the need for inhibitory control necessary to maintain spatial accuracy. As a result, spatial tradeoffs that may be used to compensate for timing error in a free-hand task are not permitted by the crank task. Thus, the necessity for correct timing between the hands is emphasised. By contrast, free-hand circle drawing tasks, requiring participants to trace carefully and continuously two model circles with the index fingers (e.g., Summers, Semjen, Carson, & Thomas, 1995), necessitate control of the limbs to constrain the movements spatially as well as temporally. Hence, it has yet to be determined whether children with ADHD perform worse than controls on bimanual circling patterns if spatial-temporal tradeoffs are permitted.

Since spatial and temporal components of bimanual circling have been shown to be tightly intertwined (Summers et al., 1995; Semjen, Summers, & Cattaert, 1995), measuring performance on tasks that are differentially sensitive to these components may help compare spatial and temporal skills in children with ADHD. Accordingly, the aim of this experiment was to decompose the motor coordination of children with ADHD by systematically measuring their spatial and temporal performance relative to age- and gender-matched controls on bimanual circling tasks, using both free-hand and constrained movements.

4.2. Hypotheses

4.2.1. Movement frequency.

Based on the timing deficits previously reported (e.g., Eliasson, Rösblad, & Forssberg, 2004; Klimkeit et al., 2004; Pitcher, Piek, & Barrett, 2002), it was expected that temporal coordination in children with ADHD would be impaired overall relative to Controls. Specifically, children with ADHD were expected to be less able than the controls to match the target frequencies paced by an auditory metronome. This between-group difference was expected to be emphasised at low frequency oscillations, since children with ADHD are more likely to be distractible with easier and less arousing tasks (Boerger & van der Meere, 2000; Scheres, Oosterlaan, & Sergeant, 2001).

4.2.2. Movement stability

Using the bimanual cranks, where the control of timing is necessary and the necessity to control spatial accuracy is minimised, it was hypothesised that children with ADHD would be less able than the controls to maintain temporal stability between the hands.

4.2.3. Spatial accuracy

It was also predicted that when the need for spatial control is increased by introducing free-hand patterns guided by circling templates, the ADHD group would show lesser ability on spatial performance than the Controls since there is some evidence showing gross motor task deficits in ADHD-C (Pitcher, Piek, & Hay, 2003).

4.2.4. Coordination mode complexity

With regards to the complexity of movement patterns, maintaining the symmetrical mode (denoted as in-phase henceforward) at high movement rates requires little attentional effort, whereas asymmetrical movements (denoted as anti-phase henceforward) are less stable and require continuous attention and inhibitory capacity to maintain the correct pattern (e.g., Semjen et al., 1995). Based on Bogaerts and Swinnen‘s (2001) proposition that difficult patterns necessitate the recruitment of inhibitory networks to prevent spontaneous phase transition, children with ADHD were expected

to show greater difficulties than the Controls in the anti-phase than in the in-phase coordination mode. This between-group difference was also expected to be greater at higher movement frequency, given the increased difficulty to stabilise rapid circling movements.

4.3. Method

4.3.1. Participants

In total, 31 boys aged 8-15 years participated in the study. Nineteen children (Mean age = 11 years 8 months) diagnosed with ADHD (ADHD-PI (N = 2), ADHD-HI (N = 2), ADHD-C (N = 15)) were recruited through private practice, public paediatric, a public child and adolescent mental health service, and via newspaper advertisement. All, including those recruited via newspaper advertisement, were professionally diagnosed by a child psychologist, child psychiatrist, or paediatrician. Attempts to identify comorbidity were made by consulting with referral agents on the child‘s condition. Subsequently, after consultation with parents, school counsellors and teachers, a short interview with the experimenter was used to determine the likelihood of comorbidity.

Twelve matched control boys (Mean age = 11 years 9 months) with similar socioeconomic backgrounds were recruited from a public and a private school in an attempt to match socioeconomic environments. However, given the difficulties encountered to recruit sufficient ADHD

participants, no attempt was made to match the groups on parent income and other socioeconomic criteria. There was no statistically significant difference between the age of children with and without ADHD, $F(1,29) = .014$, $p < .906$. In total, 27 children were right-handed and four (2 controls and 2 with ADHD) were left-handed.

The *ADHD Rating Scale-IV* (Dupaul, Power, Anastopoulos, & Reid, 1998), described below, was used as a screening device to insure that all children professionally diagnosed with ADHD conformed to the DSM-IV criteria for ADHD, and that control children did not present with any significant ADHD symptoms. Scorers were asked to rate the child's behaviour when the child is not medicated. Despite slight scoring differences between parents and teachers, none of the scores for the controls and all scores for children with ADHD fell in the clinical range of ADHD on the *ADHD Rating Scale-IV*. Table 4.1 shows ADHD symptomathology for each group.

Table 4.1. Mean and standard deviation (SD) of percentile scores for each group on the ADHD Rating Scale-IV. A high percentile score means more symptomathology.

	N	ADHD-PI	ADHD-HI	ADHD-C
Control	12	31 (29)	17 (22)	27 (25)
ADHD	19	96 (3)	97 (3)	97 (2)

Children with intellectual disability, a neurological disorder, a chronic or serious medical problem, hearing difficulty, psychosis, or a clinically significant mood or anxiety disorder were excluded. This was determined by interview with parents, teachers and clinical referrers. None of the children referred were identified with intellectual disability. If parents or teachers of a child in the control group reported that the child had motor-coordination problems, the child was excluded from the study. A motor problem was defined as general or specific coordination difficulties, such as writing, walking, running, catching a ball and general group sport activities etc. This was verified in consultation with the physical education teacher of the child.

All but one child with ADHD were medicated with stimulants. Some medicated children were tested during the school holiday and were not given medication at all throughout the holiday period. Others had their medication withdrawn on the day preceding participation (between 18 and 20 hours). This delay is appropriate since both methylphenidate and dexamphetamine take effect about one hour after administration and their effects last approximately five hours, ranging from three to six hours according to the child‘s metabolism and the break down at neurotransmitter level (Selikowitz, 1995; Wilens, Biederman, & Spencer, 2002), and rebound effects tend to arise 5 to 10 hours after stimulant medication has been taken (Jacobvitz, Sroufe, Stewart, & Leffert, 1990). One participant treated with a new, long acting, stimulant withdrew medication two days prior to testing.

One of the participants was given (short-acting) medication about 6 hours prior to testing, but the data were still included.

4.3.2. Apparatus

The *ADHD Rating Scale-IV* (Dupaul et al., 1998) is a self-report questionnaire with good validity and reliability consisting of 18 items which closely correspond to the 18 DSM-IV criteria (see sample and scoring sheet in Appendix B.1). It is able to discriminate the three DSM-IV subtypes of ADHD well. Either one or two questionnaires can be used, one reflecting the child‘s home behaviour (usually completed by a parent) and one reflecting the child‘s school behaviour (usually completed by the main teacher). For a diagnosis of ADHD on the DSM-IV, the symptoms of ADHD should not be restricted to a particular context. The child must display the symptoms in at least two out of the three following contexts: home, school and during the clinical interview with the clinician or assessor. Accordingly, to avoid the possibility of context specific symptomathology, both the parent questionnaire on home behaviour and the teacher questionnaire on classroom behaviour were sent to all parents and teachers. Handedness was confirmed with the *Edinburgh Handedness Inventory* (Oldfield, 1971) (see Appendix B.2).

A Northern Digital Optotrack 3020 3D Infrared Position Sensor was used to track and record an infrared light emitting diode (IRED) mounted on

the participant‘s index fingers, using a sampling rate of 200Hz. The 3D signals from each IRED were digitised in real time and stored as raw 3D coordinates, providing the spatial and temporal characteristics of the data.

To serve as circling models, two black circles (14 cm in diameter and set 21 cm apart centre to centre) drawn on an A3-sized laminated sheet of paper were fixed on a table surface facing the participant, positioned within comfortable forward reach and centred at the participant‘s midline, as displayed in Figure 4.1. Past studies using a bimanual circling task with adults tended to use a circle template with 10-cm diameter (e.g., Hiraga et al., 2004). However, it has been observed that movement amplitude during this task changes with age, with younger children making consistently larger circles than older children and adults (Rigenbach & Amazeen, 2005; Robertson, 2001). Accordingly, the size of the circles in this study was adapted to age of participants.

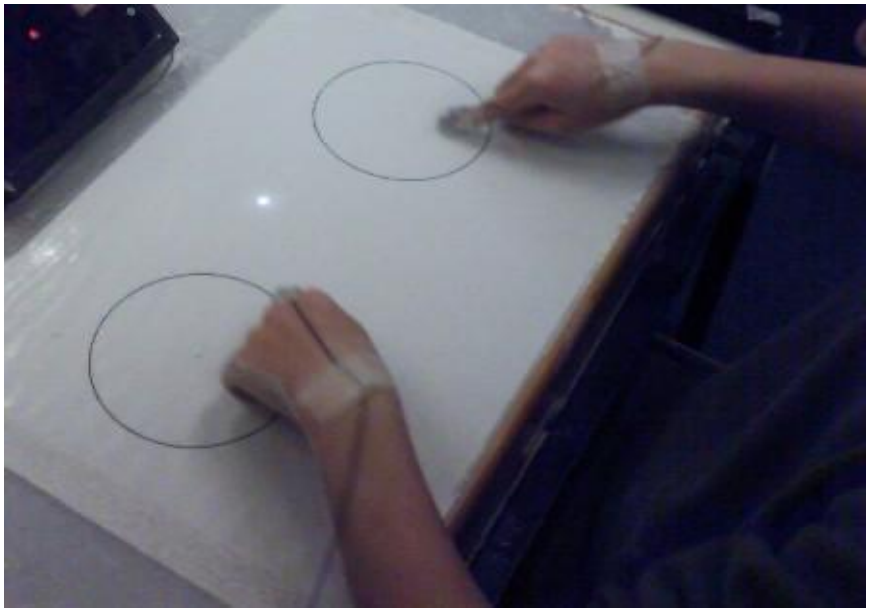

Figure 4.1. Circle templates used during the circling task. IREDs are mounted on the index finger of each hand.

Two bimanual cranks consisted of a pair of independently mounted wheels on the horizontal plane, 15 cm in diameter and set 21 cm apart centre to centre. Participants turned the cranks simultaneously by a pivoting T-shaped handle located 7 cm from the centre of each wheel. Both the circle template and the cranks were constructed in order to match postural requirements and the space between hands. A 2800 Hz computer-generated tone served as an auditory metronome to pace the movements.

4.3.3. Procedure

An information sheet (in Appendix A.1) was sent to the parents or legal guardians of the participants interested in participating. All participating children gave verbal consent and parents signed an informed consent form (in Appendix A.2) before being accepted into the study. When possible, the accompanying parent/guardian remained in the laboratory out of the child‘s sight during testing. After explanation of the procedure and implementation of inventories (as described above), each participant was comfortably seated at a table with a horizontal work plane and given identical tasks and instructions. All participants performed two movement types (free-hand with template and constrained with cranks), counterbalanced for order effects. As displayed in Figure 4.2, they were asked to perform bimanual patterns in two coordination modes: in-phase (left hand circling clockwise and right hand anticlockwise) and anti-phase (both hands circling anticlockwise). In the template conditions, the participants were asked to trace continuously the contour of the model circles with the index fingertips. In the crank conditions, they performed circular movements in the same directions holding a crank handle in each hand.

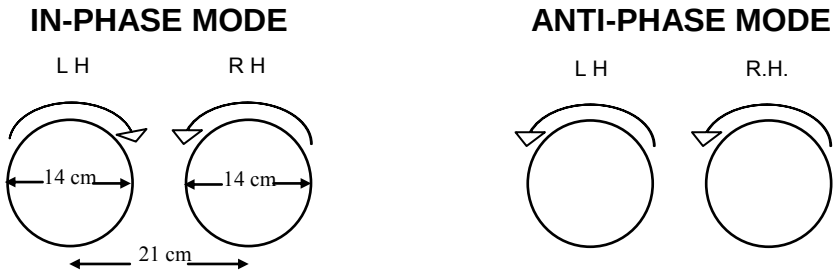

Figure 4.2. Schematic of the in-phase and anti-phase modes of bimanual coordination during circling task with both circle the template and the cranks. LH = left hand, RH = right hand.

As in Klimkeit et al. (2004), two movement frequencies were used. However, since fixed target frequencies are likely to constitute an extraneous variable, the present study followed the protocols typically used in studies of bimanual coordination to control for individual differences. Hence, one movement rate corresponded to the frequency just below phase transition (―critical"), that is, just below the point where anti-phase patterns tend to become unstable and qualitatively switch back to in-phase mode, whereas the other corresponded to a lower, more comfortable, frequency (―2/3-critical") where both in-phase and anti-phase patterns are stable. These are hereafter defined as ―high" and ―low" frequencies.

Determining individual frequencies. Each frequency was predetermined for each participant and for each task (template and crank) at the start of each session using a staircase procedure. This was done by first increasing the rate of bimanual movements (performed in the anti-phase direction) from each participant‘s preferred frequency by 0.25 Hz from a starting frequency that was most comfortable until the child was unable to perform the pattern anymore (e.g., moving in a straight line in any direction, stopping, etc), or until at least one involuntary transition to the in-phase mode occurred (see Carson et al., 1997, for detailed mechanisms underlying involuntary phase transition in circling tasks). Fine-tuning was subsequently achieved by decreasing or increasing movement rate by 0.1 Hz. The individualised movement frequency was kept constant throughout each trial and participants were asked to follow the pacing tone of the metronome while focusing on their hands and complete one full circle per tone.

Each condition included five consecutive 20-second trials, each of which was interspaced with a 20-second rest interval. To avoid possible fatigue, participants were given additional breaks as frequently as necessary. All conditions were counterbalanced for order effects. Testing was conducted over two separate sessions, each lasting approximately 50 minutes.

4.3.4. Data reduction and dependent measures

Frequency deviation. A custom peak-picking algorithm was used to estimate movement frequency for each hand. Absolute deviation of movement frequency from the target frequency was used as a measure of the timing accuracy with which participants were able to maintain the required movement.

Relative Tangential Angle (RTA). Data were low-pass filtered using a second-order Butterworth dual-pass filter with a cut-off frequency of 5 Hz. Continuous tangential angles for each limb were then derived from the normalised displacement time series and applying the two-point central difference algorithm. The magnitude of each vector corresponded to the instantaneous tangential velocity, and the angle of the vector was the tangential angle. Relative Tangential Angle (RTA) was determined by subtracting the angle of one hand from the other. This measure provides in degrees the lead-lag time of one limb in relation to the other in their respective movement cycles, with a value of 0 indicating perfect synchronisation between the hands. Absolute error of RTA (AE-RTA) was used as a measure of performance accuracy.

Variability of RTA. The standard deviation of RTA (SD-RTA) was used as a measure of variability, which determines the temporal stability between the hands. It is the dispersion of the relative tangential angle, which is traditionally calculated based on Mardia‘s (1972) circular variability

methodology. Small dispersion of the RTA gives a value close to 1 (i.e., less variable), while the maximum dispersion is indicated by a value of 0 (i.e., more variable). The circular variance was transformed to the range 0-∞, permitting the use of inferential statistics based on standard normal theory, expressed in the following form:

$$\text{SD-RTA} = [(-2 \cdot \ln(r))^{1/2}] \cdot 180/\pi$$

where *r* is the measure of dispersion in the range 0-1 and SD-RTA is the transformed dispersion (Matthews, Garry, Martin, & Summers, 2006), providing the standard deviation of RTA, a measure of variability in degrees.

Aspect Ratio. Aspect ratio (AR), a measure of the circularity of movement trajectories produced by each hand, was a measure of the spatial dimension of free-hand circling movements during the template task. AR was calculated following the procedure described by Walters and Carson (1997). An index of circularity was derived from the ratio of the lengths of the major and minor axes of the best fitting ellipse for each movement cycle. An aspect ratio of 1 indicates a perfect circle (high spatial accuracy) and an aspect ratio of 0 indicates a straight line (low spatial accuracy). Aspect ratio values were subjected to arc sine transformation prior to statistical analysis.

4.3.5. Design and analysis

A 2 (Group) × 2 (Task) × 2 (Mode) × 2 (Frequency) repeated measures design was used for the analyses of temporal data, and a 2 (Group) × 2 (Mode) × 2 (Frequency) × 2 (Hand) repeated measures design was used for the analyses of spatial data. For the temporal data, the independent variables were Group (Control and ADHD), Task (template and crank), Mode (in-phase and anti-phase), and Frequency (high and low). For the spatial data, the independent variables were Group (Control and ADHD), Mode (in-phase and anti-phase), Frequency (high and low) and Hand (dominant and non-dominant). The Task variable was not included in the spatial measurements because measuring spatial accuracy on hands that are spatially constrained by the crank would be expected to reflect a near-to-perfect circle in all participants. The dependent variables were AE-RTA, SD-RTA, Frequency Deviation, and AR. Huynh-Feldt epsilon corrections were applied, where appropriate, to the degrees of freedom for *F* tests to compensate for violation of homogeneity assumptions. Post-Hoc analyses of interactions between factors were analysed with Tukey HSD. Alpha level was set at .05 to indicate statistical differences between means. Effect size statistics were calculated with Partial eta-squared, which was described as per Cohen‘s (1988) guidelines (0.01= small effect, 0.06 = moderate effect, and 0.14 = large effect).

4.4. Results

4.4.1. Frequency data

Individualised frequencies. As mentioned earlier, critical (high) frequency was calculated individually in Hz. Based on previous bimanual circling studies, low frequency for each participant was calculated as 2/3 of their high frequency (e.g., Carson et al., 1997). In the ADHD group, high frequencies ranged from 1.35 – 2.1 Hz in the crank condition and 1.1 – 2.1 Hz in the template condition. In the Control group, high frequency ranged from 0.9 – 2.2 Hz in the crank condition and 1 – 2.4 Hz in the Template condition.

The difference between each group‘s high frequency on each task was analysed with a 2 (Group) × 2 (Task) repeated measures ANOVA. There was no main effect for Group (M_{ADHD} = 1.73, SE = 0.07; $M_{Control}$ = 1.68, SE = 0.09; $F(1,29) = .151$, $p = .7$) and no main effect for Task (M_{crank} = 1.7, SE = 0.05; $M_{template}$ = 1.7, SE = 0.06; $F(1,29) = .003$, $p = .954$). A significant interaction emerged between Group and Task, $F(1,29) = 5.103$, $p = .032$, with a large effect size (Partial eta-squared = 0.15). As displayed in Figure 4.3, the two groups displayed opposite trends showing little group difference in movement frequency with templates but on the crank task the ADHD group performed faster movements than the Control group.

However, none of the post-hoc comparisons with Tukey HSD set at the .05 alpha level reached statistical significance with template (M_{ADHD} = 1.69, SE = 0.08; $M_{Control}$ = 1.72, SE = 0.1) or crank (M_{ADHD} = 1.76, SE = 0.07; $M_{Control}$ = 1.65, SE = 0.08).

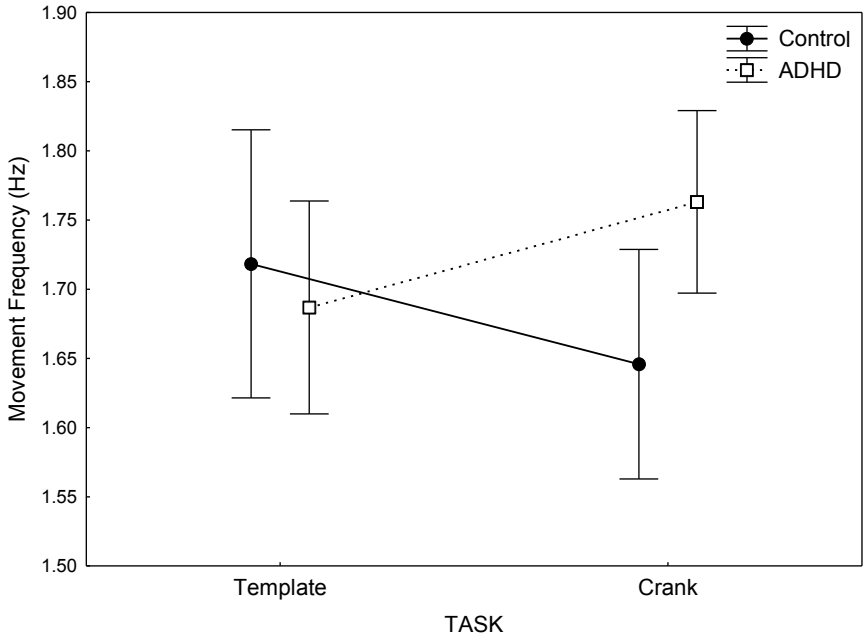

Figure 4.3. Mean for individualised movement frequencies on crank and template tasks for the ADHD and Control groups at high frequency. Vertical bars denote the standard error.

Frequency deviation. A 2 (Group) × 2 (Task) × 2 (Mode) × 2 (Frequency) repeated measures ANOVA showed a main effect of Group, $F(1,23) = 5.909$, $p = .023$, where the overall deviation from the required

frequency was significantly greater in the ADHD group (M = 0.15, SE = 0.02) than in the Control group (M = 0.06, SE = 0.03). Effect size statistics showed a large difference between group means (Partial eta-squared = 0.2). There was no main effect of Task, $F(1,23) = 0.579$, $p = .454$, or Mode, $F(1,23) = 0.571$, $p = .457$.

There was a significant Group × Task interaction, $F(1,23) = 6.577$, $p = .017$, with a large effect size (Partial eta-squared = 0.22), as represented in Figure 4.4. Post-hoc comparisons using Tukey HSD showed that

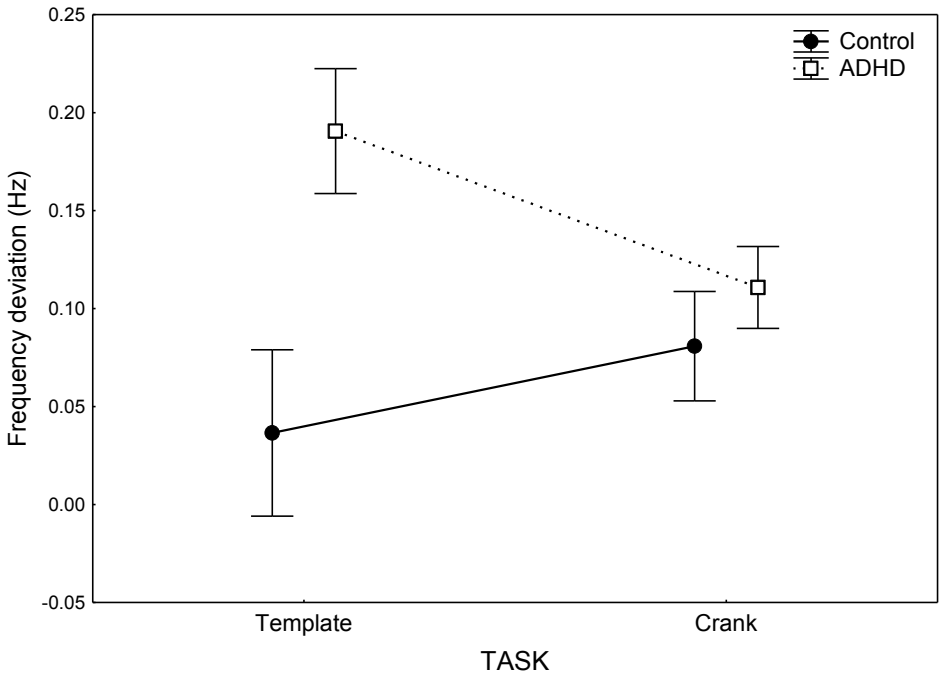

Figure 4.4. Means for absolute deviation from target frequencies (in Hz) for the ADHD and Control groups. High and Low frequencies are combined. Vertical bars denote the standard error.

movement frequency in the ADHD group was less accurate on the template (M = 0.19, SE = 0.03) than on the crank task (M = 0.11, SE = 0.02) (p = .052), whereas the Controls' performance did not differ significantly between tasks (M_{crank} = 0.08, SE = 0.03; M_{template}= 0.04, SE = 0.04) (p = .667). When comparing groups on each task, the ADHD group performed significantly poorer during the template task than did the Control group (p = .007). The groups did not differ on the crank task (p = .909).

There was also an interaction of Task and Frequency, $F(1,23)$ = 4.009, p = .057, displayed in Figure 4.5. The interaction did not reach the .05 conventional significance but the effect size was large (Partial eta-squared = 0.15). To explore the effect of Task in the presence of this trend, the effect of template and crank were explored separately. Post-hoc comparisons with Tukey HSD showed that on the crank task, both groups were more accurate at low frequency (M = 0.08, SE = 0.02) than at high frequency (M = 0.11, SE = 0.02) (p = .052), whereas on the template task, frequency deviation did not differ across high and low movement frequencies (M_{low} = 0.12, SE = 0.03; M_{high} = 0.11, SD = 0.03) (p = .94). Moreover, performance at low frequency was significantly better on the crank than on template task (p = .002), but there was no difference between tasks at high frequency (p = .798).

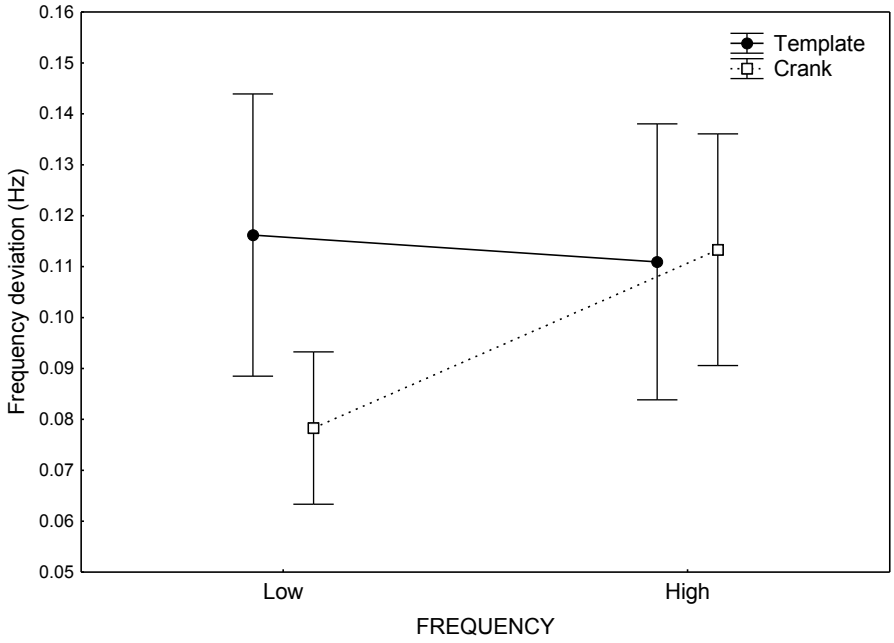

Figure 4.5. Mean Absolute deviation from target frequencies (in Hz) collapsed across Group and Mode. Vertical bars denote the standard error.

4.4.2. Absolute Error of RTA

A 2 (Group) × 2 (Task) × 2 (Mode) × 2 (Frequency) repeated measures ANOVA showed a main effect of Mode, $F(1,29) = 29.864$, $p < .0001$. The very large size of the effect (Partial eta-squared = 0.51) showed that both groups' performance accuracy was much greater with the in-phase ($M = 10.78^{o}$, $SE = 1.5$) than with the anti-phase ($M = 22.31^{o}$, $SE = 2.58$) mode of coordination. There was also a main effect of Frequency, $F(1,29) = 14.403$, $p = .001$, with a large effect size (Partial eta-squared = 0.33), indicating that

both groups‘ performance accuracy was significantly greater when moving at low frequency (M = 13.24^{o}, SE = 1.7) than at high frequency (M = 19.85^{o}, SE = 2.3).

There was no main effect of Task (M_{crank} = 17.56^{o}, SE = 2.25; $M_{template}$ = 15.53^{o}, SE = 1.85), F(1,29) = 1.122, p = .298. There was no main effect of Group (M_{ADHD} = 17.15^{o}, SE = 2.27; $M_{Controls}$ = 15.95^{o}, SE = 2.86), F(1,29) = .108, p = .745, or interaction with Group. The lack of between group differences in AE-RTA indicated that children with and without ADHD were similarly able to maintain the coordination pattern accuracy (i.e., the lead-lag between hands was not statistically different between the groups).

There was a Task × Mode interaction, F(1,29) = 4.569, p = .041, and a Task × Frequency interaction, F(1,29) = 10.943, p = .003. These were described in the context of a Task × Mode × Frequency interaction, F(1,29) = 4.884, p = .035, of which the effect size was large (Partial eta squared = 0.14). The three-way interaction is represented in Figure 4.6. At low frequency, performance accuracy was greater with in-phase than anti-phase patterns and in the template condition than in the crank condition. At high frequency, performance accuracy was greater in the crank condition, but only in the more complex (anti-phase) mode of coordination.

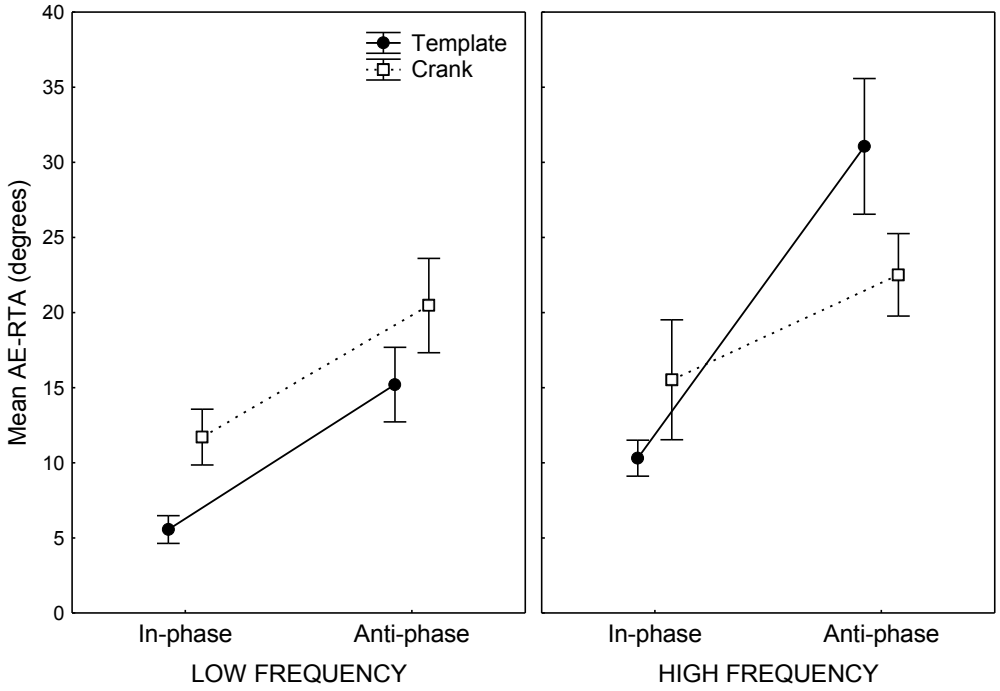

Figure 4.6. Mean Absolute Error of RTA (in degrees) for the ADHD and Control groups. Greater values represent greater lead-lag between the hands. Vertical bars denote the standard error.

Post-hoc comparisons with Tukey HSD are first described at low frequency. Although the means did not reach the .05 statistical significance, the mean performance accuracy using cranks was marginally better in the in-phase mode (M = 11.72^{o}, SE = 1.86) than in the anti-phase mode (M = 20.50^{o}, SE = 3.14) (p = .064). Similarly, performance accuracy in the template condition was significantly better in the in-phase mode (M = 5.56^{o}, SE = 0.93) than in the anti-phase mode (M = 15.21^{o}, SE = 2.49) (p = .03). At

high frequency, performance accuracy was significantly better in the template condition when circling in-phase ($M = 10.31^{o}$, $SE = 1.2$) than when circling anti-phase ($M = 31.06^{o}$, $SE = 4.52$) ($p = .0001$), but performance using the cranks did not change significantly across Modes ($M_{\text{in-phase}} = 15.53^{o}$, $SE = 3.99$; $M_{\text{anti-phase}} = 22.52^{o}$, $SE = 2.74$; $p = .461$). There was no significant performance difference between cranks and templates when circling in-phase ($p = 0.419$) and only a trend in the anti-phase mode ($p = .067$) at low frequency, nor in-phase at high frequency ($p = .461$). However, performance at high frequency in the anti-phase mode was significantly better with the cranks than with the templates ($p = .031$).

When comparing performance on each coordination mode across frequencies, performance accuracy was significantly better when circling anti-phase at low than at high frequency in the template condition ($p = .0002$), but not in the crank condition ($p = .999$; means and *SE*s are already reported above). When circling in-phase, there was no performance difference on either crank ($p = .781$) or template ($p = .742$) between the low and high frequencies (means and *SD*s are already reported above).

4.4.3. Variability of RTA.

Movement stability, as measured by the standard deviation of RTA (SD-RTA), was analysed with a 2 (Group) × 2 (Task) × 2 (Mode) × 2 (Frequency) repeated measures ANOVA. There was a significant main

effect of Task, $F(1,29) = 75.312$ $p < .0001$, showing that movement stability was significantly greater in the template condition ($M = 18.62^{o}$, $SE = 1.27$) than in the crank condition ($M = 29.69^{o}$, $SE = 2.19$). The size of the effect was very large (Partial eta-squared = 0.72). There was a main effect of Mode, $F(1,29) = 89.576$, $p < .0001$, showing that movement stability was also greater in the in-phase mode ($M = 19.98^{o}$, $SE = 1.46$) than in the anti-phase mode ($M = 28.33^{o}$, $SE = 1.96$). The effect size was also very large (Partial eta-squared = 0.76). Moreover, a main effect of Frequency, $F(1,29) = 27.463$, $p < .0001$, showed that the stability of the movement was greater when circling at low frequency ($M = 21.95^{o}$, $SE = 1.64$) than at high frequency ($M = 26.35^{o}$, $SE = 1.81$). The effect size was slightly smaller than with Task and Phase, but remained very large (Partial eta-squared = 0.49). Overall, movement stability was greater when circling with the template, in the in-phase mode and at low frequency. There was also a trend for Group, $F(1,29) = 3.531$, $p = .07$, with a moderate effect size (Partial eta-squared = 0.11) showing a better performance by the Control group ($M = 21.01^{o}$, $SE = 2.62$) than the ADHD group ($M = 27.3^{o}$, $SE = 2.08$).

There was an interaction of Group × Mode, $F(1,29) = 4.288$, $p = .047$, with a moderate effect size (Partial eta-squared = 0.13). The two-way interaction, displayed in Figure 4.7, shows that although movements were less stable in the anti-phase than in the in-phase mode for both groups, stability reduced in the anti-phase mode to greater extent in the ADHD group than in the Control group.

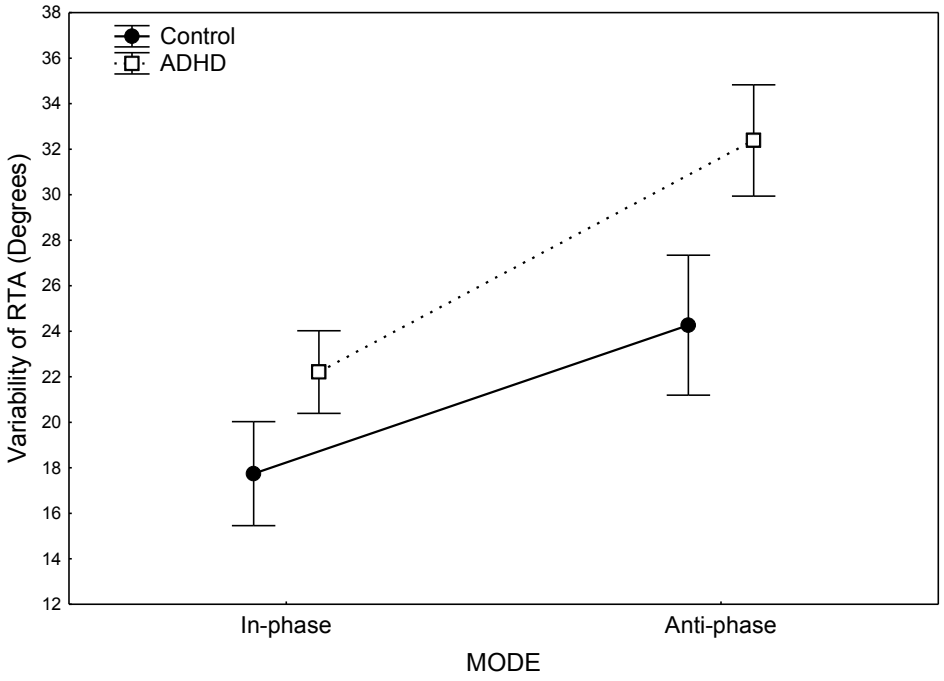

Figure 4.7. Variability of RTA (in degrees) for the ADHD and Control groups. A high variability value represents less stability. Vertical bars denote the standard error.

Post-hoc comparisons with Tukey HSD indicated that movement stability in the ADHD group was greater in the in-phase mode ($M = 22.21^{o}$, $SE = 1.82$) than in the anti-phase mode ($M = 32.36^{o}$, $SE = 2.46$) ($p = .0002$). Similarly, in the Control croup, stability of movements was significantly greater in the in-phase mode ($M = 17.74^{o}$, $SE = 2.28$ than in the anti-phase mode ($M = 24.27^{o}$, $SE = 3.08$) ($p = .0004$). However, there were no statistically significant differences between the performance of the ADHD

and the Control groups in both the in-phase mode (p = .576) or anti-phase mode (p = .108).

Finally, there was a significant three-way interaction between Task, Mode and Frequency, $F(1, 29) = 6.213$, p = .019, with a moderate effect size (Partial eta-squared = 0.13), as depicted in Figure 4.8. Overall, movement stability was greater in the template than in the crank condition, but the size of the difference changed across frequencies. Compared with low frequency, the difference between template and crank at high frequency was larger in the in-phase mode and smaller in the anti phase mode.

Post-hoc comparisons with Tukey HSD at low frequency indicated that, movements using the templates were significantly more stable in the in-phase mode (M = 11.79^{o}, SE = 0.45) than in the anti-phase mode (M = 20.82^{o}, SE = 1.71) (p = .0001). Movements using the cranks were also significantly more stable in the in-phase mode (M = 24.41^{o}, SE = 2.21) than in the anti-phase mode (M = 30.77^{o}, SE = 2.75) (p = .0007). Moreover, in both the in-phase and anti-phase modes, stability was significantly greater in the template condition than in the crank condition (both ps = .0001).

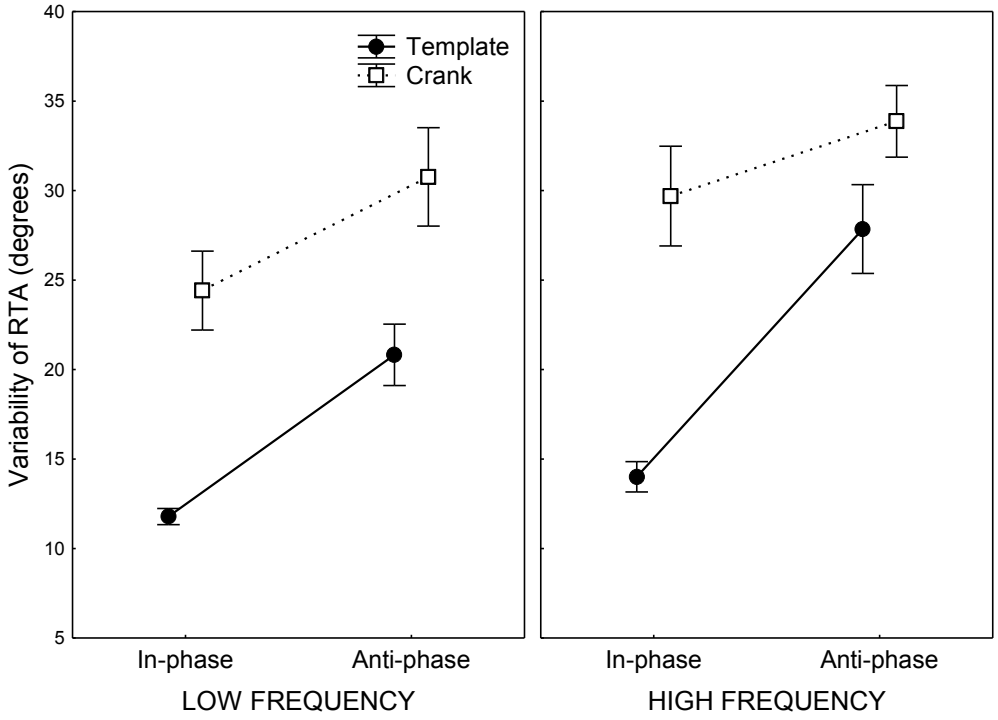

Figure 4.8. Mean Variability of RTA for all participants. High variability represents less stability. Vertical bars denote the standard error.

Comparisons at high frequency indicated that, movements using templates were also significantly more stable in the in-phase mode (M = 14.01^{o}, SE = 0.84) than in the anti-phase mode (M = 27.85^{o}, SE = 2.48) (p = .0001). However, movements using cranks were only marginally more stable in the in-phase mode (M = 29.69^{o}, SE = 2.79) than in the anti-phase mode (M = 33.87^{o}, SE = 2) (p = .065). Moreover, in both the in-phase and anti-phase modes, stability was significantly greater in the template condition than in the crank condition ($p_{in\text{-}phase}$ = .0001; $p_{anti\text{-}phase}$ = .002).

4.4.4. Aspect Ratio

Aspect Ratio (AR), as mentioned earlier, is a measure of the circularity of movement trajectory, where an AR of 1 approximates a perfect circle whereas and AR of 0 approximates a straight line. AR, therefore, provides an index of spatial accuracy, with greater values reflecting greater accuracy of movement. AR was analysed with a 2 (Group) × 2 (Mode) × 2 (Frequency) × 2 (Hand [non-dominant and dominant]) repeated measures ANOVA.

There was a main effect of Group, $F(1,29) = 4.654$, $p = .039$, where the overall spatial accuracy of movements was significantly greater in the Control group ($M = 0.84$, $SE = 0.02$) than in the ADHD group ($M = 0.79$, $SE = 0.02$). Effect size statistics shows a large difference between group means (Partial eta-squared = 0.14). A main effect of Frequency, $F(1,29) = 22.511$, $p < .0001$, with a very large effect size (Partial eta-squared = 0.44), showed that spatial accuracy was significantly greater at low frequency ($M = 0.83$, $SE = 0.01$) than at high frequency ($M = 0.79$, $SD = 0.01$). There was also a main effect of Hand, $F(1,29) = 5.99$, $p = .021$, with a large effect size (Partial eta-squared = 0.17), indicating that spatial accuracy was greater with the dominant hand ($M = 0.83$, $SE = 0.01$) than with the non-dominant hand ($M = 0.80$, $SD = 0.02$). There was no main effect of Mode, ($M_{\text{in-phase}} = 0.82$, $SE = 0.01$; $M_{\text{anti-phase}} = 0.81$, $SE = 0.01$; $F(1,29) = .2.832$, $p = .103$. There was a non-significant interaction of Group × Mode × Hand, $F(1,29) =$

2.975, p = .095. In summary, spatial accuracy was greater in the Control group, at low frequency and with the dominant hand.

4.4.5. Summary of results

The analysis of individually determined critical frequencies revealed that the ability to maintain the movement pattern at high movement rates in children with ADHD was not overall poorer than that of matched controls. Whereas movement frequency in both groups was comparable when circling with the templates, children with ADHD were notably faster than the controls on the crank task.

The ability to match the required frequency was poorer in the ADHD group than in the controls when using the templates, but timing error did not differ between the groups when using the cranks. However, the ability of ADHD children to match the required frequency was not significantly affected by the movement rate required; high or low.

In terms of movement accuracy, as measured by the lead-lag between the hands, the results show no group differences or interaction with Group. However, when using the circling templates, the ADHD group exhibited poorer spatial accuracy than the controls. There was a trend showing that movement stability in the ADHD group was poorer during more complex tasks. The type of task was a better predictor of impairment in ADHD than coordination mode and frequency.

4.5. Controlling for comorbidity

4.5.1. Rationale for a Re-analysis with 3 groups

Recently, an increasing number of studies have shown that the motor impairment in children diagnosed with ADHD may be better attributed to another disorder, classified by the DSM-IV as Developmental Coordination Disorder (DCD) (e.g., Miyahara, Möbs, & Doll-Tepper, 2001; Miyahara et al., 2006; Piek et al., 2007; Sergeant et al., 2006). Piek and colleagues (e.g., Pitcher et al., 2002) have shown the problem of undiagnosed comorbidity with DCD and confounding diagnosis criteria in the DSM-IV. For instance, the DSM-IV criteria for DCD include:

1. Performance on daily motor activities is substantially below expected performance given the person‘s chronological age and measured intelligence. There can be marked delays in achieving major milestones.

2. The coordination problems interfere with academic achievements or activities in daily living

To clarify the difference between ADHD and DCD, the DSM-IV stipulates that ―Individuals with ADHD may fall, bump into things, or knock things over, but this is usually due to distractibility and impulsiveness, rather than to a motor impairment. If criteria for both disorders are met, both diagnoses can be given” (DSM-IV-TR, 2000, p. 57).

One of the problems with this criterion is that it merely provides an aetiological differentiation and this differentiation cannot be directly

observed by the assessor, let alone be measured. An additional difficulty in differentiating the two is the ambiguity of the statement: "…usually due to distractibility…". For assessors and clinicians, this precision does not provide any reliable basis on which to decide whether a particular child's motor impairment has been due to motor impairment or ADHD symptoms. For example, discussions with 11 child psychologist colleagues revealed that none of them had diagnosed an ADHD child with comorbid DCD in the last 3 years.

One of the major issues is the difference in treatments chosen for ADHD-PI and for DCD, which can also include difficulties with paying attention due to the physical discomfort DCD children experience and the supplementary effort they must generate to maintain ordinary motor functioning (Visser, 2003; see also Geuze, Jongmans, Schoemaker, & Smits-Engelsman, 2001, for a comprehensive discussion of diagnostic issues). Although the topic of treatment is beyond the scope of this research, it seems important to note that whereas stimulant medication may be appropriate for ADHD-PI, it is not appropriate for DCD. Hence, there are several reasons to suggest that the comorbidity of DCD and ADHD should be taken into account in the present research. It was, therefore, decided to re-analyse the entire set of data from this experiment, to identify the possible presence of DCD comorbidity in the sample.

4.5.2. Re-grouping participants

Since the children in this study had already been tested on two occasions in the lab and only few of them (or their parents) were willing to return for further assessment, it was decided to send a parent-rated questionnaire to screen for DCD symptomathology. The *Developmental Coordination Disorder Questionnaire* (DCDQ; Wilson, Kaplan, Crawford, Campbell, & Dewey, 2000) was used. The DCDQ consists of 17 items rated on a 5-point Likert scale and clustered into four scales: Control During Movement, Fine Motor / Hand Drawing, Gross Motor / Planning, General Coordination, and a Total Score (see sample questionnaire and scoring sheet in Appendix B.3). If the total raw score falls within a range of 58-85, the respondent scores between the 26th and the 100th percentile. This means that, according to the rater‘s observations, the child‘s motor performance is similar to about 26% to 100% of children in his or her age group and that the child is labelled as ―probably not DCD”. If the total raw score falls within a range of 49-57, the respondent scores between the 11th and the 25th percentile, attracting the label ―suspect DCD”. If the total raw score falls within a range of 0-48, the respondent scores between 0 and the 10th percentile, labelled as ―indication of DCD”. Studies have shown that the DCDQ is a valid and reliable instrument, capable of distinguishing children with and without motor difficulties (Crawford, Wilson, & Dewey, 2001; Wilson et al., 2000). It is a sensitive screening instrument to detect DCD in children at risk of motor coordination impairment (Schoemaker, et al., 2006); the overall sensitivity

is 84.6% and specificity 70.8%.

Once the questionnaires were returned and the data computed, the ADHD group was divided into two groups, an ADHD group without DCD (N = 12) and an ADHD group with motor dysfunction (N = 6), denoted hereafter by "ADHD/DCD". All children in the ADHD and the ADHD/DCD groups fit the criteria for ADHD-C (Combined type). The scores on the DCDQ for each group are summarised in Table 4.2.

All children in the Control group scored above the 10th percentile on the DCDQ. Children with ADHD whose total score was above the 10th percentile were in the ADHD group. Children with ADHD whose total score was at or below the 10th percentile were in the ADHD/DCD group. The DCDQ percentile score for one of the Control participants was at the 4th percentile, which fits the criteria for DCD, but his percentile scores on ADHD symptomathology were insufficiently high to fulfil the requirements for ADHD diagnosis (ADHD-PI = 80; ADHD-HI = 50; ADHD-C = 80). The entire data set for this participant was removed from the study, so that comparisons could be restricted to the Control, ADHD and ADHD/DCD groups.

Table 4.2. Mean Total, standard deviation (SD), and range on the DCDQ for the control, ADHD and ADHD/DCD groups. A low mean score represents more impairment.

	N	Mean	SD	Range
Control	12	70.83	9.61	55-84
ADHD	12	59.75	8.16	50-78
ADHD/DCD	6	38.50	4.97	31-44

The main hypothesis was that the performance of children in the ADHD/DCD group would be worse than that of children in the ADHD and Control groups overall. This group difference was expected to be more pronounced on the most complex motor coordination tasks (anti-phase patterns and high frequency).

4.6. Results

To avoid repetitions and redundant information, this results section will only include significant effects involving Group as a factor. Note also that some of the means reported in the first results section may not match exactly those in this results section (when they should) because the data set of one participant (with DCD) has been excluded in this second analysis. Moreover, given the small *N* for the ADHD/DCD group (*N* = 6), the discussion of these results will emphasise effect sizes rather than relying as

heavily on the statistical significance of the potential effects.

4.6.1. Frequency data

Individualised frequency. The mean high frequency for each group appears in Figure 10.9. As mentioned in the previous results section, low frequency for each participant was calculated as 2/3 of their high (critical) frequency. In the Control group, high frequency ranged 1 – 2.4 Hz in the template condition and 0.9 – 2.2 Hz in the crank condition. In the ADHD group, high frequency ranged 1.3 – 2.1 Hz in the template condition and 1.4 – 2.1 Hz in the crank condition. In the ADHD/DCD group, high frequency ranged 1.1 – 2 Hz in the template condition and 1.5 – 2.1 Hz in the crank condition.

The difference between each group‘s high frequency on each task was analysed with a 3 (Group) × 2 (Task) repeated measures ANOVA. There was no statistically significant main effects for Group ($M_{control}$ = 1.72, SE = 0.09; M_{ADHD} = 1.75, SE = 0.09; $M_{ADHD/DCD}$ = 1.65, SE = 0.12), $F(2,27)$ = .256, p = .776, or Task ($M_{template}$ = 1.68, SE = 0.06; M_{crank} = 1.73, SE = 0.06), $F(2,27)$ = 1.728, p = .2. Effect sizes for each factor was very low (Partial eta-squared for Group = 0.02, and for Task = 0.06).

There was a non-statistically significant interaction of Group × Task, $F(2,27)$ = 2.783, p = .08, reported because of its large effect size (Partial eta-squared = 0.17) and theoretical significance. As represented in Figure 4.9,

the interaction shows that compared to the movement frequency of the Control and ADHD groups, movement frequency in the ADHD/DCD group on the template task was slower. However, the frequency of the three groups did not seem to differ on the crank task. None of the post-hoc comparisons with Tukey HSD resulted in statistically significant differences.

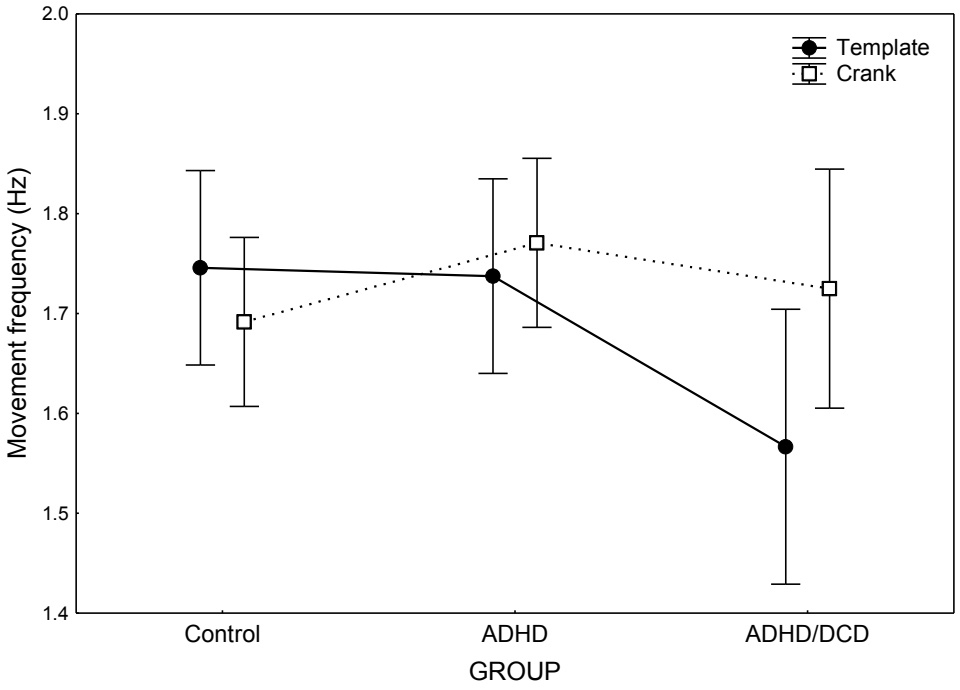

Figure 4.9. Individualised movement frequencies on crank and template tasks for the Control, ADHD and ADHD/DCD groups at high frequency. Vertical bars denote the standard error.

Frequency deviation. A 3 (Group) × 2 (Task) × 2 (Mode) × 2 (Frequency) repeated measures ANOVA showed no main effect of Group ($M_{Control}$ = 0.07, SE = 0.03; M_{ADHD} = 0.14, SE = 0.03; $M_{ADHD/DCD}$ = 0.16, SE = 0.04), $F(2,22) = 2.38$, $p = .116$. There was no main effect of Mode ($M_{in\text{-}phase}$ = 0.12, SE = 0.02; $M_{anti\text{-}phase}$ = 0.13, SE = 0.02), $F(1,22) = 0.59$, $p = .45$, or Task ($M_{template}$ = 0.15, SE = 0.03; M_{crank} = 0.1, SE = 0.02), $F(1,22) = 3.023$, $p = .096$. However, the effect size for Group was large (Partial eta-squared for Group = 0.18). Effect size for Task was moderate (Partial eta-squared = 0.12) and very small for Mode (Partial eta-squared = 0.03). There was no interaction involving group as a factor.

4.6.2. Absolute Error of RTA

A 3 (Group) × 2 (Task) × 2 (Mode) × 2 (Frequency) repeated measures ANOVA showed main effects of Mode and Frequency, as previous reported in the first Results section, but no main effect of Group ($M_{\text{control}} = 16.87^{o}$, SE = 2.95; $M_{\text{ADHD}} = 15.74^{o}$, SE = 2.95; $M_{\text{ADHD/DCD}} = 17.85^{o}$, SE = 4.18), $F(2,27) = .091$, $p = .913$, (Partial eta-squared = .007) or interaction with Group. The lack of between group differences in AE-RTA indicated that children in the three groups were similarly able to maintain the coordination pattern accuracy.

4.6.3. Variability of RTA

Movement stability, as calculated with the standard deviation of RTA (SD-RTA), was re-analysed with a 3 (Group) × 2 (Task) × 2 (Mode) × 2 (Frequency) repeated measures ANOVA. A significant main effect was obtained for each of the four factors. The main effect of Group, $F(2,27) = 3.588$, $p = .042$, showed that movement stability in the Control group ($M = 21.47^{o}$, $SE = 2.54$) was significantly greater than in the ADHD/DCD group ($M = 33.21^{o}$, $SE = 3.6$) ($p = .033$), as calculated with Tukey HSD post-hoc test. Stability did not differ significantly between the Control group and the ADHD group ($M = 24.51^{o}$, $SE = 2.54$) ($p = .679$), or between the ADHD and the ADHD/DCD groups ($p = .138$). The size of the effect was large (Partial eta-squared = 0.21). The main effects of Task, Mode and Frequency have already been reported in the first Results section, showing that the stability of the movement was overall greater when circling with the template, in the in-phase mode and at low frequency.

There was a four-way interaction of Group × Task × Mode × Frequency, $F(2, 27) = 5.214$, $p = .012$, with a large effect size (Partial eta-squared = 0.28). To ease interpretation, it will be described in the context of two three-way interactions.

One of the three-way interactions, represented in Figure 4.10, was between Group, Mode and Frequency, $F(2, 27) = 3.592$, $p = .041$. The effect size was large (Partial eta-squared = 0.21). Stability for the Control and

ADHD groups was overall greater in the in-phase mode and at low frequency, but the (poorer) stability of ADHD/DCD group was just as impaired at both frequencies.

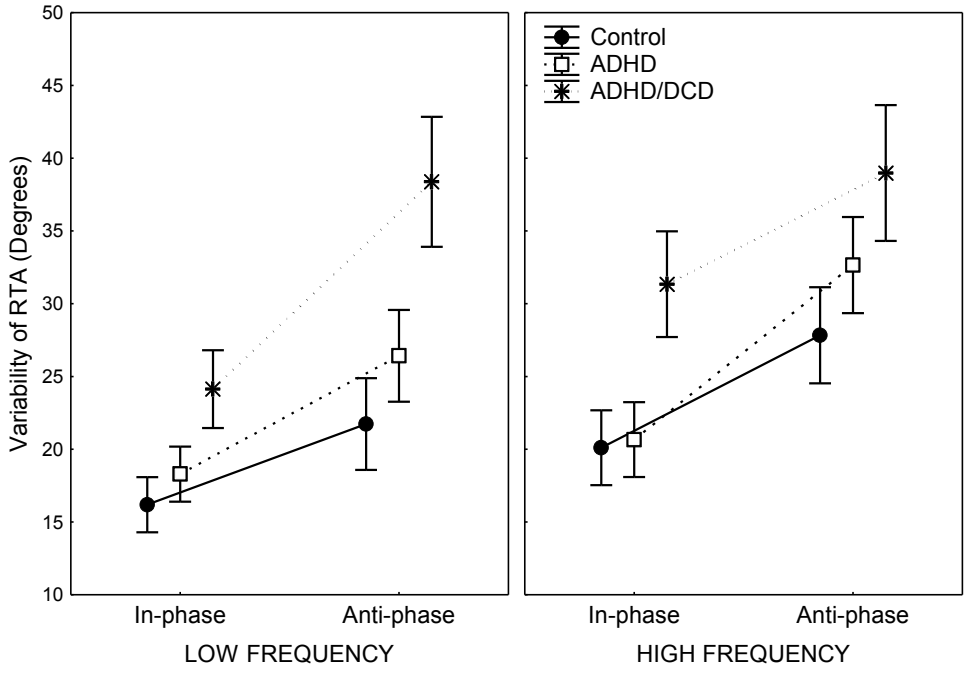

Figure 4.10. Variability of RTA (in degrees) for the three groups across modes and frequencies; where greater variability of RTA represents poorer movement stability. Vertical bars denote the standard error.

Post-hoc comparisons with Tukey HSD were first calculated at low frequency. Movement stability was marginally greater in the in-phase mode ($M = 16.19^{o}$, $SE = 1.89$) than in the anti-phase mode ($M = 21.73^{o}$, $SE = 3.16$)

for the Control group (p = .075). Significant differences in the same direction between coordination modes were also obtained for the ADHD group ($M_{\text{in-phase}} = 18.29^{o}$, SE = 1.89; $M_{\text{anti-phase}} = 26.42^{o}$, SE = 3.16) (p = .002) and for the ADHD/DCD group ($M_{\text{in-phase}} = 24.13^{o}$, SE = 2.66; $M_{\text{anti-phase}} = 38.38^{o}$, SE = 4.46) (p = .0002). None of the groups differed significantly from one another in both the in-phase and anti-phase modes of coordination (i.e., all ps > .05).

When post-hoc comparisons were calculated for high frequency, the same pattern of effects emerged. Movement stability was significantly greater in the in-phase mode ($M = 20.10^{o}$, SE = 2.57) than in the anti-phase mode ($M = 27.83^{o}$, SE = 3.30) for the Control group (p = .0003). Significant differences in the same direction between modes were also obtained for the ADHD group ($M_{\text{in-phase}} = 20.66^{o}$, SE = 2.57; $M_{\text{anti-phase}} = 32.65^{o}$, SE = 3.30) (p = .0001) and for the ADHD/DCD group ($M_{\text{in-phase}} = 31.34^{o}$, SE = 3.64; $M_{\text{anti-phase}} = 38.98^{o}$, SE = 4.68), although the difference did not reach conventional statistical significance (p = .089).

Comparisons across frequencies found that, in the in-phase mode, none of the groups demonstrated significant differences in stability across frequencies (all ps > .13). In the anti-phase mode, however, stability was significantly greater at low than at high frequency for the control (p = .035) and the ADHD (p = .029) groups, but no difference was found for the ADHD/DCD group (p = .1).

The other interaction was between Group, Task and Mode, $F(2, 27) = 3.138$, $p = .059$. Although the interaction, represented in Figure 4.11, did not achieve .05 statistical significance, the size of the effect was large (Partial eta-squared = 0.19). Whereas movement stability in all groups was greater when using the templates in the in-phase mode, it was so only for the ADHD group in the anti-phase mode. Stability in the Control and ADHD/DCD groups was similar across tasks.

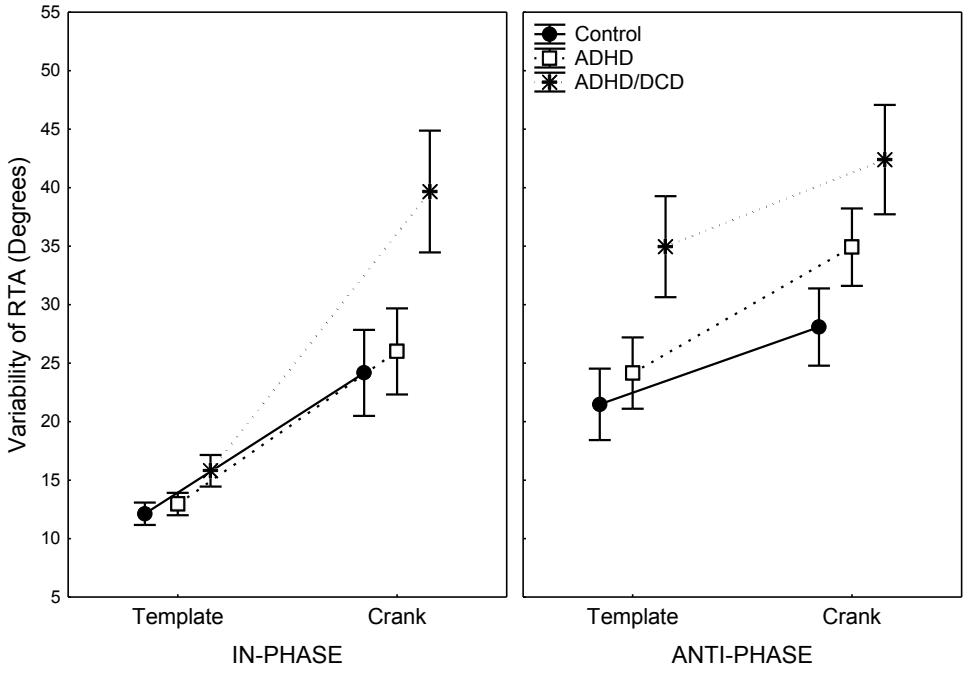

Figure 4.11. Variability of RTA (in degrees) for the three groups across tasks and modes; where greater variability of RTA represents poorer movement stability. Vertical bars denote the standard error.

Post-hoc comparisons with Tukey HSD were first calculated for the in-phase mode of coordination. Stability in the Control group was significantly greater in the template condition ($M = 12.13^{o}$, $SE = 0.95$) than in the crank condition ($M = 24.17^{o}$, $SE = 3.68$) ($p = .001$). In the ADHD group, stability was also significantly greater in the template condition ($M = 12.95^{o}$, $SE = 0.95$) than in the crank condition ($M = 26^{o}$, $SE = 3.68$) ($p = .0004$). Similarly, stability in the ADHD/DCD group was greater using the templates ($M = 15.8^{o}$, $SE = 1.35$) than when using the cranks ($M = 39.67^{o}$, $SE = 5.2$) ($p = .0001$). None of the groups differed significantly from one another on either the template or crank tasks (all ps > .454).

When post-hoc comparisons were calculated for the anti-phase mode, significant differences in movement stability across tasks were found only in the ADHD group, which performed better with the templates ($M = 24.15^{o}$, $SE = 3.05$) than with the cranks ($M = 34.92^{o}$, $SE = 3.31$) ($p = .004$). As it was the case for the in-phase mode, none of the groups differed significantly on either task in the anti-phase mode (all ps > .57).

Comparisons across coordination modes found that, in the template condition, each group was significantly more stable in the in-phase than in the anti-phase mode ($p_{control} = .018$; $p_{ADHD} = .003$; $p_{ADHD/DCD} = .0003$). In the crank condition, a statistically significant difference in stability emerged only in the ADHD group, which performed better with the template than with the crank ($p_{ADHD} = .028$; $p_{control} = .861$; $p_{ADHD/DCD} = .999$).

In summary, stability in the three groups decreased with the cranks when the coordination was simpler (in-phase), but with the more complex coordination mode (anti-phase), the decrease in stability with the cranks was only apparent for the ADHD group.

4.6.4. Aspect Ratio

Aspect Ratio (AR) indexes spatial accuracy by measuring the circularity of movement trajectory. AR was re-analysed with a 3 (Group) × 2 (Mode) × 2 (Frequency) × 2 (Hand [non-dominant and dominant]) repeated measures ANOVA. There were main effects of Frequency and Hand, as reported in the previous Results section, but no main effect of Group, $F(2,27) = 1.908$, $p = .168$ (Partial eta-squared = 0.12).

An interaction emerged between Group, Mode and Hand, $F(2,27) = 3.097$, $p = .062$, with a large effect size (Partial eta-squared = 0.19). As displayed in Figure 4.12, spatial accuracy in the ADHD/DCD group was poorer than in the other groups on both hands. Whereas the ADHD group did not appear to differ from the Control group with the dominant hand in both modes, it was less accurate than the controls in the anti-phase mode with the non-dominant hand, although post-hoc comparisons with Tukey HSD did not yield statistically significant effects.

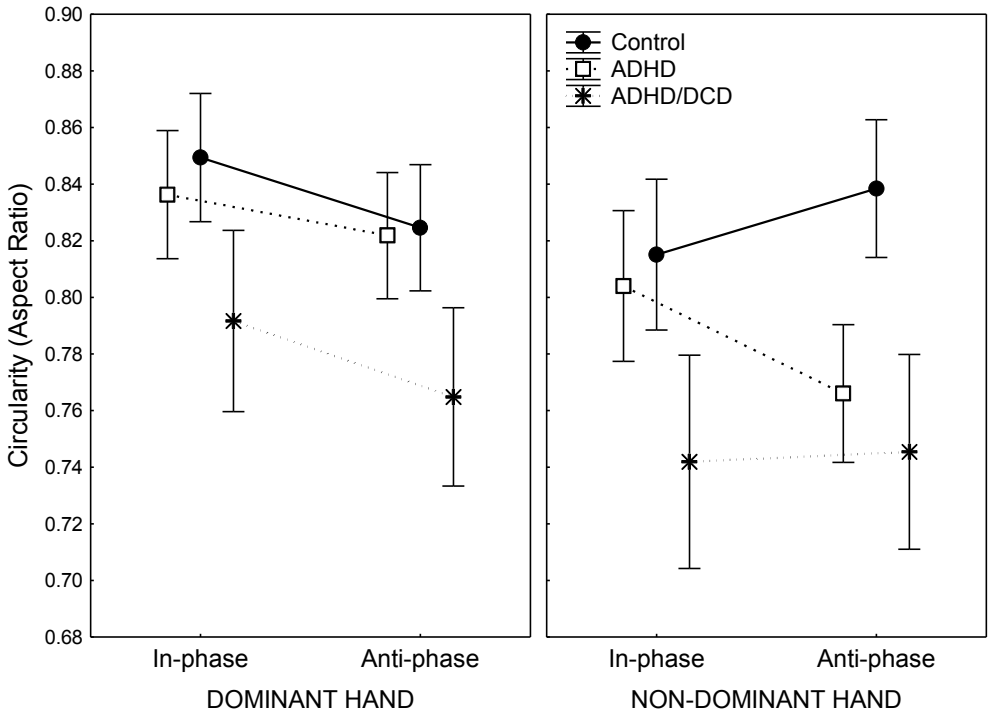

Figure 4.12. Mean Aspect Ratio for the 3 groups. 1 represents perfect circularity and 0 a perfect line. Vertical bars denote the standard error.

4.7. Discussion

Given the paucity of studies investigating the dynamics of motor coordination in ADHD, the aim of the present study was to explore facets of bimanual coordination during a continuous task in a group of children with ADHD and age- and gender-matched controls. This was done by decomposing motor coordination by systematically measuring spatial and temporal performance on bimanual circling tasks, using both free-hand and movements constrained by cranks.

4.7.1. Diagnosis

The problem of diagnosis was evident in this study. As mentioned in Chapter 1, numerous studies and reviews reported high rates of comorbidity in ADHD, which is a major hindrance to diagnosis (e.g, Baron, 2007; Miyahara et al., 2001; Sergeant et al., 2006). In the present study, participants were diagnosed by professionals (Child Psychologists, Paediatricians and Child Psychiatrists). Although all children diagnosed with ADHD scored in the ADHD-C range on the *ADHD Rating Scales-IV*, motor coordination deficit in the ADHD sample had not been noted as a separate or additional impairment.

Consistent with previous observations (e.g., Miyahara et al., 2001; Miyahara et al., 2006; Piek et al., 1999), when participants were screened for DCD Comorbidity, six participants in the ADHD group and one participant in the Control group met the criteria for DCD. As shown by the two separate sets of results, observations and conclusions may vary greatly when this confound is not addressed. It is clear from this and previous research that studies investigating motor coordination in ADHD need to include a formal assessment of DCD, perhaps using a standardised battery of tests such as the *Movement Assessment Battery for Children* (Henderson & Sugden, 1992).

4.7.2. Critical frequency

Based on coordination deficits previously reported, it was expected that the temporal aspects of bimanual coordination in children with ADHD would be impaired overall relative to Controls. This general prediction was not supported by the present results.

The first analysis of individually determined critical frequencies in the 2-group model (Results 1a) revealed that the ability to maintain the movement pattern at high movement rates in children with ADHD was not overall poorer than that of matched controls. The significant interaction between Group and Task showed that whereas movement frequency in both groups was comparable when circling with the templates, children with ADHD were notably faster than the controls on the crank task.

However, the second analysis of the results (Results 1b), using a 3-group model to control for DCD comorbidity, revealed that the ability of children with ADHD to maintain movement pattern at high frequency was dependent on their motor skill rather than ADHD symptomathology.

In particular, the interaction between Group and Task demonstrated that children in the Control group and those with ADHD without motor deficit did not differ at the high movement frequency, whether they used templates or cranks. In contrast, the movement frequency produced by children with ADHD and comorbid DCD (ADHD/DCD) was markedly lower than that of the controls and children with ADHD without DCD, but

only in the template condition. Children in the ADHD/DCD group were just as fast as other children when using the cranks.

The most direct explanation is that children in the ADHD/DCD group had a lower critical frequency because they were unable to maintain the spatial component of the task (maintain the circular trajectories of the templates) at a frequency comparable to that of other groups. Based on dynamical principals in motor coordination (e.g., Kelso, 1995; Monno, et al., 2002), attempting to produce faster movements would have led to spontaneous transitions in the ADHD/DCD group. This is consistent with research showing that children with DCD demonstrate weaker coupling strength between hands than healthy controls (e.g., Volman & Geuze, 1998). Moreover, this could also be linked to "associated" movements occurring more in children with comorbid DCD. Associated movements (AMs) are involuntary movements occurring within parts of the body that are not directly involved in the execution of a motor skill, causing deterioration of motor performance (Geuze, 2004; Licari, Larkin, & Miyahara, 2006). Whereas AMs subside with age in normally developing children (Wolff, Gunnoe, & Cohen, 1983), their persistence may reflect neurological impairment or developmental delay (Willoughby & Polatajko, 1995). Recently, Licari et al. (2006) showed that the severity of AMs was related to the level of motor performance rather than attentional difficulties. It is therefore possible that the poorer bimanual performance of children with ADHD/DCD on the template task in the present study could be associated

with AMs. Future research may consider including a measure of AM during bimanual circling tasks.

In the crank condition, since the circularity of their movement was already constrained by the trajectory of the cranks, the critical frequency on this task was higher. This would suggest that maintaining the required pattern at high frequency may be difficult in children with ADHD and comorbid DCD because of difficulties managing the spatial, rather than temporal, requirements of the task.

4.7.3. Timing accuracy

Moreover, children with ADHD were expected to be less able than the controls to match the target frequencies paced by the auditory metronome. This hypothesis was partially supported by Results 1a. A Group by Task interaction showed that the ability to match the required frequency was significantly poorer in the ADHD group than in the controls when using the templates, but timing error did not differ between the groups when using the cranks. As aforementioned, this may also be explained in terms of difficulties of the motor system to correct movement error to maintain spatial trajectory (see Figure 4.4). Although the Results 1b analysis did not yield a statistically significant effect of group, perhaps due to the small sample size of the two experimental groups, the effect size was large (Partial

eta-squared = .18) for a trend showing that timing was more accurate in the controls than in the other groups, and the ADHD group was more accurate than the ADHD/DCD group.

It was expected that between-group (controls and ADHD) differences in timing accuracy would be emphasised at low frequency movements, on the basis that children with ADHD have been observed to be distractible with easier and less arousing tasks (Boerger & van der Meere, 2000; Scheres, Oosterlaan, & Sergeant, 2001; Zentall, 1985). This hypothesis was not supported, whether the data were analysed with two or three groups. The ability to match the required frequency was not significantly affected by the movement rate required; high or low. A possible explanation is that even at low frequency, the tasks were sufficiently challenging and arousing for the ADHD groups to attend with as much effort as they did in the high frequency condition.

4.7.4. Movement accuracy

Although no prediction was made regarding the accuracy of movements, as measured by the lead-lag between hands (AE-RTA), it is notable that both sets of results showed no group differences or interaction with Group. When comorbidity is taken into account, these results do not support the view that children with ADHD are less accurate than children with normal development in bimanual coordination (Klimkeit et al., 2004). Piek et al.

(2004) also found that children with DCD were slower but just as accurate as the controls.

4.7.5. Movement stability

Using the bimanual cranks, where the control of timing is necessary and the need to control spatial accuracy is minimised, it was hypothesised that children with ADHD would be less able than the controls to maintain movement stability. In other words, children with ADHD were expected to show greater variability of the lead-lag between hands. This hypothesis was not clearly supported by the analysis of Results 1a. There was a trend (p = .07) showing better performance in the Control than in the ADHD group, especially in the more complex mode of coordination (anti-phase); as reflected by the Group by Mode interaction. Overall, movement stability in both groups was significantly greater (i.e., less variability) when using the templates than when using the cranks and when circling at low than at high frequency.

Analysis of Results 1b found a main effect of Group, showing that when comorbidity was taken into account, movements in the Control and the ADHD groups were overall more stable than in the ADHD/DCD group, whereas the controls and the ADHD groups did not differ. The interaction between Group, Task and Mode (Figure 4.11) shows that, as in Results 1a, all participants performed significantly more stable movements when using

the templates than when using the cranks; although this was only a trend for the controls and ADHD/DCD in the anti-phase mode.

In the anti-phase mode, movement stability was also greater at low than at high frequency in the Control and ADHD groups, as would be expected, but no difference was found between frequencies in the ADHD/DCD group. Movement stability in ADHD/DCD children was just as impaired at low frequency as at high frequency when moving anti-phase (i.e., when the movement was complex). This may indicate that the complexity of the pattern, as determined by the coordination of non-homologous muscles during anti-phase patterns, was a major determinant of movement stability in children with ADHD and comorbid DCD.

On the whole, the consistent trend represented by both Group × Mode × Frequency and Group × Task × Mode interactions in Results 1b (Figures 4.10 and 4.11) suggests that children in the ADHD/DCD group were not as able to stabilise the timing between hands as their control and ADHD counterparts. The lack of conventional statistical significance with Tukey‘s post hoc test in these interactions may be best attributed to the small size of the ADHD/DCD sample (n = 6). This impairment reflected a difficulty in stabilising anti-phase movements that required resisting the intrinsic coupling of the hands. Poor coupling strength is usually associated with motor ability rather than ADHD symptomathology (Volman & Geuze, 1998). Moreover, the lack of evidence for movement instability in the

ADHD group is not in support of findings derived from ADHD samples in which high comorbidity with DCD was not taken into account (e.g., Klimkeit et al., 2004).

4.7.6. Spatial accuracy.

It was predicted that when the need for spatial control is increased by introducing free-hand patterns guided by circling templates, the ADHD group would exhibit poorer performance on the spatial aspect of the task than the controls since there is some evidence showing gross and fine motor task deficits in ADHD-C ((Denkla & Rudel, 1978; Pitcher et al., 2003 Shaywitz & Shaywitz, 1984). The main effect of Group in Results 1a supported this hypothesis.

Taking DCD comorbidity into account (Results 1b) resulted in a marginally significant three-way interaction between Group, Mode and Hand (dominance). Spatial accuracy in the ADHD/DCD group was poorer than in the other groups for both dominant and non-dominant hands. The Control and ADHD groups were comparably accurate but only on the dominant hand. Movement circularity in the ADHD group decreased considerably from in-phase to anti-phase on the non-dominant hand. This may be explained in terms of task complexity, which would be consistent with other studies (e.g., Klimbeit et al., 2004; Wuyts et al., 1996; see also Monno, Chardenon, Temprado, Zanone, & Laurent, 2000, for a review).

On the whole, spatial accuracy data showed that the ADHD/DCD group was less accurate in following the circle templates than their control and ADHD counterparts. Consistent with frequency and stability data, this impairment may reflect a difficulty in controlling movement trajectories which was associated with motor skill rather than ADHD symptomathology. This overall observation fits with the notion that DCD involves a deficit in visual-spatial processing (Wilson & McKenzie, 1998) but this is not necessarily the case for ADHD (Piek & Pitcher, 2004). As expected, all groups performed overall more efficiently with easier conditions; at low frequency and with the dominant hand.

4.7.7. Coordination mode complexity

Since maintaining the in-phase mode at high movement rates requires little attentional effort, and anti-phase movements are less stable and require continuous attention and inhibitory capacity to maintain the correct pattern (e.g., Semjen et al., 1995), children with ADHD were expected to show greater difficulties than the controls in the anti-phase than in the in-phase coordination mode. This between-group difference was also expected to be greater at higher movement frequency, given the increased difficulty to stabilise rapid circling movements.

The analysis from Results 1a supported this hypothesis but only in relation to the movement stability data. The large effect size of the Group by

Mode interaction showed that the decrease in movement stability, as a function of coordination complexity, was greater in the ADHD group than in the Control group; although the statistical significance of the difference did not reach the .05 alpha level.

The analysis of Results 1b did not support this hypothesis in relation to the movement stability data. The interaction between Group, Mode and Frequency showed that the decrease in movement stability, as a function of coordination complexity, was not significantly greater in either of the groups. Similarly, the interaction between Group, Task and Mode (albeit non-statistically significant) showed that movement stability decreased in the ADHD group as a function of coordination complexity, but only when using the cranks.

With regards to spatial accuracy, the analysis from Results 1b showed that movement circularity was poorer in the anti-phase than in the in-phase mode for the ADHD group, but only for the non-dominant hand. Spatial accuracy in the other groups was not significantly different across modes of coordination.

Overall, the three groups performed better when the coordination mode was less complex (in-phase and low frequency). Coordination complexity and the frequency of movements were poorer predictors of impairment than the type of task (template or crank).

4.7.8. Conclusion

In summary, the results of the present study supported the view that decomposing motor coordination into spatial and temporal components during a continuous circling task may contribute to our understanding of motor impairment in children with ADHD. It was found that the spatial component during continual movements may be central to the timing problem in children with ADHD and comorbid DCD.

It also provided further insight into the problem of comorbidity and supported previous findings that the motor impairment observed in about half the children with ADHD may, in many cases, be better attributed to a comorbid DCD. The suggestion that ADHD includes a deficit in bimanual coordination (Klimkeit et al., 2004) was not supported. In particular, it was found that when controlling for DCD comorbidity, children with ADHD were nearly as able to maintain movement stability, accuracy and circularity as the controls. Since most aspects of motor coordination impairment were attributable to DCD, rather than ADHD-C symptomathology, the results of this study lend strong support for the increasingly accepted view that DSM-VI diagnostic criteria should be amended to address the problem of comorbidity.

However, the results need to be considered in the light of some methodological limitations, including the small sample size of the ADHD/DCD group and the possible loss of ecological validity given the

unique laboratory context for testing children. Further investigation using larger samples are necessary and should also consider the inclusion of a tighter assessment of DCD, using a standardised battery of tests.

Chapter 5

Experiment 2

5.1. Aims and rationale

Given the paucity of studies reporting on the role of inhibitory control on motor coordination, the extent to which the motor impairment in ADHD-C is associated to central processing is not clear (Sergeant, 1998), especially in the light of new evidence suggesting that ADHD involves deficits in motor inhibition but not in attentional inhibition (Carr, et al., 2006). Piek et al. (2007) found that, when controlling for DCD comorbidity, performance of ADHD and controls children did not differ on a range of executive functions (working memory, set-shifting, processing speed and goal directed planning). The authors proposed that some of the inconsistencies between findings may be due to unidentified comorbidity with DCD in other studies. Piek and colleagues also observed that when motor ability is taken into account the processing deficit usually observed in ADHD is less evident (Miyahara et al., 2006; Pitcher et al., 2002).

Accordingly, Experiment 2 investigated the role of inhibitory functions during continuous and discrete motor tasks in children with ADHD with and without DCD, and their matched controls. It used a Stop-re-engagement task paradigm with a dynamic (hand-circling) motor task, described in detail below. The main aim was to determine whether

inhibitory deficits at the central level of processing and/or appropriate allocation of effort observed in several ADHD studies equally extend to affect movement coordination.

Experiment 2 used an intentional switching paradigm, traditionally applied within the Dynamical Systems approach to bimanual coordination (e.g, Byblow et al., 2000). Within the information-processing framework, a response-switch paradigm enables the examination of executive control processes necessary in both preparing for a response and inhibiting a previously activated and ongoing response (Cepeda et al., 2000; Shallice, 1994). Thus, intentional switching from one movement pattern to another requires the cooperation of inhibitory systems in a way similar to the Change Task, which requires inhibiting an ongoing response and re-engaging in another (Schachar et al., 1995; Tannock et al., 1995).

Given the observation in Experiment 1 that motor coordination in ADHD children can be affected by comorbid DCD symptoms, Experiment 2 controlled for the presence of DCD using a standardised measure of movement coordination (described in the Method section) and included an ADHD/DCD group. Stefanatos and Baron (2007) suggested reducing within-group heterogeneity by using comorbid disorders instead of just ~~"n~~ormal controls".

5.2. Hypotheses

Based on observed deficits in inhibitory control (Oosterlaan & Sergeant, 1998; Pennington & Ozonoff, 1996; Schachar et al., 1995, 2000), it was hypothesised that children with ADHD and ADHD/DCD would take longer than age-matched controls to switch their circling movement to a newly required direction following a switch signal. It was also expected that children in the ADHD/DCD group would find it more difficult than children in the Control and ADHD groups to stabilise the switch process in the newly required movement direction, that is, they would require a longer time to stabilise the new pattern once the switch has been completed. This is because children with ADHD who do not present with motor impairment were expected to have significantly less difficulty at stabilising an already produced switch than those with motor problems.

Based on the reported deficits in executive functions in ADHD (Barkley, 1997, 1999; Pennington & Ozonoff, 1996), it was also expected that children in the Control group would make less errors than those in the ADHD and ADHD/DCD groups. In particular, it was hypothesised that children with ADHD and ADHD/DCD would (1) omit to switch and switch in the wrong direction more often than the controls due to lesser ability to attend to the switch signal and direct their response accurately, (2) would display impulsivity by switching more than once or earlier than the switch signal presentation.

5.3. Method

5.3.1. Participants

In total, 40 boys aged 8-15 years participated in the study. Initially, 17 children (Mean age = 12 years 4 months) who had been professionally diagnosed with ADHD by a child psychologist, child psychiatrist, or paediatrician, were recruited through private practice, public paediatric, a public child and adolescent mental health service, and via newspaper advertisement.

Twenty three matched control boys (Mean age = 11 years 9 months) were recruited from a public and a private school in an attempt to match socio-economic backgrounds. There was no statistical difference between the age of children with and without ADHD, $F(1,38) = .638$, $p = .429$. An information sheet (in Appendix A.1) was sent to the parents or legal guardians of the participants interested in participating.

An effort was made to recruit children in both ADHD and control groups from the same schools and other sources to control for socioeconomic status. All participating children gave verbal consent and parents signed an informed consent form (in Appendix A.2) before being accepted in the study. Children with intellectual disability, Autism, a neurological disorder, a chronic or serious medical problem, hearing difficulty, psychosis, a clinically significant mood or anxiety disorder or notable conduct and oppositional behaviours were excluded.

The *ADHD Rating Scale-IV* (Dupaul, Power, Anastopoulos, & Reid, 1998), described in Chapter 2, was used as a screening device to ensure that all children professionally diagnosed with ADHD matched the DSM-IV criteria for ADHD, and that control children did not present with any significant ADHD symptoms. To determine the clinical significance of motor dysfunction and control for DCD comorbidity, the *Developmental Coordination Disorder Questionnaire* (DCDQ; Wilson, et al., 2000), described in Chapter 2, and the *Movement Assessment Battery for Children* (MABC; Henderson & Sugden, 1992), described in the next section, were also used.

Participants were identified with DCD if they meet the DSM-IV criteria and their total impairment score on the MABC fell at or below the 5th percentile of their peer group. Taking into account the recommendations of Geuze et al. (2001) for quantitative criteria in DCD research, an additional cut-off criterion at the 15th percentile was added with the following specifications. Since the range between the 5th and 15th percentiles is considered "borderline", children whose MABC total score was in this range were also identified as DCD if (a) at least one of the cluster scores was below the 5th percentile, (b) none of the cluster scores was above the 15th percentile, and (c) the total score on the (parent-rated) DCDQ fell within the DCD range (0-10th percentile). None of the participants whose MABC score fell in the borderline range (n = 4) had MABC cluster scores below the 5th percentile or above the 15th percentile, and all of their DCDQ

ratings were in the non-DCD range (26th - 100th percentile). These participants were accordingly not identified as DCD.

Taking parent observations into account helped contextualise the ~~–b~~orderline score" and minimise the influence of extraneous variables, such as test anxiety. There is evidence that children and adolescents with DCD tend to experience higher levels of state- and trait-anxiety than non-impaired children (Skinner & Piek, 2001) and that anxiety increases in children with poor motor coordination when they are told they are about to engage in physical activity due to fear of failure (Schoemaker & Kalverboer, 1994). The presence of extraneous variables such as high levels of anxiety is likely to invalidate test results. Inclusion of self-report data to ascertain the validity of objective data was found to be a valuable procedure (e.g., Cousins & Smyth, 2003). Geuze and colleagues have emphasised the need to take into account the extent to which activities of daily living affect the well being of children with DCD to support research (Geuze et al., 2001). Adding a parent-rated questionnaire such as the DCDQ to the present assessment process was useful in providing wider and contextual information about the child activities of daily living. It also provided information on the child's writing skills, which is not provided by the MABC (see Geuze et al, 2001, for a comprehensive review).

Following assessment on these three measures, all children who met the criteria for ADHD met the diagnosis of ADHD_C. The reallocation of

participants to the Control, ADHD, and ADHD/DCD groups resulted in the following changes: Five children recruited as being in the Control group met the criteria for DCD (without ADHD) and were excluded. Three children recruited as ADHD participants met the criteria for DCD (without ADHD) and were also excluded. Two children recruited as being in the Control group met the criteria for ADHD and were allocated to the ADHD group. One child recruited as being in the Control group met the criteria for both ADHD and DCD and was allocated to the ADHD/DCD group. Six children recruited as having ADHD met the DSM-IV criteria for both ADHD and DCD and were reallocated to the ADHD/DCD group. One child recruited as having ADHD did not meet the criteria for either ADHD or DCD and was reallocated to the Control group. Thus, the three groups comprised the remaining 32 participants. Table 5.1 displays the motor and ADHD symptomathology for the three groups on each assessment tool.

Table 5.1 Mean Total score on DCDQ and percentile scores, on the MABC and ADHD Rating Scale-IV for each group

	N	DCDQ Total	MABC (%ile)	*ADHD Rating Scale-IV* (%ile)
Control	16	74	38	50
ADHD	9	63	18	95
ADHD/DCD	7	50	4	95

In total, 21 children were right-handed and three were left-handed. There was no statistical difference between the age of children across the three groups, $F(2,29) = .307$, $p = .738$. Age and handedness data are presented in Table 5.2. Although effort was made to match the groups for age, the reallocation of children to the three group led the age range for the ADHD/DCD to be narrower than that of the other groups.

Table 5.2. Mean age, standard deviation (SD), and range for each group.

	N	Mean (y:m)	SD (y:m)	Range (y:m)	RH	LH
Control	16	12:4	2:4	8:0–15:0	15	1
ADHD	9	11:8	2:1	8:6–15:0	8	1
ADHD/DCD	7	12:5	1:0	11:6–12:8	6	1

All but two children with ADHD were medicated with stimulants. The children had their medication withdrawn on the day preceding participation (between 18 and 20 hours pre-testing). As discussed in Chapter 2, this withdrawal delay is appropriate for research purposes.

5.3.2. Apparatus and material

Assessments tools. The *Edinburgh Inventory* (Oldfield, 1971) was

used to confirm handedness. The *ADHD Rating Scale-IV* was used to assess ADHD symptomathology according to DSM-IV criteria. The DCDQ and the MABC were used to assess the coordination ability of participants. A description of the DCDQ and *ADHD Rating Scale-IV* was provided in Chapter 2.

The MABC is a standard and well-documented test battery used for the assessment of motor abilities in children aged 4-12+. The authors point out that "Although the main focus of the battery is on children in their elementary school years, it can be used with children both older and younger" (Henderson & Sugden, 1992, p. 7). The MABC has been used with samples of 13-year olds (Miyahara et al., 2006), 14-year olds (Skinner & Piek, 2001) and adults (Cousins & Smyth, 2003). Investigations into the psychometric data of the MABC have shown good reliability and validity (Wiart & Darrah, 2001) and it is commonly used for research as well as in clinical settings by multidisciplinary staff for the diagnosis of motor dysfunction.

The MABC consists of a set of tasks for each of the three main scales: Manual Dexterity, Ball Skills, and Static and Dynamic Balance. The tasks included for the rating of those scales vary according to age. For example, in the 11- and 12-years age band, Manual Dexterity involves a peg board task (turning pegs on a board), cutting out the printed shape of an elephant with a pair of scissors, and tracing a flower trail with a pen. The

Ball Skills scale includes catching a tennis ball with one hand and throwing a tennis ball at a target. The Static and Dynamic Balance scale includes keeping balance while standing on the small rim of a wooden board, jumping above knee level while clapping hands rapidly as many times as possible, and walking backwards on a straight line. Coordination is considered to be below normal functioning when the total score converted to a percentile score is at or below the 15th percentile (i.e., when motor coordination in 85% of children of his/her age group is better). When the percentile score is at or below the 5th percentile (i.e., when motor coordination in 95% of children of his/her age group is better), the diagnosis for DCD is warranted. As mentioned earlier, the range between the 5th and the 15th percentiles is considered ―borderline" (Henderson & Sugden, 1992).

Motor task. As in Experiment 1, a Northern Digital Optotrack 3020 3D Infrared Position Sensor was used to track and record an infrared light emitting diode (IRED) mounted on the participant's index fingers, using a sampling rate of 200Hz. The 3D signals from each IRED were digitised in real time and stored as raw 3D coordinates, providing the spatial and temporal characteristics of the data.

Only the template was used for the circling task. As in Experiment 1, to serve as circling models, two black circles (14 cm in diameter and set 21 cm apart centre to centre) drawn on an A3-sized laminated sheet of paper were fixed on a table surface facing the participant, positioned within

comfortable forward reach and centred at the participant‘s midline, as displayed in Figure 4.1. The circle templates were positioned to match postural requirements and the space between hands. A 2800 Hz computer-generated tone served as an auditory metronome to pace the movements.

A 25-cm wide black box (20 x 12 cm) with two visual signals (arrows) was positioned on the midline of the participant, above the circle template (see Figure 5.1). A small LED (the fixation point) was placed in the centre of the box. On each side of the fixation point were blocks of LEDs lighting up in the shape of an arrow when activated. The arrows were separated by 12 cm. In each trial the circling direction was indicated by a lighted arrow.

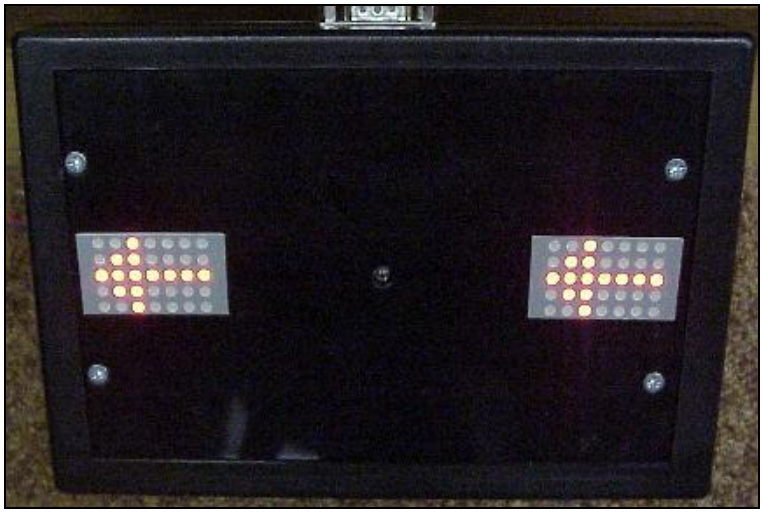

Figure 5.1. Stimulus box with arrows signalling to switch to anti-phase left.

5.3.3. Procedure

Assessments. As in Experiment 1, when possible, the accompanying parent/guardian remained in the laboratory out of the child's sight during testing. For each participant, the assessment of motor coordination was provided by the DCDQ parent questionnaire, filled in by the parent present during testing, and through measurement of motor performance with the MABC. Performance on each task was recorded by the assessor on the age-appropriate record form. Assessment of ADHD symptomathology was done with the *ADHD Rating Scale-IV*. It was specified that the scoring must reflect the child's behaviour when not medicated. Subscale, total, and percentile scores on all assessment tools were calculated after completion of the entire testing session. The groups were then re-organised, as described earlier, according to the children's performance on the MABC and the scores on the *ADHD Rating Scale-IV*.

Motor tasks. After explanation of the main aspects of the motor task procedure, each participant was comfortably seated at a table with a horizontal work plane and given identical tasks and instructions. Each performed circling movements in in-phase and anti-phase patterns, as detailed below, using the templates as circling guides. Movements were paced by a computer-generated metronome at 1Hz throughout each trial.

For the first 5 seconds, participants were asked to follow the pacing tone of the metronome while focusing on their hands and complete one full

circle per tone with as much accuracy as possible. They were asked to begin circling movements as soon as the tone was presented. After 5 circles (i.e., as soon as data recording started) participants were asked to shift their attention to the fixation point in the centre of the stimulus box. In all trials, the recording of the data took place in the following 25 seconds of the trial. All participants performed 3 blocks of 5 consecutive 30-second trials totalling 46 trials.

Block 1 consisted of 20 baseline trials, during which participants performed 4 circling patterns in each of the four coordination modes displayed in Figure 5.2: in-phase inward (II), in-phase outward (IO), anti-phase left (AL), and anti-phase right (AR). This block of trials provided baseline measures of movement coordination which do not require motor inhibition, as determined by the independent variables used in Experiment 1 (Frequency Deviation, RTA, SD-RTA, and Aspect Ratio). These measures have been described in detail earlier.

Block 2 consisted of 6 practice trials for familiarisation with switch signals. Accordingly, the data from Block 2 were not recorded. Block 3 involved 20 experimental trials during which switch data were recorded.

In all trials of Blocks 2 and 3, participants were instructed to start circling in the II mode while keeping the pattern as accurately as possible (i.e., with the right arrow pointing to the left and the left arrow pointing to the right, towards the fixation point) until one or both arrows pointed to the

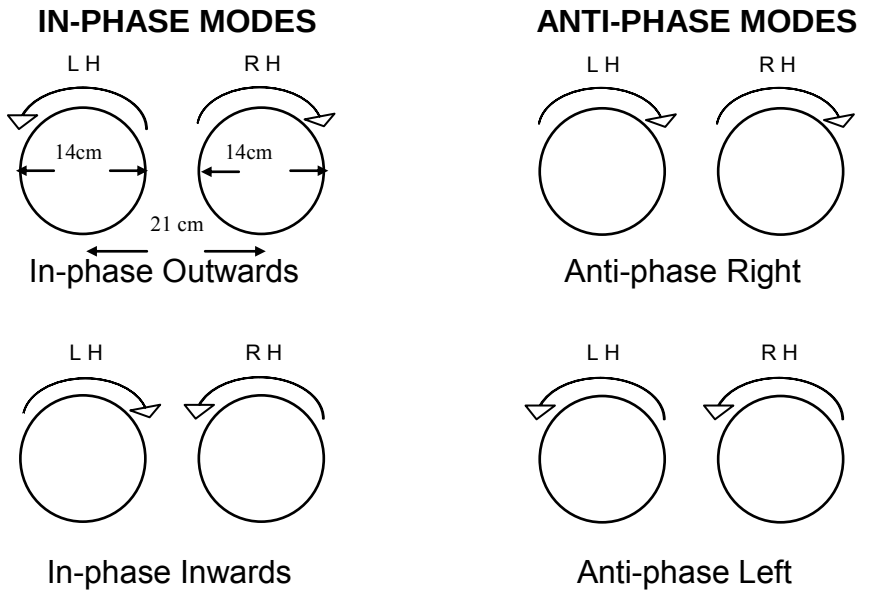

Figure 5.2. Schematic of the two in-phase and two anti-phase modes of coordination used in Block 1 (LH = left hand; RH = right hand).

direction of the required switch. The arrows on the signal box were always activated together in order to model the direction in which the hands should move. Participants were asked to focus on the hand movement for the first 5 cycles (i.e., 5 seconds) and then focus their attention on the fixation point at the centre of the stimulus box, attending to a potentially imminent switch (see Figure 5.3). Each switch signal occurred within the second or third quartile of each trial recording period, i.e. between 6.3 and 18.8 seconds following the start of data recording (i.e., between 11.3 and 22.8 sec following trial onset).

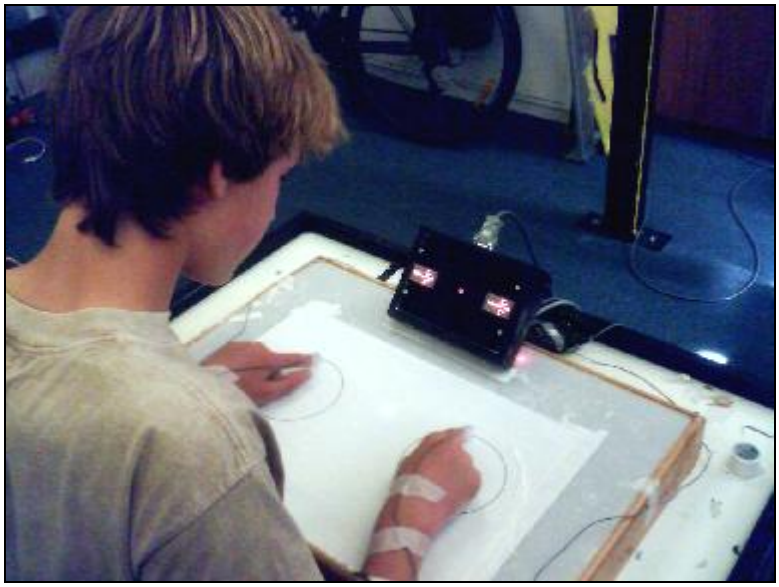

Figure 5.3. Photograph of a participant who was signalled to switch to the anti-phase right (AR) mode.

Participants were asked to respond as quickly as possible to a change in the arrow(s)'s direction by switching their II movement in the new direction indicated by the arrows. Figure 5.4 shows all potential switches.

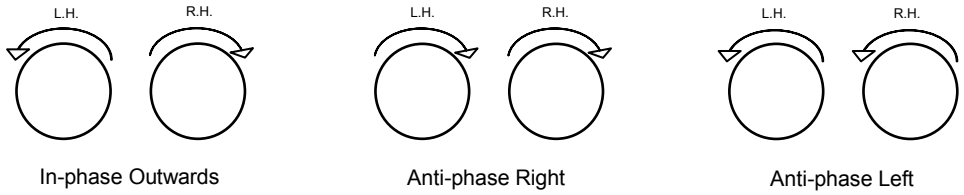

Figure 5.4. Schematic representation of the three switch directions.
Figure 5.4. Schematic representation of the three switch directions.

In some trials the arrows pointed in the opposite direction, one to the left and one to the right, either inward (arrows pointing to the participant midline) or outward (arrows pointing opposite to the participant midline), directing the participant to either remain in the II mode or to switch to the IO mode, respectively. In other trials the arrows pointed in same direction, either to the left or to the right, directing the participant to switch to the AL or to the AR mode, respectively. Participants were told that in some trials, switch signals would require only one hand to switch in the new direction (AL and AR) whereas other trials would require both hands to switch (IO). Figure 5.3 depicts a signal to switch from II to AR (both arrows pointing to the right on the signal box).

Block 2 (practice switch trials) contained two trials for each of the switch modes used: II to IO, II to AL, and II to AR, presented in a serial order. Block 3 (experimental switch trials) contained 5 trials for each of the 3 switch modes, and five II trials (i.e., without switch).

The trial distribution, represented in Table 5.1, is based on Schachar et al.'s (1995) methodology. Each condition appeared equally often. To prevent participants predicting that the switch type required (e.g., II to AL) would be systematically different from one trial to the next, two identical trials (e.g., AL) followed each other in each condition, but this occurred only once. Apart from these restrictions, all trials were randomised. This semi-randomised order was presented to all children identically.

Table 5.3. Experimental trials distribution in Block 3. Each black dot represents the condition to which participants were required to switch. Dots in the II column represent trials in which no switch signals were presented.

Trial order in Block 3	In-phase Inward (II)	In-phase Outward (IO)	Anti-phase Left (AL)	Anti-phase Right (AR)
1	●			
2		●		
3		●		
4				●
5	●			
6			●	
7				●
8		●		
9			●	
10			●	
11				●
12		●		
13	●			
14	●			
15			●	
16				●
17				●
18		●		
19	●			
20			●	

For Block 3, the participants were told that in some trials switch signals would not be presented and therefore they would not be required to switch in all of the trials. They were instructed to continue circling in the

new direction following the switch. They were also told that for all switch trials, only one switch was required.

To avoid possible fatigue, participants were given breaks as frequently as necessary. The overall testing time (including assessment on the MABC) lasted between 90 and 120 minutes.

5.3.4. Data reduction and dependent measures

All dependent measures of hand-circling performance (Frequency Deviation, Relative Tangential Angle [RTA], Variability of RTA (SD-RTA), and Aspect Ratio) used in this experiment were used and described in Experiment 1. Switch and error measurements were included as additional dependent variables

Switch measures (calculated in milliseconds) were Switch Reaction Time (Switch-RT) and Switch Duration. Switch-RT was the time elapsed between the onset of the switch signal and the onset of the switch. Switch onset was determined using Serrien, Bogaerts, Suy and Swinnen's (1999) methodology. Within-hand relative phase (between *X* and *Y* axes) was analysed to detect change in the sign (+ −), which indicated a change in circling direction. Given that each trial began in the II direction, the phase offset between the *X*- and *Y*- axes components was approximately 90 degrees. A change above 3 standard deviations (SDs) from 90 degrees of relative phase was taken as a definite switch—analyses with less than 3 SDs

were too sensitive to poor movement stability and did not clearly distinguish a switch. When two hands were necessary for the switch (i.e., when switching to IO), this analysis was performed on the hand that first initiated the onset of the switch. Switch-RT was taken as a measure of motor inhibition and re-engagement because it requires inhibiting the ongoing II pattern and re-engage (switch) in a different circling pattern.

Switch Duration was the time elapsed between the onset of a switch and the stabilisation of the movement to the new coordination pattern. This was determined as follows: First, the mean relative phase (between hands) occurring within the 5-second region preceding the onset of the switch was calculated—if an involuntary switch occurred in this region, when possible, another (switch-free) 5-sec long pre-switch region was used. The value obtained was considered to reflect a ―mean stability" value. When the mean of between-hand relative phase in the post-switch region was sufficiently decreased to fall within 3 standard deviations of the (pre-switch) mean stability, the switch was considered to have been completed. From this point forward in the trial, coordination was expected to be stable since the participants were told that for all switch trials, only one switch was required. Given the significant role of attention in stabilising coordination dynamics within regions of instability (e.g., Summers, et al.,1998), Switch Duration was taken as a measure of motor coordination as well as the ability to use attention to stabilise post-switch patterns.

Error measures were Omissions (the number of trials in which no switch was produced when a switch was required or when a switch took place 5 or more sec following the onset of the switch signal), Directional Errors (the number of switches made in the incorrect direction), Pre-Switch Reversals (the number of involuntary switches which occurred before presentation of the switch signal), and Post-Switch Reversals (the number of involuntary switches which occurred after the appropriate switch was produced). Error measures were calculated as the number of occurrences.

Longer Switch-RTs were taken as poor processing speed. In terms of ADHD symptomathology, Omissions and Directional Errors were taken to indicate poor attention, and Pre-Switch Reversals were taken as a reflection of impulsivity. This operational definition was based on the repeated observation that switching from in-phase (easy pattern) to anti-phase (more difficult pattern) is not a spontaneous occurrence and requires intention (see Kelso, 1995, for details). Accordingly, a pre-switch reversal from in-phase to anti-phase mode can be better attributed to impulsivity than to inattention. Longer Switch Duration and Post-Switch Reversals were considered to reflect poor coordination, characterised by a lack of movement stabilisation (for Switch Duration) and motor inhibition (for Post-Switch Reversals).

5.3.5. Design and analysis

For all analyses of the baseline data, a mixed between-within (repeated

measures) design was used. The design for other analyses is described in the text as appropriate. As for Experiment 1, Huynh-Feldt epsilon corrections were applied, where appropriate, to the degrees of freedom for *F* tests to compensate for violation of homogeneity assumptions. Post-Hoc analyses of interactions between factors were analysed with Tukey HSD. Alpha level was set at .05 to indicate statistical differences between means. Effect size statistics were calculated with Partial eta-squared, which was described as per Cohen's (1988) guidelines (0.01= small effect, 0.06 = moderate effect, and 0.14 = large effect).

Baseline trials. For the temporal data, the independent variables were Group (Control, ADHD, ADHD/DCD) and Mode (II, IO, AL, AR). For the spatial data, the independent variables were Group (Control, ADHD, ADHD/DCD), Mode (II, IO, AL, AR), and Hand (dominant [D] and non-dominant [ND]). The dependent variables were AE-RTA, SD-RTA, Frequency Deviation, and Aspect Ratio.

Experimental trials. For the switch data, the independent variables were Group (Control, ADHD, ADHD/DCD) and Switch Pattern (IO, AL, AR). The dependent variables were Switch-RT and Switch-D. For the error data, the independent variable was Group (Control, ADHD, ADHD/DCD) and the dependent variables were Omission, Directional Error, Pre-Switch Reversals and Post-Switch Reversals.

5.4. Results

5.4.1. Frequency data in baseline trials

Frequency Deviation. Given that separating in-phase inward (II) from in-phase outward (IO) and anti-phase left (AL) from anti-phase right (AR) conditions did not produce any findings of interest, the two in-phase modes and the two anti-phase modes were grouped to form a single in-phase and a single anti-phase condition. Accordingly, deviation from target frequency (in Hz) was analysed with a 3 (Group) × 2 (Mode) repeated measures ANOVA. There were no main effects of Group ($M_{Control}$ = 0.04, SE = 0.01; M_{ADHD} = 0.05, SE = 0.01; $M_{ADHD/DCD}$ = 0.05, SE = 0.02), F(2,29) = .332, p = .72, or Mode ($M_{in\text{-}phase}$ = 0.05, SE = 0.01; $M_{anti\text{-}phase}$ = 0.05, SE = 0.01), F(1,29) = 0.079, p = .78, and no interaction between Group and Mode.

Analysis of the variability of frequency deviation was also analysed with a 3 (Group) × 2 (Mode) repeated measures ANOVA. There were no main effects of Group ($M_{Control}$ = 0.02, SE = 0.01; M_{ADHD} = 0.03, SE = 0.01; $M_{ADHD/DCD}$ = 0.03, SE = 0.007), F(2,29) = 1.073, p = .36, or Mode ($M_{in\text{-}phase}$ = 0.03, SE = 0.01; $M_{anti\text{-}phase}$ = 0.02, SE = 0.003), F(1,29) = 1.09, p = .31, and no interaction between Group and Mode.

5.4.2. Performance accuracy and stability in baseline trials

Absolute Error of RTA. As was the case for the analysis of frequency deviation, II and IO were combined into a single in-phase condition and AL and AR were combined into a single anti-phase condition. Accordingly, AE-RTA was analysed with a 3 (Group) × 2 (Mode) repeated measures ANOVA. There was a main effect of Mode, $F(1,29) = 40.856$, $p < .0001$, with a very large effect size (Partial eta-squared = 0.58) showing that performance accuracy was significantly greater in the in-phase mode ($M = 7.56^{o}$, $SE = 0.52$) than with anti-phase mode ($M = 16.05^{o}$, $SE = 1.32$). There was no main effect of Group ($M_{control} = 11.12^{o}$, $SE = 1$; $M_{ADHD} = 12.32^{o}$, $SE = 1.33$; $M_{ADHD/DCD} = 11.98^{o}$, $SE = 1.51$), $F(2,29) = 0.283$, $p = .756$, or interaction between Group and Mode.

Variability of RTA. As in the above analyses, II and IO were combined into a single in-phase condition and AL and AR were combined into a single anti-phase condition. Movement stability, as measured by the standard deviation of RTA (SD-RTA), was analysed with a 3 (Group) × 2 (Mode) repeated measures ANOVA. A significant main effect was obtained for Mode, $F(2,29) = 92.614$, $p < .0001$, showing that movement stability was significantly greater in the in-phase mode ($M = 12.21^{o}$, $SE = 0.64$) than in the anti-phase mode of coordination ($M = 23.8^{o}$, $SE = 1.55$). The size of the effect was very large (Partial eta-squared = 0.76). There was no main effect of Group, ($M_{Control} = 15.97^{o}$, $SE = 1.36$; $M_{ADHD} = 20.37^{o}$, $SE = 1.82$;

$M_{ADHD/DCD}$ = 17.67°, SE = 2.06), $F(2,29) = 1.874$, $p = .172$, or interaction.

5.4.3. Spatial data in baseline trials

Aspect Ratio. Aspect Ratio (AR) was analysed with a 3 (Group) × 2 (Mode) × 2 (Hand [non-dominant and dominant]) repeated measures ANOVA. There was a main effect of Hand, $F(1,29) = 14.14$, $p = .0008$, with a large effect size (Partial eta-squared = 0.33), showing that spatial accuracy was significantly greater with the dominant hand (M = 0.85, SE = 0.02) than with the non-dominant hand (M = 0.83, SE = 0.02). There was a Main effect of Mode, $F(3, 87) = 4.8554$, $p = .004$, with a moderate effect size (Partial eta-squared = 0.10), showing that spatial accuracy was significantly greater in the IO (M = 0.86, SE = 0.02) and AL (M = 0.85, SE = 0.02) modes than in the AR mode (M = 0.83, SE = 0.02) ($p_{IO} = .009$, $p_{AL} = .04$). The remaining pot-hoc comparisons (Tukey HSD) were not statistically significant. No main effect of Group was found ($M_{Control}$ = 0.85, SE = 0.02; M_{ADHD} = 0.82, SE = 0.03; $M_{ADHD/DCD}$ = 0.86, SE = 0.04), $F(2,29) = 0.467$, $p = .632$. There was no interaction.

5.4.4. Switch data in switch trials

Switch reaction-time. Switch-RT was analysed with a 3 (Group) × 2 (Mode) repeated measures ANOVA. There was a main effect of Group, $F(2,29) = 3.481$, $p = .044$, with a large effect size (Partial eta-squared =

0.19). The effect is represented in Figure 5.5. Tukey post-hoc test showed no statistical significance between the Control group (M = 615ms, SE = 66) and the ADHD/DCD group (M = 877ms, SE = 100) (p = .091) despite the large size of the main effect. The differences between Control and ADHD (M = 849ms, SE = 88) and ADHD and ADHD/DCD groups were not statistically significant (ps = .104 and .975 respectively). There was no main effect of Mode ($M_{\text{in-phase}}$ = 742ms, SE = 59; $M_{\text{anti-phase}}$ = 819ms, SE = 59), $F(1,29) = 1.352$, p = .254, or interaction, showing that the effect of time to switch within a coordination mode (II to IO) was not significantly different than switching between coordination modes (II to AL or AR).

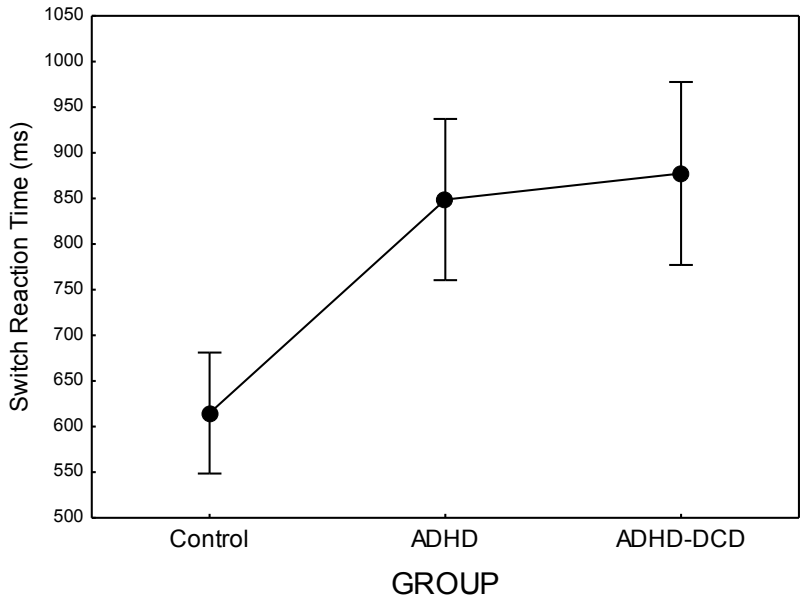

Figure 5.5. Mean switch-RT (ms) for the Control, ADHD and ADHD/DCD group. Vertical bars denote the standard error.

Switch duration. Switch-D was analysed with a 3 (Group) × 2 (Mode) repeated measures ANOVA. No statistically significant differences were found between groups, $F(2,29) = 2.552$, $p = .10$, and the effect size was at the moderate range (Partial eta-squared = 0.13). Switch duration in the ADHD group (M = 1263ms, SE = 175) was longer than that of the Control (M = 768ms, SE = 135) and ADHD/DCD (M = 885ms, SE = 198) groups. There was no significant main effect of Mode, $F(1,29) = 0.478$, $p = .138$, for which the size of the effect was very small (Partial eta-squared = 0.02) and no interaction between Group and Mode.

5.4.5. Error data in switch trials

Based on the predictions for this analysis, one group included the controls (n = 16) and the other all children with ADHD (i.e., both ADHD and ADHD/DCD [~~"a~~ll-ADHD"]; n = 16). When comparing the total number of errors produced by all-ADHD against the total number of errors in the Control group, the all-ADHD group made 5.9 times more errors than the Control group. A 2 (Group) × 4 (Error Type) repeated measures ANOVA showed a significant effect of Group, $F(1, 30) = 4.175$, $p = .049$, with a moderate effect size (Partial eta-squared = 0.12). Overall, the all-ADHD group (M = 1.23, SE = 0.35) made significantly more errors than the Control group (M = 0.22, SE = 0.35).

There was a main effect of Error Type, $F(3, 90) = 2.571$, $p = .059$, although it did not reach conventional level of significance. The magnitude of the effect was moderate (Partial eta-squared = 0.08). In total, involuntary switch errors (Pre-switch [$n = 34$] + Post-switch [$n = 37$]) were about 3 times more frequent than errors of inattention (Omission [$n = 11$] + Direction [$n = 11$]).

Although the Group by Error Type interaction did not reach the conventional level of statistical significance, $F(3, 90) = 2.154$, $p = .098$, it had a moderate effect size (Partial eta-squared = 0.10). Given the weight of the theoretical implications of this interaction (displayed in Figure 5.6), the occurrence of errors amongst the groups was analysed with one-way ANOVAs for each error type. As reflected by a moderate effect size (Partial eta-squared = 0.11), only Post-switch errors separated the Control group from the all-ADHD group, $F(1, 30) = 3.835$, $p = .059$, ($M_{Control} = 0.13$, $SE = 0.74$; $M_{all\text{-}ADHD} = 2.19$, $SE = 0.74$),. All other comparisons did not show differences (all ps > .12).

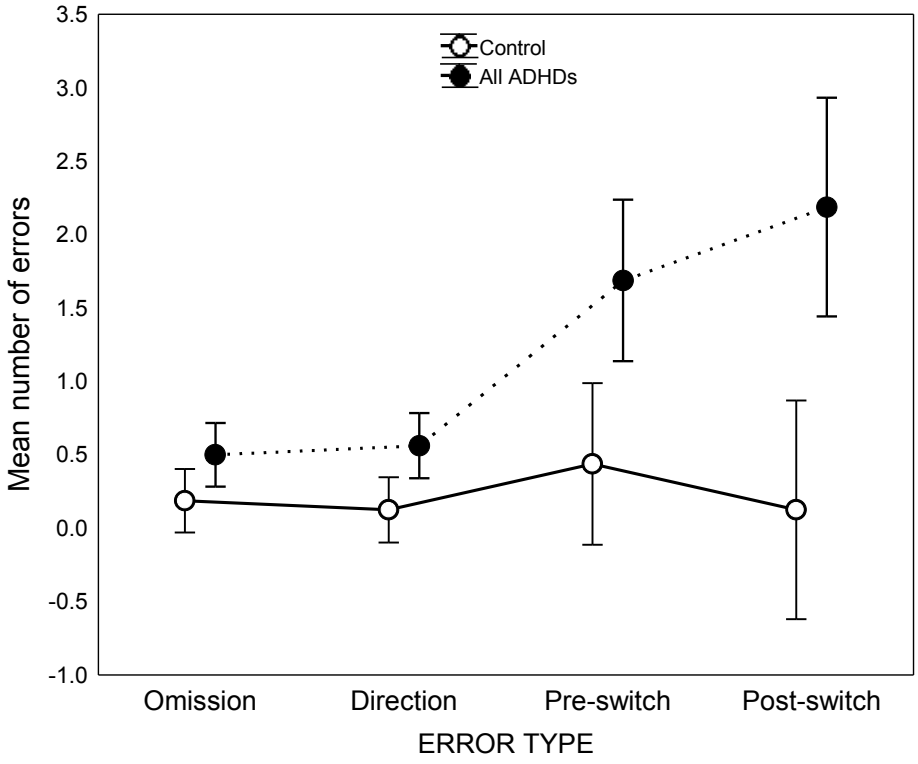

Figure 5.6. Mean number of errors for each error type in the Control and all-ADHD groups. Vertical bars denote the standard error.

Because it was also of theoretical interest to investigate potential differences between the three groups, the occurrence of errors amongst the Control, ADHD and ADHD/DCD groups was analysed with one-way ANOVAs for each error type. Overall, the ADHD group made 2.5 times more involuntary switches than the Control group. In particular, the ADHD group made significantly more Pre-switch errors than the Control group, $F(1, 23) = 4.374$, $p = .047$, ($M_{ADHD} = 3.00$, $SE = 0.60$; $M_{Control} = 1.44$, $SE = 0.45$). The size of the effect was large (Partial eta-squared = 0.16).

Given the potential significance of this difference, a correlational analysis of the relationship between general motor performance (MABC percentile scores and DCDQ Total scores) and Pre-switch errors was performed on the full sample. Based on Cohen's (1988) parameters, there was a non-significant small negative correlation between Pre-switch errors and MABC percentile scores (r = -.20, p = .29). There was a moderate negative correlation between Pre-switch errors and DCDQ Total scores (r = -.33, p = .082).

The ADHD group also made significantly more Post-switch errors than the Control group, $F(1, 23) = 4.873$, p = .037, (M_{ADHD} = 3.78, SE = 0.96; $M_{Control}$ = 1.13, SE = 0.72). The size of the effect was similarly large (Partial eta-squared = 0.17). All other comparisons between the Control and ADHD groups were non-significant ($p_{Omission}$ = .14, $p_{Direction}$ = .13).

Comparisons between the Control and the ADHD/DCD group did not yield any significant differences on any of the error types (all ps > .13). Similarly, none of the differences between the ADHD and the ADHD/DCD group were significant on any of the error types (all ps > .20). In summary, the only differences found were between the Control and ADHD groups for both Pre- and Post-switch errors.

5.5. Discussion

Within the information-processing framework, a response-switch paradigm

enables the examination of executive control processes necessary in both preparing for a response and inhibiting a previously activated and ongoing response (Cepeda et al., 2000; Shallice, 1994). This experiment used an intentional switching paradigm, traditionally applied within the Dynamical Systems approach to bimanual coordination, as an analogue of the Stop-re-engagement or Change Task with a dynamic (hand-circling) motor task. The main aim was to determine whether the deficits in inhibition at the central level (e.g., Schachar et al., 1995) and/or appropriate allocation of effort observed in several ADHD studies equally extend to affect movement coordination.

5.5.1. Diagnosis

As in Experiment 1, the problem of diagnosis was as evident in this experiment. Participants were also diagnosed by professionals (Child Psychologists, Paediatricians and Child Psychiatrists) and reassessed with the same tools and parameters used in Experiment 1, with the addition of the *Movement Assessment Battery for Children* (MABC; Henderson & Sugden, 1992) given the high ADHD and DCD comorbidity observed in Experiment 1. In accordance with Geuze et al's (2001) recommendations, the MABC was used to formally evaluate the presence of DCD comorbidity, determined by a total score falling below the 5th percentile of the MABC, with at least one of the cluster scores below the 5th percentile, none of the

cluster scores above the 15th percentile, and a total score on the (parent-rated) DCDQ falling within the DCD range (0-10th percentile). As in Experiment 1, motor coordination deficit in the ADHD sample had not been noted as a separate or additional impairment.

Consistent with the literature reporting high DCD comorbidity in the ADHD population (e.g., Piek et al., 1999; Miyahara et al., 2006; Sergeant et al., 2006), six participants in the ADHD group met the criteria for DCD on the MABC and three children recruited as ADHD participants met the criteria for DCD but not ADHD. Even more notable, when formal assessment of motor coordination was used, five children recruited as controls also met the criteria for DCD (without ADHD) and had not been identified as having motor coordination difficulties. Moreover, one child recruited as having ADHD did not meet the criteria for either ADHD or DCD. In line with past observations (e.g., Geuze et al., 2001), it appears from these (albeit small) samples that DCD is not only an undetected comorbid condition which complicates the diagnosis of ADHD, it is also under-diagnosed when it occurs on its own. The results also point to the importance of assessing motor coordination using more objective measures rather than solely relying on parent-teacher questionnaires to identify the presence of DCD more effectively, as pointed-out by Geuze et al. (2001).

5.5.2. Baseline data

Although no predictions were made for the baseline data, it may be useful to compare the present results with those from Experiment 1. Given the small samples sizes which resulted from group reallocation, it was not expected that this set of data would replicate the previous pattern of results. However, some of the findings were replicated. Given the small community in which the study was carried out, the preferred option of recruiting more participants for the study was not feasible.

Timing accuracy. Consistent with the results from Experiment 1, there was no main effect of Frequency Deviation or variability of Frequency Deviation. The three groups were comparably able to match the target frequency. This is not surprising given that this experiment included only one frequency (1 Hz), reported in previous studies to be a relatively comfortable pace during a circling task (e.g., Summers, Cayoun, Elder, Sharvi, Hiraga, & Fujiyama, 2007).

Movement accuracy. The lack of main effect of Group or interaction with Group is consistent with the results of Experiment 1. The three groups were comparably able to maintain movement accuracy.

Movement stability. Although the trend was in the expected direction (controls performed better than ADHD/DCD) with a moderate effect size, (Partial eta-squared = 0.11), there was no statistically significant main effect or interaction with Group. Most importantly, as in both sets of results of

Experiment 1, the present results did not support previous findings that children with ADHD perform less stable circling movements than their control counterparts (Klimkeit et al., 2004).

Spatial accuracy. As in Experiment 1 no main effect of Group was found in the spatial data. In line with Experiment 1 (Results 1a), there was no interaction involving Group. In Results 1b of Experiment 1, the ADHD and controls were also comparably accurate unless hand dominance was taken into account. When hand dominance was not specified, the group difference was mainly due to the ADHD/DCD group. The present finding further supports the results from Experiment 1, showing that children with ADHD (without DCD) did not show impairment in the spatial component of circling movements. Nevertheless, the poorer spatial performance of the ADHD/DCD group found in Experiment 1 (Results 1b) was not replicated in the present experiment.

5.5.3. Switch data

Switch-RT. Based on previous research showing inhibitory impairment in ADHD (Barkley, 1997; Pennington & Ozonoff, 1996; Schachar et al., 1995), it was hypothesised that the groups of children with ADHD (ADHD and ADHD/DCD) would take longer than age-matched controls to switch their circling movement in a new direction at a given signal. This hypothesis was supported by a significant main effect of Group

and a large effect size; although post-hoc comparisons did not permit statistical conclusions about specific group differences, presumably due to small sample sizes. This is also in accordance with previous research showing abnormality in brain activation during motor inhibition and task switching in children with ADHD (Smith et al., 2006).

However, Switch-RT reflects an ensemble of so called executive processes, including inhibiting an ongoing action (circling in-phase/inward [II]) at a given signal and relying on cognitive flexibility (re-engaging in another circling pattern as soon as possible). Since the Control group stopped the ongoing II pattern significantly faster than the other groups, the data lend support for the hypothesis of a slower inhibitory process in ADHD (Barkley, 1997). The results also support the hypothesis that inhibitory control of an ongoing action, which has been mainly associated with processing in prefrontal cortices (Bradshaw, 2001; Pennington & Ozonoff, 1996; Stefanatos & Baron, 2007), extends to motor inhibition during ongoing movements.

However, Switch-RT can also be influenced by at least three other mechanisms. Participants with slow processing speed would perform poorly on this task. Indeed, the data can be explained by a slower overall processing speed in children with ADHD (Oosterlaan, et al., 1998). Participants with normally developed inhibitory capacity who cannot sustain attention to the visual switch signal would also perform poorly on this task.

As discussed below, however, poor attention capacity was not an essential factor in Switch-RT outcomes, as reflected by Error data. Moreover, since changing the direction of movement also requires re-engagement capacity (cognitive flexibility) it was difficult to determine whether the marked difference in Switch-RT should be best attributed to an earlier processing (response inhibition) or later processing (response re-engagement) in inhibitory control. This question may be best answered using a traditionally delivered Change Task (e.g., Oosterlaan & Sergeant, 1998; Schachar et al., 2000), which enables the discrimination between Stop reaction time and re-engagement measures.

Switch duration. The controls and children with ADHD without motor dysfunction were expected to have less difficulty with stabilising an already produced switch than those with DCD comorbidity (i.e., the ADHD/DCD group would require longer switch duration). The results failed to support this hypothesis. The lack of group discrimination by Switch Duration indicated that, at such low frequency of movement, no deficit in motor coordination and ability to use attention to stabilise post-switch patterns emerged in either of the groups. In the present study, only low frequency was presented to ensure that children with more severe motor impairment could perform the most complex tasks (e.g., anti-phase). It is not clear whether this lack of group discrimination would remain when using higher movement frequencies and future studies may benefit from varying frequency.

5.5.4. Error data

On the basis that ADHD has been shown to include impairment in executive functioning (e.g., Barkley, 1999), it was also expected that children in the Control group would make less errors overall than those in the ADHD and ADHD/DCD groups. The results supported this hypothesis. The combined ADHD and ADHD/DCD groups (n = 16) made 5.9 times more errors than the Control group (n = 16). This difference was statistically significant.

Interestingly, the results showed that involuntary switch errors (Pre-Switch and Post-Switch) were about 3 times more frequent than errors of inattention (Omission and Direction), as reflected by a marginal effect of Error Type (p = .059). For the Control group, the ratio of Pre-switch to Post-switch errors was 3.5:1, whereas it was less than 1 for the two groups with ADHD participants. This may be tentatively explained in terms of greater preparedness to switch in the Control group than in the other groups. A greater preparedness to switch would be congruent with the dysfunctional states model (Sergeant, 2000), whereby the effort and activation states are impaired in ADHD.

There were no differences in number and type of errors between the ADHD and ADHD/DCD groups or between the Control and ADHD/DCD groups. The only differences on any of the error types were found between the Control and ADHD groups for both Pre- and Post-switch errors. The finding that error was not linked to DCD symptomathology is in support of

previous studies (Piek et al., 2004; Piek et al., 2007).

Inattention. In particular, given the reported working memory deficit in ADHD (e.g., Barkley, 1997), it was hypothesised that children with ADHD and ADHD/DCD would omit to switch and switch in the wrong direction more often than the controls. Consistent with recent research (Piek et al., 2007; Wolfe & Riccio, 2005), this hypothesis was not supported. Both groups were comparably attentive to the onset of the switch and to the direction in which the switch was required.

Impulsivity. It was predicted that children with ADHD and those with ADHD/DCD would display greater impulsivity by switching earlier than the switch signal presentation more frequently than the controls. This hypothesis was based on the observations that switching from in-phase (easy pattern) to anti-phase (more difficult pattern) is usually not an involuntary response and requires intention. Accordingly, pre-switch from in-phase to anti-phase mode can be better attributed to impulsivity than to inattention.

There were no significant group differences when children in the ADHD and ADHD/DCD groups combined were compared with the controls. However, this prediction was supported for the ADHD group only, which made 2.6 times more Pre-switch errors than the controls. Surprisingly, there was little difference between the ADHD/DCD and the controls.

A guarded explanation is that motor impairment in the ADHD/DCD group may have moderated impulsivity symptoms in this group. Since impulsivity was found to be positively correlated with lessened motor impairment in adult males (Nagoshi, Wilson, & Rodriguez, 1991), it is possible that increased motor impairment decreases impulsive behaviour. However, the correlational analysis of the relationship between motor performance on the MABC DCDQ and Pre-switch errors did not clearly support this effect. There was a non-significant small negative correlation between Pre-switch errors and MABC percentile scores (r = -.20, p = .29) but there was a trend shown by a moderate negative correlation between Pre-switch errors and DCDQ Total scores (r = -.33, p = .082).

Admittedly, the power of a correlational analysis with such a small sample size is limiting any firm conclusion. Perhaps future studies could examine the hypothesis that increased motor impairment decreases impulsive behaviour by introducing a range of levels of motor impairment to see whether the number of pre-switch errors varies as a function of motor impairment.

Motor control. Given that maintaining movement stability in the anti-phase mode is markedly more complex than in the in-phase mode, especially in clinical populations (Bogaerts & Swinnen, 2001), it was hypothesised that the ADHD/DCD group would have greater difficulties than the other groups in preventing involuntary switches (phase transitions)

after a switch had occurred to the anti-phase mode. This hypothesis was not supported by the data. The ADHD/DCD group made 5 times more Post-Switch errors than the controls but the effect was not statistically significant (p = .13). On the other hand, the ADHD group made significantly (12.5 times) more Post-Switch errors than the controls. Although both experimental groups contributed to the overall difference, the number of errors in the ADHD group accounted for most of the variance—as was the case for the Pre-Switch data.

The large difference between control and both groups with ADHD children in Post-Switch errors cannot be directly associated with a dysfunction in inhibitory processes and is better explained in terms of deficit in energetic states (e.g., Sergeant et al., 1999). Since a Post-Switch error occurs after the switch has been performed (i.e., in the absence of expecting a switch), it is possible that maintaining attentional effort to prevent phase transition back to the more stable in-phase pattern was too difficult (Wuyts et al., 1996). In Sergeant and colleagues‘ model, it may be argued that the activation pool was impaired. However, the reasons for which the ADHD group made 2.5 times more Post-Switch errors than the ADHD/DCD group is not easily explained by existing models and must be viewed with caution given the high variability of scores and the small size of the samples.

5.6. Conclusion

In summary, the results of this study supported previous findings that ADHD-C involves a deficit in the ability to inhibit an ongoing action (Barkley, 1997). They also supported the hypothesis that a lack of inhibitory control, usually associated with central processing, extends to motor inhibition during continuous movements, as measured by Switch-RT; although the small sample size of the experimental groups weakens the certainty of the results. Given the lack of ADHD-PI and ADHD-HI participants in this experiment, caution in generalising the findings to all ADHD subgroups is also necessary.

However, it is not clear whether impaired Switch-RT was primarily caused by a poor process of inhibition or a deficit in energetic states that regulate sustained and phasic attention. The overall attentional capacity did not appear significantly different across the three groups, but speed of execution and its variability were impaired. Assuming that slower Switch-RT during bimanual tasks is best attributed to impaired inhibition, research is needed to clarify whether the apparent delay in inhibition of a continuous movement and its re-engagement in a different direction were mostly due to impaired inhibitory control, impaired cognitive flexibility (re-engagement process), or both. This may be clarified by reassessing the same participants on a task, such as the Change Task (e.g. Oosterlaan & Sergeant, 1998), which divides the inhibitory process from the re-engagement process.

The results also supported the mounting evidence that ADHD is highly comorbid with DCD and that future studies need to assess the possible presence of DCD in ADHD samples. They further reinforced the view that DSM-IV criteria need to be altered to address the problem of comorbidity (Miyahara et al., 2006). Future studies of motor coordination in ADHD may benefit from comparing intentional switching during continuous movement across all subgroups, include more than one movement frequency and investigate the possible role of motor impairment as a potential moderating factor in impulsivity symptoms.

Chapter 6

Experiment 3

6.1. Aims and rationale

Experiment 3 used the Change Task, as traditionally delivered by computer (Oosterlaan & Sergeant, 1998; Schachar et al., 1995). As described in Chapter 1, the Change paradigm is believed to enable an examination of two separate executive control processes, the ability to inhibit an ongoing action or prepotent response (response inhibition) and response re-engagement, which is the ability to execute an alternative response immediately following the inhibited response (Logan & Burkell, 1986). This task has been described as a task-switching method because the response to the stop signal, which constitutes the secondary task, requires an immediate, separate and overt response to the stop signal (Schachar et al., 1995). The ability to switch rapidly and appropriately from one thought or action to another is a primary component of cognitive flexibility (Grattan & Eslinger, 1990).

The primary objective of this third experiment was to investigate the source of the poor Switch-RT performance in ADHD and ADHD/DCD during Experiment 2. As discussed earlier, it is not clear whether the apparent delay in inhibition of a continuous movement and its re-engagement in a different direction were due to impaired inhibitory control or impaired cognitive flexibility (re-engagement process). To enable

discrimination between these two processes, this experiment used the Change task, as traditionally delivered (e.g., Oosterlaan & Sergeant, 1998; Schachar et al., 1995), with the same participants.

6.1.1. Hypotheses

Based on the inhibitory dysfunction hypothesis (Barkley, 1997; Barkley, 1999; Pennington & Ozonoff, 1996), it was predicted that children with ADHD and ADHD/DCD would be less able than the controls to inhibit their Go response following presentation of a Stop signal, both in terms of probability and speed of inhibition. Based on the findings of Schachar et al. (1995) and Oosterlaan and Sergeant (1998), it was also hypothesised that children with ADHD and ADHD/DCD would be slower than the controls on the re-engagement task. Given the recent meta-analyses supporting the evidence of working memory deficits in ADHD (e.g., Boonstra, Oosterlaan, Sergeant, & Buitelaar, 2005; Martinussen et al., 2005; Willcutt, Doyle, Nigg, Faraone, & Pennington, 2005), it was further predicted that children with ADHD would make more errors than the controls on the primary task, which required skills necessary for rapid choice of correct response to Go signals. According to Barkley‘s (1997) theory of ADHD, a working memory deficit should appear only if the inhibitory process is impaired.

6.2. Method

6.2.1. Participants

The children who participated in this experiment were the same children who participated in Experiment 2 and the same exclusion and grouping protocols were applied. All medicated children had had their last medication administered at least 18 hours prior to testing. However, two participants were excluded as they (their parents) were not available to return for Experiment 3. Thus, the entire sample of participants (N = 32) consisted of 16 children in the Control group, nine in the ADHD (ADHD-C) group and seven in the ADHD/DCD group.

6.2.2. Apparatus and stimuli

Based on Livesey et al. (2006), the visual stimuli consisted of two coloured shapes of the same size, a blue disk (5.5 cm diameter) and a blue square (5.5 × 5.5 cm), which appeared in the upper centre of a laptop computer screen. Each shape also appeared permanently on each upper corner of the screen. Figure 6.1 shows the computer screen just prior to primary task stimulus presentation. The Stop signal was a 2000-Hz tone, 100 ms in duration, also generated and presented by the laptop computer.

A tracking algorithm, which dynamically adjusts the Stop signal delay (SS-Delay; the interval between the Go and the Stop signal) by 50 ms on each trial according to performance, was used (Livesey et al., 2006;

Ridderinkhof, Band & Logan, 1999; Schachar et al., 2000; Schachar, & Tannock, 1997). If the Go response was successfully inhibited on a Stop

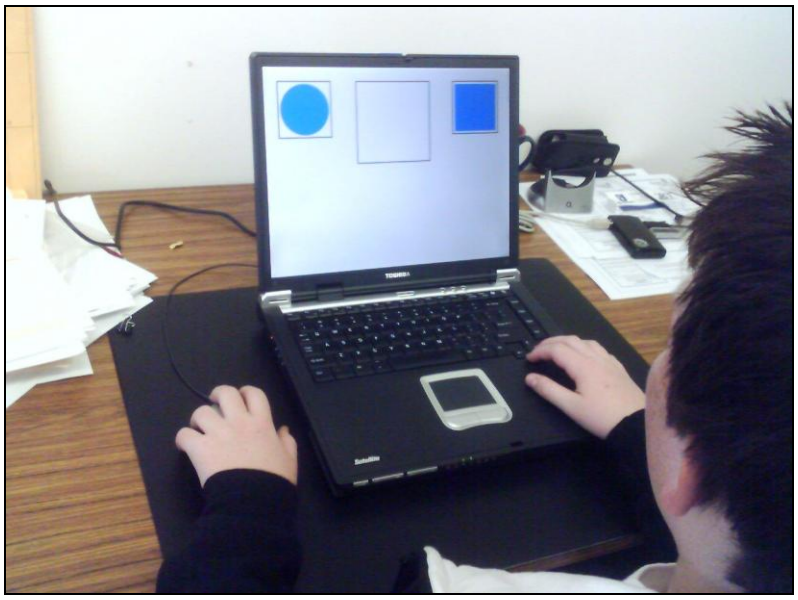

Figure 6.1. Computer screen before stimulus presentation.

trial, the SS-Delay on the next Stop trial was increased by a further 50 ms, rendering the response to the Go signal more difficult to inhibit. If the Go response was unsuccessfully inhibited on a Stop trial, the SS-Delay on the subsequent Stop trial was decreased by 50 ms, rendering the response to the Go signal easier to inhibit. Accordingly, the probability of inhibition was close to 0.5 in normally functioning children. Based on prior piloting trials, the SS-Delay was set initially at 350 ms. Time allowed for a response before a trial timed out and was registered as an error was 2000 ms.

6.2.3. Procedure

After explanation of the main aspects of the tasks, all participants performed all tasks in exactly the same way. Based on previous methodologies (e.g., Oosterlaan & Sergeant, 1998; Schachar et al., 1995), the response to the primary task (rapid choice between two responses; i.e., Go signal) was done with the non-dominant hand, on the computer mouse, and the response to the secondary task (alternative response following the Stop signal) was done with the dominant hand, on a key of the keyboard.

The entire procedure consisted of 12 blocks of trials totalling 278 trials. Based on previous methodologies, this amount of trials is feasible for this age group of children with and without ADHD (e.g, Oosterlaan & Sergeant, 1998; Schachar et al., 2000). Each visual stimulus (disc and square) occurred equally often within each trial. Block 1 contained 12 training trials for the Go trials, the primary task, which consisted of a two-choice reaction time task. Participants began each trial by attending to an empty square-shape surface (fixation point) in which one of two smaller geometrical shapes was about to appear (Figure 6.1). During Block 1, participants were required to recognise whether the stimulus (the blue shape which appeared in the empty square in the upper centre of the screen) corresponded to the shape permanently posted on the left or right side of the screen and to respond as quickly as possible by clicking the side of the computer mouse corresponding to the side of the screen where the appearing

shape ~~c~~ame from". For example, when the blue disc appeared in the empty square in the centre of the screen, participants were asked to click the left side of the computer mouse ~~b~~ecause the circle always comes from the left". When the square appeared in the large empty square in the centre of the screen, participants were asked to click the right side of the computer mouse, ~~b~~ecause the square always comes from the right".

Figure 6.2 displays the two modes of stimulus presentation (A and B) and the two types of visual feedback (C for correct responses and D for incorrect responses). In addition to the visual feedback, a soft bell sound accompanied the ~~h~~appy face" (C) when the response was correct and a soft low-tone buzz (about 500 Hz) accompanied the ~~sa~~d face" (D) when the response was incorrect. The purpose of this feedback was to reinforce correct responses and help maintain motivation and alertness to errors. Whether or not a response took place, each trial timed out after 2 seconds. The feedback display lasted for 1 second.

Block 2 consisted of 26 training trials for the Stop trials, which contained 70% Go trials and 30 % Stop trials. During these trials, participants were required to respond to Go signals and to do their best to stop their response (on the computer mouse) when a high-pitch tone was presented just after the visual stimulus appeared. Children were told to respond as quickly and accurately as possible to Go signals and not to wait for the Stop signal. Based on Ridderinkhof et al.'s (1999) recommendations

to prevent a strategy of ―waiting for a possible Stop signal" to trade speed of responding for accuracy of inhibition, instructions emphasised that speed was rewarded and that the probability of stopping a Go response was approximately 50%, regardless of waiting strategies.

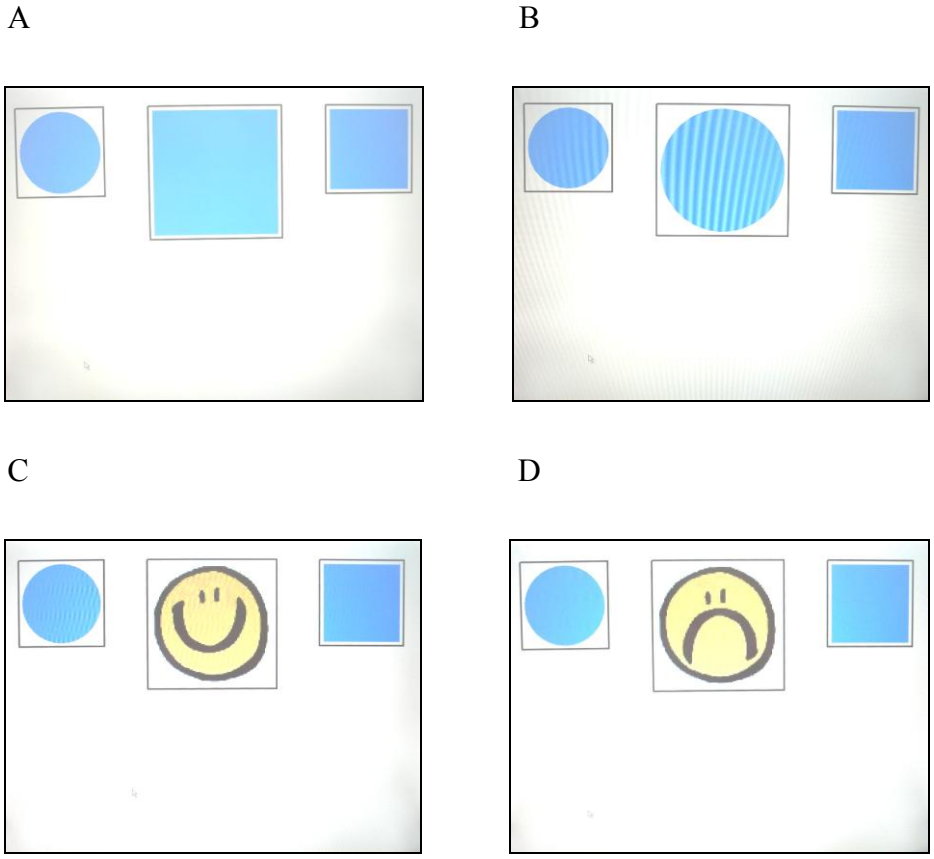

Figure 6.2. Computer screen showing stimulus presentations in A and B. C shows the image response on the screen following a correct response and D shows the image response on the screen following an incorrect response.

Block 3 consisted of 24 training trials for the Stop re-engagement trials, which also contained 70% Go trials and 30 % Stop trials. As in Block 2, participants were required to respond to Go signals and to do their best to stop their response when the Stop signal was presented. In addition, they were asked to press a key on the keyboard as fast as possible after the Stop signal presentation (re-engagement task). To prevent errors due to missing a key during rapid movement, participants were allowed to press one of four keys which were adjacent to each other on the keyboard. As in Block 2, children were asked to respond as quickly and accurately as possible to Go signals and not to wait for the Stop signal.

Blocks 4 to 12 were 9 experimental blocks. Each block consisted of 24 trials containing 70% Go trials and 30 % Stop re-engagement trials. In total these 9 experimental blocks included 70 Stop re-engagement trials, which was well above the minimum of 40 Stop trials required for reliable data (Ridderinkhof et al., 1999). Participants were asked to continue to perform the tasks required during Block 3. Each of these blocks lasted approximately 2.5 minutes. Only these 9 blocks were used for data analysis.

To avoid possible fatigue, participants were given short 10- to 30-second breaks after each block, as needed. The overall testing time lasted between 40 and 50 minutes.

6.2.4. Data reduction and dependent measures

Accuracy measures. Dependent measures of accuracy were calculated in percentages. They were the percentages of Correct Go trials, Correct Stop trials, and Correct Re-engagement trials. The percentage of Correct Re-engagement trials included only the trials on which re-engagement was successful.

Performance measures. Dependent measures of performance were reaction-time (in milliseconds) for Correct Go Trials (Go-RT), variability of Go-RT, as measured by the standard deviation (SD of Go-RT), Stop Signal Reaction Time (SSRT), Stop Signal Delay (SS-Delay), and reaction-time for re-engagement (Change-RT). SS-Delay is the mean interval between the Go and the Stop signal, calculated by the tracking algorithm, which dynamically adjusts the interval between the Go and the Stop signal by 50 ms at a time according to performance, as explained earlier. SSRT is calculated by subtracting SS-Delay from Go-RT. Since SSRT provides a measure of the time necessary to disengage from a response, shorter SSRT indicates better inhibitory control. Change-RT, a measure of cognitive flexibility which also requires inhibitory control (Schachar et al, 1995), is the mean latency of responding calculated across stop trials on which the response to Go trials was successfully inhibited, that is, across Correct Stop trials (Oosterlaan & Sergeant, 1998).

6.2.5. Design and analysis

Each measure was analysed separately with one-way ANOVA with Group (Control, ADHD and ADHD/DCD) as the factor. Post-Hoc analyses were analysed with Tukey HSD. Alpha level was set at .05 to indicate statistical differences between means. Effect size statistics were calculated with Partial eta-squared, described as per Cohen's (1988) guidelines.

6.3. Results

6.3.1. Accuracy measures

Accuracy data were analysed with one-way ANOVAs. There were no statistically significant differences between groups on any of the accuracy measures: percentage of Correct Go trials, ($M_{Control}$ = 90.69, SE = 1.53; M_{ADHD} = 90.19, SE = 2.04; $M_{ADHD/DCD}$ = 95.42, SE = 2.31), $F(2, 29) = 1.787$, p = .185, percentage of Correct Stop trials, ($M_{Control}$ = 51.59, SE = 0.95; M_{ADHD} = 50.39, SE = 1.27; $M_{ADHD/DCD}$ = 51.06, SE = 1.44), $F(2, 29) = 0.285$, p = .754, and percentage of Correct Re-engagement trials, ($M_{Control}$ = 44.25, SE = 1.93; M_{ADHD} = 45.80, SE = 2.57; $M_{ADHD/DCD}$ = 51.11, SE = 2.91), $F(2, 29) = 1.948$, p = .161, showing that all groups were similarly accurate in the primary and secondary tasks.

6.3.2. Performance measures.

For Go-RT, one-way ANOVA showed a significant group difference, $F(2, 29) = 6.183$, $p = .006$, with a large effect size (Partial eta-squared = 0.30). The effect is displayed in Figure 6.3. Post-hoc comparisons showed that the

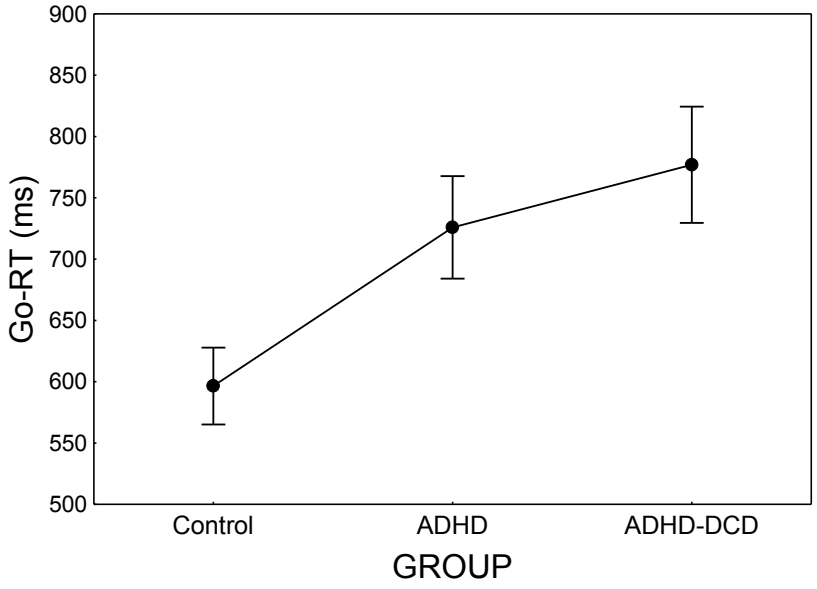

Figure 6.3. Mean reaction-time (ms) to correct Go trials for each group. Vertical bars indicate standard error.

Control group ($M = 597$ ms, $SE = 31$) was significantly faster than the ADHD ($M = 726$ ms, $SE = 42$; $p = .049$) and ADHD/DCD ($M = 778$ ms, $SE = 47$; $p = .009$) groups, and the performance difference between the ADHD and ADHD/DCD groups was not statistically significant ($p = .701$).

There was also a significant group difference in the within-subject variability of Go-RT, as measured by SD of Go-RT, $F(2, 29) = 35.437$, $p < .00001$, with a very large effect size (Partial eta-squared = 0.69). The

effect is displayed in Figure 6.4. Post-hoc comparisons showed that Go-RT in the Control group (M = 129 ms, SE = 12) was significantly less variable than in the ADHD (M = 230 ms, SE = 15; p = .0002) and the ADHD/DCD (M = 295 ms, SE = 17; p = .0001) groups. The difference in Go-RT variability between ADHD and ADHD/DCD was also significant (p = .025).

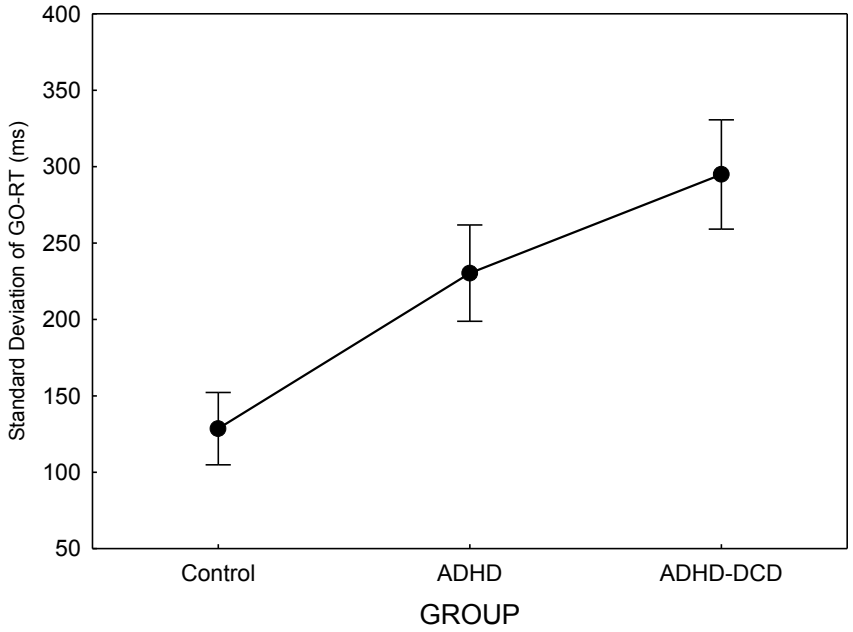

Figure 6.4. Standard deviation of reaction-time (ms) to correct Go trials for each group. Vertical bars indicate standard error.

For the SSRT measure, one-way ANOVA failed to show significant differences between groups, $F(2, 29) = 0.519$, $p = .601$. Children in the Control group ($M = 318$ ms, $SE = 23$) were comparable to those in the ADHD ($M = 283$ ms, $SE = 32$) and the ADHD/DCD ($M = 326$ ms, $SE = 36$) groups in their ability to inhibit their response.

One-way ANOVA for Stop re-engagement performance (Change-RT) yielded a statistically significant difference in the groups‘ rapidity to switch task, $F(2, 29) = 3.819$, $p = .034$, with a large effect size (Partial eta-squared = 0.21). The effect is displayed in Figure 6.5. Tukey‘s post-hoc test showed that Change-RT in the Control group ($M = 775$ ms, $SE = 49$) was faster than in the ADHD group ($M = 971$ ms, $SE = 65$), although the statistical difference between means was marginal ($p = .056$). Change-RT was not statistically different between the Control and the ADHD/DCD ($M = 957$ ms, $SE = 74$; $p = .116$) group. The difference in Change-RT between the ADHD and ADHD/DCD groups was not significant ($p = .998$). The effect shows that children in the Control group were significantly faster at re-engaging to the secondary task.

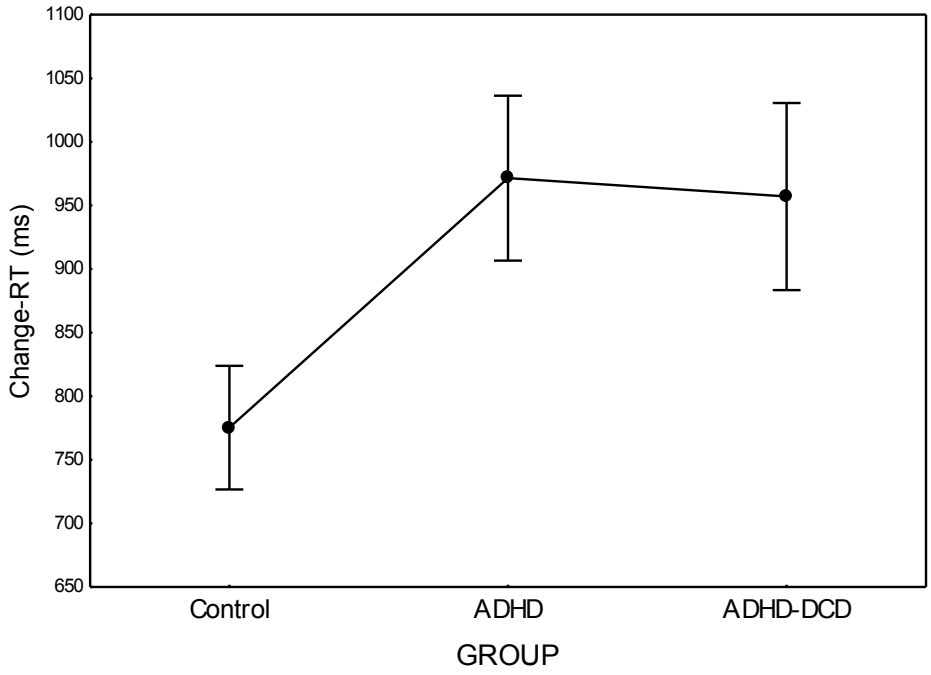

Figure 6.5. Mean Change reaction-time (ms) for each group. Vertical bars denote the standard error.

6.4. Discussion

This experiment used the Change task as traditionally delivered (e.g., Oosterlaan & Sergeant, 1998; Schachar & Tannock, 1995; Schachar et al., 1995) to investigate the source of poor Switch-RT performance during continuous movements observed in Experiment 2, with the same participants. In particular, it attempted to clarify whether the apparent delay in inhibition of a continuous movement and its re-engagement to a different movement pattern were due to impaired inhibitory control or impaired cognitive flexibility (response re-engagement process).

6.4.1. Accuracy measures

The probability of inhibition, as measured by Correct Stop trials, was very close to 50% for each group, indicating that the staircase tracking algorithm was effective. The overall probability of inhibition was 51% in this study and 51.7% in Schachar et al. (2000).

It was expected that children in the ADHD and ADHD/DCD groups would be less able to inhibit their response to the Stop signal (e.g., Oosterlaan & Sergeant, 1998). Contrary to prediction, the percentage of Correct Stop trials did not show statistically significant group differences. Probability of inhibition was 51.6% in the Control group, 50.4% in the ADHD group and 51.1% in the ADHD-DCD group. The results of this experiment are consistent with the findings of Schachar et al. (2000), which showed no difference in the probability of inhibition between their four groups (Normal Controls = 51.1%, ADHD = 51.3%, Conduct Disorder = 52.7%, and ADHD+Conduct Disorder = 52.2%). The difference in findings between Oosterlaan and Sergeant (1998) and the present study may be due to methodological differences. First, to calculate the probability of inhibition, the present study and Schachar et al. used a dynamic tracking algorithm, whereas Oosterlaan and Sergeant used an inhibition function (see Logan, 1994, for detailed procedure). Second, because of this tracking algorithm, the procedure in Oosterlaan and Sergeant was about three times longer than in Schachar et al. and twice longer than in the present study.

This alone can produce differences in attention demands and mental fatigue. Moreover, Oosterlaan, Logan, and Sergeant (1998) suggested that poor response inhibition is associated with children with disruptive behaviour, rather than being unique to ADHD. This observation is congruent with the results of the present study, in which none of the ADHD and ADHD/DCD children were characterised as disruptive.

The lack of significant group differences in the percentage of Correct Go trials also contrasts with Oosterlaan and Sergeant's (1998) finding. Moreover, accuracy in response re-engagement did not separate the groups. As in Experiment 2 and in other findings (e.g., Alvarez Del Pino, 1996; Schachar & Logan, 1990a; Taylor, 1995; Vaughn, 1997), there was no evidence of deficit in overall attentional capacity in any of the groups when processing speed was taken into account.

6.4.2. Performance measures

The prediction that the performance of ADHD and ADHD/DCD children would be significant poorer than that of the controls on the Go-RT task was supported. Consistent with past research (e.g., Houghton et al., 2004; Schachar et al., 1995, 2000; Smith et al., 2006), the controls were significantly faster than the ADHD and ADHD/DCD groups at responding correctly to Go signals than other children. This is also consistent with Experiment 2 of the present study, during which the controls were faster at

switching direction during continuous circling movement.

In line with the literature (e.g., Oosterlaan & Sergeant, 1998; Schachar et al., 1995, 2000; Smith et al., 2006), the variability of Go-RT was also significantly greater in the ADHD group than in the Control group. This difference was exacerbated in the ADHD/DCD group, which was significantly more variable than the ADHD and Control groups. The results reflect a generally slower mode of processing information in children with ADHD, in line with the notion that ADHD is associated with slower motor output (Sergeant, 2000); although an overall impairment in processing speed would be expected to also impair SSRT (Oosterlaan et al., 1998; Tannock, 1998).

It was further predicted that children with ADHD and ADHD/DCD would display longer inhibitory process, as measured by SSRT. As in several studies (e.g., Boerger & van der Meere, 2000; Wolfe & Riccio, 2005), the present results did not support this hypothesis. There was no indication of slower SSRT in children with ADHD and ADHD/DCD. Stefanatos and Baron‘s (2007) comprehensive review also points out that slow response inhibition may be best attributed to general constraints in processing speed than to a specific response inhibition deficit. This view is consistent with the present data, showing slower and more variable processing speed in ADHD and ADHD/DCD in both experiments. These results add to a growing number of ADHD studies unable to replicate the

findings of abnormally slow inhibitory process when factors such as motivation (Shaw et al., 2005), testing context (Lawrence et al., 2002) and the role of reinforcement (Aase & Sagvolden, 2006; Johansen et al., 2002) are taken into account.

Motivational and reinforcement factors were taken into account in shaping the procedure of the present experiment. Visual and auditory rewards were presented on screen systematically after each successful response in the form of a –happy face" and a soft bell sound (Figure 3.6). A low-tone buzz accompanied by a –sad face" were presented systematically when the response was incorrect. In addition, positive feedback and motivational statements (e.g., –great job", –well-done", –you're very fast") were systematically offered to all participants at completion of each block. At the beginning of the subsequent blocks, motivational statements (such as –let's see if you can do as well on this block", or –show me how well you can do on these trials") were also given systematically to all participants. It is possible that such frequent reinforcement may have offset some aspects of inhibitory impairment.

Moreover, while children with ADHD were impaired in stopping an ongoing motor action (Experiment 2), they were unimpaired in suppressing a prepotent response (Experiment 3). Accordingly, the data from both experiments, in which the same children participated, may indicate that different inhibitory processes underlie the ability to stop an ongoing action

and the ability to stop a prepotent response. It has been pointed out that deficit in SSRT may be produced by different mechanisms (Sergeant, 1998). Thus far, it has been assumed that inhibition of an ongoing action and inhibition of a prepotent response are enabled by the same mechanism (e.g., Barkley, 1997; Pennington & Ozonoff, 1996). More research is needed to establish whether both processes follow the same neuropsychological and physiological pathways.

This experiment was primarily concerned with the source of poor Switch-RT performance observed in Experiment 2; with the same participants. As predicted, the latency of response re-engagement, possibly a more demanding aspect of inhibitory mechanisms (Schachar et al., 1995), was impaired in Children with ADHD and ADHD/DCD. This deficit has been demonstrated by other studies (Schachar & Tannock, 1995; Schachar et al.'s (1995). Alvarez Del Pino (1996) also found that ADHD and control children did not differ in their ability to divide and allocate attention but ADHD children were impaired in their ability to reallocate (re-engage) attention. The data showed that the apparent delay in inhibition of a continuous movement was principally associated with re-engagement mechanisms rather than an earlier process required for ~~"p~~ure" inhibition. It appears that the main impairment for these ADHD groups was in cognitive flexibility and processing speed. Schachar et al. (1995) also explained slower go, stop and switch processes in ADHD in terms of ~~"a~~ generalized deficit in speed of response" (p. 428).

It may also be that the mechanisms involved in inhibiting and re-engaging a continuous movement in Experiment 2 were more demanding than the traditional button-press task used in Experiment 3. However, if the physical force exerted to stop a circling movement and re-engage in a new direction was a significant factor, it would be expected that children with motor impairment would perform worse than others (Piek & Skinner, 1999). This was not the case. The comparability in Change-RT between the ADHD and ADHD/DCD groups (p = .975) may suggest that the impairment in cognitive flexibility may be best attributed to differences in processing speed or allocation of attention required for decision-making (Sergeant, 2000).

6.5 Conclusion

In summary, the present results reflect a slow mode of information processing in ADHD rather than a deficit in the processes necessary to inhibit a prepotent response. The results indicated that the delay in inhibition of a continuous movement and its re-engagement in a different direction observed in Experiment 2 were principally affected by slowed re-engagement response, rather than impaired inhibitory process per se. This observation was enhanced in children with motor dysfunction, indicating that difficulties in cognitive flexibility and motor coordination were the main deficits in these samples.

However, although keeping the same participants in both experiments was a strength in this study, the results were weakened by the small sample size of the groups. Replication of these results is therefore necessary. Moreover, it is possible that the process of inhibiting an ongoing motor action does not rely on the same mechanism which subserves the process of suppressing a discrete prepotent response. Future studies are needed to clarify the assumption of a single process for both types of inhibition.

Chapter 7

General Discussion

Although ADHD is one of the most studied developmental disorders in Western countries (Tannock, 1998), it remains essentially difficult to understand. ADHD performance over time, across tasks, and in different situations, shows large variability (Mash & Wolfe, 1999; van der Meere & Sergeant, 1987), and the role of motor coordination in ADHD research has been largely underrepresented. As reflected by the DSM-IV description, the common view is that poor motor coordination observed in about half the children with ADHD is caused by impulsivity, which emerges from deficits in behavioural inhibition (Barkley, 1997). However, it has also been argued that motor impairment in ADHD is largely the consequence of DCD comorbidity in samples studied (e.g., Miyahara et al., 2001; Piek et al., 1999; Sergeant et al., 2006) or brain abnormalities in motor networks that are unrelated to impulsivity (e.g., Klimkeit et al., 2004). The present research aimed to provide further understanding of impaired motor coordination in children with ADHD by systematically measuring the dynamics of their bimanual coordination during continuous circling patterns.

7.1. Comorbidity

A consistent difficulty encountered by both clinicians and researchers is the lack of adequate diagnostic criteria in DSM-IV (Miyahara et al., 2006). The limitation of the current DSM taxonomy results in uncontrolled subtype heterogeneity in many ADHD samples chosen for research (Stefanatos et al., 2007). Nonetheless, the performance of children categorised with ADHD-C cannot be assumed to reflect that of children given a ADHD-PI or ADHD-HI diagnosis and there is no conclusive support for the assumption that ADHD-PI and ADHD-HI are even parts of the same disorder (Woo & Rey, 2005). However skilled a clinician, relying on imprecise, and sometimes confusing, sets of criteria for diagnosis can render interventions disappointingly ineffective and research redundant when inclusion of comorbid conditions occurs.

In particular, the present studies further demonstrated the substantial comorbidity between ADHD and DCD, and how controlling for DCD confound in ADHD samples can lead to considerably different conclusions. In the first experiment, 30% of the children professionally diagnosed with ADHD were identified with undiagnosed comorbid DCD. Similarly, in the second study, 35% of the children with ADHD met the criteria for both ADHD and DCD and three met the criteria for DCD but not ADHD.

In Experiment 1, the first analysis of results showed that movement stability in children with ADHD was maintained at a higher frequency than

that in the controls on the crank task, but not on the template task. However, when controlling for DCD comorbidity, the second analysis failed to show such group difference. On the other hand, the maximum movement frequency at which stability was maintained on the template task was slower in the ADHD/DCD group than in the Control and ADHD groups. There was no difference on the crank task.

This contrasting observation reoccurred in Experiment 1 on the principal measure of stability (variability of the lead-lag between hands), as measured by the standard deviation of the relative tangential angle. Whereas not controlling for DCD comorbidity resulted in concluding that movement stability was poorer in ADHD than in control children, reanalysing the data to account for comorbidity showed no stability difference between control and ADHD children. Alternatively, the results demonstrated that the variance observed in the first analysis was mostly attributable to the comorbid ADHD/DCD group.

These observations reinforce the recent call for caution in ADHD research and highlight the importance of controlling for comorbidity confounds (Baron, 2007; Miyahara et al., 2006; Piek et al., 2007; Sergeant et al., 2006). The results also suggest the need for further investigation of the role of physical exercise in multimodal treatment of ADHD. From what was observed in the first experiment, one would predict that motor control training would be mostly beneficial to ADHD children with comorbid DCD

but not necessarily to those without comorbid DCD. If such observation is made following further examination, treatment resources could be allocated more efficiently, which could increase the child's potentiality for improvement. Indeed, three children whose symptoms fit only the criteria for DCD were diagnosed with, and pharmacologically treated for, ADHD, where motor control training may have been more beneficial. According to parent reports, two ADHD (only) children had motor control training and did not improve, and none of the ADHD/DCD children were given motor control training.

7.2. Spatial versus temporal deficit

A goal of this research was to provide greater understanding of the spatial and temporal components of bimanual coordination in ADHD. In the first experiment, when bimanual cranks were used, the need to maintain spatial accuracy was minimised so that the ability to maintain temporal stability (lead-lag) between hands was made explicit. In contrast, with free-hand circling, using circle templates, it was necessary to control both spatial accuracy and temporal stability at the same time.

In all groups, movement stability (as measured by SD-RTA) was overall greater in the template than in the crank condition. A hypothetical explanation is that when using the templates, participants traded off spatial accuracy for temporal stability. This was done by making smaller, larger or

more elliptic movements to compensate the inaccurate timing between the hands and to avoid increases in instability of the bimanual movement. However, when circling movements were locked to the circular trajectory of the cranks, spatial tradeoffs were not permitted, thereby limiting the compensatory effect of making spatial adjustments on temporal stability. This hypothesis suggests that the stability of free-hand bimanual circling depends on factors which include allocating and sustaining attention to detect timing differences between hands and correct these differences by adjusting the size and shape of the pattern. It is also possible that the dynamic interplay between the spatial and temporal components during the template task is less a conscious process than that and does not necessarily rely on an intentional process of strategically maintaining pattern stability. However, some amount of attention would be required. Given that attention has been shown to help preserve bimanual pattern stability (e.g., Monno et al., 2000; Wuyts et al., 1996), the data also suggests that ADHD-C and control children were comparably able to allocate and sustain attention to the task and did so more effectively that the ADHD/DCD group.

In the first experiment, movement timing in the controls was just as accurate on both templates and cranks, suggesting that the controls were able to maintain comparable timing accuracy whether the spatial component was minimised by the cranks or maximised by the templates. In contrast, children with ADHD symptomathology had significantly more difficulties matching target frequency when using the templates but not when using the

cranks. In other words, a timing difficulty was apparent, but only when the spatial component of the task was presented. It is understandable that more variable and less accurate patterns would decrease timing accuracy. Thus, timing error in these children, especially in the ADHD/DCD group, was poorer than in the controls because of impairment in the spatial component of the movement.

There is some evidence that DCD involves visual-spatial deficits (Ameratunga, Johnston, & Burns, 2004; Piek et al., 2004; Wilson & McKenzie, 1998), which could explain the present results. Spatial accuracy data in Experiment 1 supported the view that DCD comorbidity produced an increased deficit in spatial performance. The proposition that poor visuo-spatial processing in DCD could lead to timing error was also offered by Piek et al.'s (2007) recent investigation of executive functioning in ADHD and DCD, and is an area which requires more investigation.

It also emerged from the data of the first experiment that stability in the ADHD/DCD group in the anti-phase mode was equally poor at both low and high movement frequencies compared to the other groups. Hence, even slow movements requiring the coordination of non-homologous muscles during anti-phase patterns can be too complex for this group. It appears that the mode of coordination, rather than movement frequency, determines the complexity of the movement and is central to the stability of continuous movement in ADHD with comorbid DCD. Accordingly, it seems a

reasonable assumption that DCD comorbidity would reflect a deficit in the production of new and complex coordination patterns, especially those requiring non-homologous muscle activations. The present results showed no evidence of such impairment in the ADHD (only) group. In fact, a deficit in bimanual coordination occurring in ADHD children was only shown by a study which did not control for DCD comorbidity (Klimkeit et al., 2004). It is therefore possible that the observed bimanual coordination deficit in ADHD was largely caused by DCD comorbidity.

Experiment 1 was also useful in examining whether the crank-versus-template paradigm was a useful way of investigating spatial and temporal components during circling patterns. A main effect of Task showed that between-hand stability was significantly greater on the template task than on the crank task in the in-phase and anti-phase modes. It appears that comparing bimanual cranks and free-hand patterns was effective in measuring the extent to which spatial tradeoffs moderated between-hands temporal instability. A testable prediction would be that when such tradeoffs are necessary to preserve pattern stability, individuals with impairment in the spatial component of the movement will fail to trade off efficiently and allow temporal instability, as measured by SD-RTA. This can also be observed through phase transition during anti-phase patterns. Poor spatial-temporal trade-off (due to spatial impairment) is expected to produce phase transitions at slower movement velocities. While this proposition needs to be supported empirically, the crank-versus-template methodology seems to

be a valid and useful approach for future studies investigating the dynamic relationship between spatial and temporal components of continuous bimanual movements.

7.3. Response inhibition and energetic states

The data from the first and second experiments of the second study were a better fit for the energetic states dysfunction model (Sergeant, 2000; Sergeant et al., 1999, 2006; Sergeant & van der Meere, 1990) than for the theory of ADHD which asserts a deficit in the behavioural inhibitory process (Barkley, 1997; Pennington & Ozonoff, 1996; Quay, 1988). Although the first experiment showed a deficit in Switch-RT, the lack of replication with SSRT measure with the same participants in the second experiment suggests that Switch-RT may not be evaluating the same inhibitory processes measured by the Stop Task. Since GO-RT and Change-RT were impaired in the second experiment, Switch-RT during continuous bimanual movement may be better conceptualised as a composite measure of response execution and cognitive flexibility.

Sergeant (1998) pointed out that whether the hypothesised inhibitory deficit in ADHD reflects a central (cortical) or peripheral (motor) deficit remains unclear. It is also unclear whether the mechanism in the inhibitory process involved more motor selection or motor preparation (Sergeant, 1998). The lack of certainty regarding the types of inhibitory processes was

also expressed by Livesey et al. (2006), who attempted to test the validity of the Stop Signal task as a measure of response inhibition in young children (5 and 6 year-old) with externalising behaviours. The results did not support the Stop Signal task as a measure of response inhibition, as there was only a negligible relationship between scores on the Stop Signal task and other measures of response control, such as the Day-Night Stroop (Gerstadt, Honh, & Diamond, 1994). Whereas motor performance was not related to SSRT, it was significantly related with more ecologically valid measures of behavioural inhibition, including the Stroop performance, which also measures processes such as attention (MacLeod, 1991). It was concluded that SSRT measures an aspect of inhibition that is different from aspects measured by other tests of behavioural inhibition. Moreover, Since Experiment 2 required changing a response (switching direction) within the same task (ongoing circling movements), it may not have required cognitive flexibility in the same way as the Change Task implemented via a cognitive modality (i.e., when delivered via computer).

In the present research, the lack of evidence for a primary deficit in inhibitory process, associated with a reliable observation of impairment in response execution (replicated in both Experiments 1 and 2) and higher variability of speed of responding in ADHD, is in line with past studies (e.g., Scheres et al., 2001). This suggests that the effort and/or activation pool in Sergeant and van der Meere‘s (1990) model may be impaired in ADHD.

The effort pool is associated with phasic arousal and activated when a sudden response is required. Both Switch-RT (Experiment 2) and Go-RT (Experiment 3) were impaired in the ADHD groups. The activation pool is associated with tonic arousal, which allows allocation of attention to produce a state of high behavioural flexibility and is directly associated with motor output (Sergeant, 1998). The energetic processes necessary for maintaining attention to the visual cue (arrows) until a switch was required (in Experiment 2) and re-engaging in the secondary task (in Experiment 3) were impaired in children with ADHD symptomathology. Taken together, this would suggest impairments neurologically identified with the basal ganglia and corpus striatum (Pribram & McGuiness, 1975).

Furthermore, recent findings have led authors to stress the importance of context in ADHD research (e.g., Brophy et al., 2002). It is not sure that similar bimanual tasks would result in the same group differences when implemented in more ecologically valid contexts. It may be possible to design a laboratory-based "driving" task, whereby the child is required to hold (one or) two wheels simultaneously and attempts to avoid (simulated) obstacles, with intermittent requirements for breaking suddenly (task-switching). The methodology could also include distractors to further investigate the possible implication of sustained interference inhibition, which has recently been proposed as a more accurate description of the inhibitory impairment in ADHD (Lawrence et al., 2002).

7.4. Limitations of the studies

This series of experiments encountered several limitations, some of which can easily be prevented in future studies. One is the small sample size of the ADHD and ADHD/DCD groups. Given the small community in which this research was carried out, future research facing this dilemma may consider multi-site investigations. This is also one of the very few investigations on bimanual coordination dynamics in ADHD and replication of the findings using larger groups is necessary. Future motor coordination research in ADHD would also benefit from the inclusion of a DCD (only) group. This would help verify the proposition that most motor impairments observed in the present research are best attributable to DCD than to ADHD symptomathology.

7.5. Summary and future directions

Overall, the data from the present research were a better fit for the aetiological hypothesis of energetic states dysfunction (Sergeant, 2000; Sergeant & van der Meere, 1990) than for the theory of ADHD which asserts a primary deficit in response inhibition (Barkley, 1997; Quay, 1997). Future studies investigating bimanual coordination in ADHD may consider the use of experimental designs which test more specifically the activation pool in the states dysfunction model.

Moreover, advances in technology have permitted reliable neurological observations that chronic stress can impair executive functions such as cognitive flexibility (Liston et al., 2006). It may therefore be useful in future research to control for stress-related variables when selecting participants and perhaps include a stress-reduction method to monitor the possible effects of stress on attention-shifting processes necessary for cognitive flexibility.

Two potentially major factors for the present results are an emphasis on reinforcement mechanisms during testing and controlling for DCD comorbidity. Comorbidity is recognised to be a major confounding variable in ADHD research. One of the main findings of the present research is that most impaired components of bimanual coordination usually attributed to ADHD were actually related to DCD comorbidity. Observations from studies which do not control for the presence of DCD and derive definitive conclusions from observations made during motor tasks, whether continuous or discrete, are likely to be misleading. Accordingly, the present findings support the claim that it is essential for future ADHD studies to include an assessment of motor coordination (e.g., Piek et al., 2007).

Moreover, in line with previous suggestions (e.g., Miyahara et al., 2006; Sergeant et al., 2006), the lack of adequate diagnostic criteria in DSM-IV will have to be addressed in DSM-V. Although doing so is likely to improve efficacy of treatment and help produce more fruitful research,

this may also be problematic given the categorical taxonomy of this diagnostic tool. Indeed, the rather convincing data which suggest that ADHD should modelled as a continuum and that no discrete dysfunction can be assumed to cause it (Haslam et al., 2006) deserves careful attention. Perhaps, the utilisation of the bimanual crank-versus-template paradigm, whether modified or as used in the present research, could contribute to the process of finding a better categorisation of ADHD.

The overall aim of this research was to combine measurement tools use by the information-processing and the dynamical-systems approaches to help clarify the sub-components of motor coordination deficits in ADHD. It was found that impairment in the temporal stability of bimanual circling patterns was mostly attributable to difficulties in controlling the spatial component of the task, and that this impairment was mostly evident in children with comorbid ADHD and DCD. Children with ADHD without motor dysfunction did not show impairment in the spatial component of circling movements. Based on the present results, it is concluded that children with ADHD without DCD do not suffer from a bimanual coordination impairment.

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Appendices

Appendix A

A.1. Information sheets

A.2. Consent forms

Appendix B

B.1. *ADHD Rating Scale-IV* and scoring sheets

B.2. *Edinburgh Inventory*

B.3. *Developmental Coordination Disorder Questionnaire* and scoring sheet

Appendix A.1

Information sheets

UNIVERSITY OF TASMANIA

School of Psychology

INFORMATION SHEET FOR PARENTS OR GUARDIANS

Title of Study

The Dynamics of Bimanual Coordination in Attention Deficit Hyperactivity Disorder (ADHD)

Researchers

Professor Jeffery J. Summers, Associate Professor Clive Skilbeck, and Mr. Bruno Cayoun, Human Motor Control Centre, School of Psychology, University of Tasmania.

Purpose of the study

The aim is to better understand ADD and ADHD by studying the difficulties that a large number of children with ADD/ADHD have in coordinating their movements. The research will ask -

- Are these difficulties to do with the timing of movements?
- Is the main problem in attention or in stopping ongoing movements?

The answers may help in the treatment of ADD/ADHD.

The project is being undertaken as part of a PhD in clinical psychology.

Criteria to join the Study

The research will involve right-handed boys (aged 8-15 years) who are

- diagnosed with ADD/ADHD by a Paediatrician, Child Psychiatrist, or Child Psychologist

AND

- boys of the same age group who do not have ADD/ADHD

Boys with a general learning disability requiring special classes at school, neurological disorder (such as epilepsy), other chronic or serious physical medical problem, hearing difficulty, psychosis, or a clinically significant mood or anxiety disorder will not take part. If you are willing for your son to join the research you will be asked to fill in a very short questionnaire on home behaviour. A very short questionnaire on classroom behaviour will also be sent to your son's teacher(s). This will ensure that all children diagnosed with ADD or ADHD fit the criteria for this study. Also, this ensures that boys without a diagnosis of ADD or ADHD do not have too many symptoms of inattention or hyperactivity.

Study procedures

If you agree to your son joining the study, the information on this sheet will be explained to you later in more detail and you will be asked to sign a consent form. The study will be explained to your son in a simpler form. He will also be asked to agree to participate, to ensure that he is willing to do so.

The project compares motor and attention performances of both children with and without ADD/ADHD. Participation in the studies will require your son to attend two sessions lasting up to 50 minutes, which will take place in the Human Motor Control Centre, Room 228, Arts Building (Level 2), at the University. You can stay in the room, out of your son's sight, during testing.

After explanation of the procedure, your son will be comfortably seated at a table. In each experiment, he will be asked to continuously trace the outside of circles with his index fingers using two forms of coordination. He will follow a tone to pace the movements.

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Sometimes he will be asked to change the direction of the movement pattern when a light appears. Each run has five 20-second trials, each with a brief rest interval. To avoid fatigue, your son can be given breaks as frequently as necessary. Another part of the study involves your son pressing a button as fast as he can when a signal appears on a computer screen or when a sound occurs.

It is important that boys with ADD/ADHD participating in the research are not under the effect of medication (such as Ritalin or dexamphetamine) at the time of testing. Therefore, for children who are medicated, testing will be at least six hours after their last medication intake.

Payment to participants

You will be reimbursed for out of pocket expenses associated with travel to and from the University.

Possible risks or discomforts

To avoid fatigue, your son will be given breaks as frequently as necessary. All possible effort will be made to ensure a pleasant and interesting experience for him. Also, you can remain in the room (out of your son's sight) during testing.

For some boys with ADD or ADHD, the brief withdrawal of medication might lead to some hyperactive symptoms. If your son has a diagnosis of ADD/ADHD and is medicated, your presence will assist a smooth and effective procedure. If your son cannot perform the tasks due to hyperactive symptoms, the session will be stopped and postponed. If necessary, the period of medication withdrawal can be decreased to five or four hours for the next session.

Confidentiality

Confidentiality will be maintained and only the researchers will have access to your son's data. Information gathered will include name, age and general medical condition. For boys with ADD or ADHD, the medication (type and dosage) and a brief description of the medical history from the clinician (Paediatrician, Child Psychiatrist, Child Psychologist) will also be noted.

Freedom to refuse or withdraw

Joining the study is voluntary. With your approval and supervision, if your son agrees to participate he is free to withdraw from the study at any time. Withdrawal will not affect your child's care and treatment by the health services.

At all stages of the study, the research team has a continuing interest in the well-being of the boys. If for any reason your child is not willing to continue at any stage of the study, he will be thanked and complimented for his effort, to end his participation in a pleasant manner.

Contact persons

If you wish more information about the study, please contact Professor Jeff Summers (6226 2884) or Associate Professor Clive Skilbeck (6226 7459), or Bruno Cayoun (PhD candidate) on 6226 2261 (Email: bcayoun@postoffice.utas.edu.au).

Concerns or complaints

The project has received ethical approval from the Southern Tasmania Social Sciences Human Research Ethics Committee. However, if you have any concerns of an ethical nature or complaints about the manner in which the project is conducted, you may contact the Chair A/Professor Margaret Otlowski (ph. 6222 8195), or the Executive Officer of the Committee, Mrs Amanda McAully (ph. 6226 2763).

Results of the Research

If you wish, you can be informed of the results of the study at its end. You can also obtain feedback on your son's results. You will be given a copy of the Information Sheet and Consent Form to keep.

UNIVERSITY OF TASMANIA

School of Psychology

INFORMATION SHEET (12-15 years)

Title of investigation

The Dynamics of Bimanual Coordination in Attention Deficit Hyperactivity Disorder (ADHD)

Investigators

Professor Jeffery J. Summers, Associate Professor Clive Skilbeck, and Mr. Bruno Cayoun, Human Motor Control Centre, School of Psychology, University of Tasmania.

Purpose of the study

We are interested in looking at the movement of the hands in children with ADD and ADHD to see how they coordinate their movements. This will help us to understand better ADD and ADHD. In particular we would like to answer the following questions:

- Is the timing of movements a difficulty for those children?
- Is the main problem in attention or in stopping ongoing movements?

If we can answer these questions, this will have implications for the treatment of ADD/ADHD.

Who can participate?

The research will involve right-handed boys (aged 8-15 years) diagnosed with ADHD by a Paediatrician, Child Psychiatrist, or Child Psychologist; but this research will not need all children to have ADD or ADHD. The research also needs boys of the same age who do not have ADD or ADHD. If you would like to participate in the research, a short questionnaire on home behaviour will be sent to your parents and a questionnaire for teachers on classroom behaviour will be sent to your teacher(s). The reason for this is that we would like to make sure that the research suits you.

Study procedures

If you agree to participate, the information on this sheet will be explained to you later in more detail. You will be asked if you really agree to participate.

Participation in the studies will require you to attend two sessions lasting up to 50 minutes, which will take place in the Human Motor Control Centre, Room 228, Arts Building (Level 2), University of Tasmania. Your parent (or guardian) can stay in the room, out of your sight, during the exercises.

After having been explained the procedure and answered all questions, each boy will be comfortably seated at a table. In each experiment, the boys will be asked to continuously trace the outside of two circles with their index fingers. They will make circling movements in two directions and the speed of these movements will be guided by a small tone that sounds like a "bip" made by a computer.

Sometimes children will be asked to change the movement pattern to a different direction when a light appears in front of them. Each run has five 20-second trials, each with a brief rest interval. To avoid fatigue, children can be given additional or longer breaks as frequently as they need. Another part of the study involves children pressing a button on a box as fast as possible when a signal appears on a computer screen while or when a sound occurs.

It is important that children in the study are not under the effect of medication (such as Ritalin or dexamphetamine) at the time of testing. Therefore, for children who are medicated, testing will be at least six hours after they have taken their medication last.

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Payment to participants

You/your parent will be reimbursed for the cost of your travel to and from the Human Motor Control Centre at the University of Tasmania.

Possible risks or discomforts

To avoid fatigue, you will be given breaks as frequently as necessary. All possible effort will be made to ensure a pleasant, interesting and smooth experience for the children. Also, your parent (or guardian) can remain in the room where children do the hand movements. It is possible that some children who take medication for ADD or ADHD will be a little agitated during the brief time where they will be without medication. In that case, the presence of their parent (or guardian) will make it easier. If you cannot perform the movements due to some agitation (which we call hyperactive symptoms), the session will be stopped and postponed.

Confidentiality

No one other than the people who do the research will see how you perform. Information gathered will include your name, age and information about your health in general. Also, we will look at the type and dosage of medication that some Children with ADD or ADHD take.

Freedom to refuse or withdraw

Participation in the research is completely voluntary. This means that, with your parent's approval and supervision, if you agree to participate in the study, you are free to stop participating at any time.

Withdrawal of a participant form the project by the investigators

At all stages of the study, the people who do the research care very much for the children who will participate. If for whatever reason you don't want to continue at any stage of the study, the people who do the research will thank you and compliment you for your effort, and you won't have to come back.

Contact persons

If you wish more information about the study, please contact the chief investigator Professor Jeff Summers (6226 2884) or Associate Professor Clive Skilbeck (6226 7459) during office hours, or to Bruno Cayoun (PhD candidate) on 6226 2261 (Email: bcayoun@postoffice.utas.edu.au).

Concerns or complaints

The project has received ethical approval from the Southern Tasmania Social Sciences Human Research Ethics Committee. However, if you have any concerns of an ethical nature or complaints about the manner in which the project is conducted, you may contact the Chair A/Professor Margaret Otlowski (ph. 6222 8195), or the Executive Officer of the Committee, Mrs Amanda McAully (ph. 6226 2763).

Results of the Research

If you wish, you can know the results of the study at its end. You can also be given feedback on your own results. You will be given a copy of the Information Sheet and Consent Form to keep.

UNIVERSITY OF TASMANIA

School of Psychology

INFORMATION SHEET (8-11 years) ON *Moving Hands Game*

Who has the Game?

Jeff, Clive, and Bruno at the University.

What is the game for?

We would like to look at how children move their hands in circles.

If we know what happens when children draw circles, this might help children who have problems with concentration and those who can't keep still.

What is the Game?

If you want to play the game, we can tell you about it. We can also tell you more later, if you decide to play the Game. The game is at the University of Tasmania, where you will need to come for a little less than one hour twice if you agree. Your parent (or guardian) can stay with you during the game.

If you come, you will sit at a table. You will be asked to continuously trace the outside of two circles with your fingers. It is like drawing two small circles at the same time. You will draw the circles in two directions. The speed of your movements will follow a computer tone that sounds like a "bip".

Sometimes you will be asked to change the direction of your circles when a light appears.

You will be given rests, so you won't feel tired. In another part of the game, you will also be asked to press a button as fast as you can when the computer screen changes. Sometimes you have to stop pressing the button when a sound comes on.

If you take special medication to do with problems of attention you will not take it just before coming to play the game, but you will be able to take it just after.

Any Problems?

Your mum or dad (or guardian) can stay in the room where you do the game. If you cannot do the game on one day, you can come back another day to do it. If you feel that you are doing something you do not want to do or you need to speak with someone else than the people who run the game, you can tell your parents and they can decide to contact the people who authorised the game: Mrs Margaret Otlowski (ph. 6222 8195), or Mrs Amanda McAully (ph. 6226 2763).

How well did I do?

If you wish, we can tell you how well you did the game. We won't tell other children how you did.

Do I have to do the game?

NO. We only want you to do the game if you are happy to do it and if your parents agree too. Also, you can also stop doing the game at any time. You don't have to continue if you don't want to, and you won't have to come back.

Any questions?

If you need to know more about the game and your parents are not sure how to answer your questions, they can phone Jeff (6226 2884) or Clive (6226 7459) or Bruno (6226 2261), or Email: bcayoun@postoffice.utas.edu.au.

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Appendix A.2

Consent forms

UNIVERSITY OF TASMANIA

School of Psychology

STATEMENT OF INFORMED CONSENT FOR PARENTS OR GUARDIANS (Control)

Chief Investigator: Prof. Jeffery J. Summers *Co-Supervisor:* A/Prof. Clive Skilbeck
PhD Candidate: Bruno A. Cayoun

Title of Study

The Dynamics of Bimanual Coordination in Attention Deficit Hyperactivity Disorder (ADHD)

I have read and understood the 'Information Sheet'. The nature and possible effects of the study have been explained to me.

I understand that the study involves two sessions lasting up to 50 minutes with the following procedures:

- Attaching small sensors to the index fingertips
- Producing circling movements with the hands at differing speed while, at times, changing the direction of the circling movements as quickly as possible when a green light flashes and stopping changing the direction if a red light flashes.
- Pressing the correct button on a box as fast as possible when a signal appears on either side of a computer screen while, at times, pressing a different button on a different box when a short sound appears.

I understand that some physical fatigue may occur during this task.

I understand that all research data will be treated as confidential.

Any questions that I have asked have been answered to my satisfaction.

I agree that research data gathered for the study may be published provided that I/my son cannot be identified as a participant.

I agree to participate/I agree to my son's participation in this study and understand that I/my son may withdraw at any time without prejudice to his care and treatment by the health services.

Name of participant .....

Signature of both parents/guardians.....

Date .....

Would you like to receive a copy of the findings of the research? Please tick YES ☐ NO ☐

I have explained this project and the implications of participation in it to this volunteer and I believe that the consent is informed and that he/she understands the implications of participation.

Name of investigator .....

Signature of investigator .....Date.....

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UNIVERSITY OF TASMANIA

School of Psychology

STATEMENT OF INFORMED CONSENT FOR PARENTS OR GUARDIANS (ADD/ADHD)

Chief Investigator: Prof. Jeffery J. Summers *Co-Supervisor:* A/Prof. Clive Skilbeck
PhD Candidate: Bruno A. Cayoun

Title of Study

The Dynamics of Bimanual Coordination in Attention Deficit Hyperactivity Disorder (ADHD)

I have read and understood the 'Information Sheet'. The nature and possible effects of the study have been explained to me.

I understand that the study involves two sessions lasting up to 50 minutes with the following procedures:

- Attaching small sensors to the index fingertips
- Producing circling movements with the hands at differing speed while, at times, changing the direction of the circling movements as quickly as possible when a green light flashes and stopping changing the direction if a red light flashes.
- Pressing the correct button on a box as fast as possible when a signal appears on either side of a computer screen while, at times, pressing a different button on a different box when a short sound appears.
- Desist from having any medication 6 hours prior to the test.

I understand that some physical fatigue may occur during this task.

I understand that all research data will be treated as confidential.

Any questions that I have asked have been answered to my satisfaction.

I agree that research data gathered for the study may be published provided that I/my son cannot be identified as a participant.

I agree to participate/I agree to my son's participation in this study and understand that I/my son may withdraw at any time without prejudice to his care and treatment by the health services.

Name of participant .....

Signature of both parents/guardians.....

Date .....

Would you like to receive a copy of the findings of the research? Please tick YES ☐ NO ☐

I have explained this project and the implications of participation in it to this volunteer and I believe that the consent is informed and that he/she understands the implications of participation.

Name of investigator .....

Signature of investigator .....Date.....

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UNIVERSITY
OF TASMANIA

School of Psychology

STATEMENT OF INFORMED CONSENT (12-15 years-Control)

Chief Investigator: Prof. Jeffery J. Summers *Co-Supervisor:* A/Prof. Clive Skilbeck
PhD Candidate: Bruno A. Cayoun

Title of investigation

The Dynamics of Bimanual Coordination in Attention Deficit Hyperactivity Disorder (ADHD)

I have read and understood the 'Information Sheet'. The type and possible effects of the study have been explained to me.

I understand that the study involves two sessions lasting up to 50 minutes with the following procedures:

- Attaching small metal disks to the index fingertips
- Making circling movements with the hands at differing speed while, at times, changing the direction of the circling movements as quickly as possible when a green light flashes and stopping and changing the direction if a red light flashes.
- Pressing the correct button on a box as fast as possible when a signal appears on either side of a computer screen while, at times, pressing a different button on a different box when a short sound appears.

I understand that I can become tired during these exercises.

I understand that all results of the research will not be given to anyone but me or my parents if we wish to have them.

I am satisfied with the way my questions have been answered.

I agree that the results of the research may be published provided that no one can know that I participated in it.

I agree to participate in this study and understand that I can stop participating to it at any time without being disapproved.

Name of participant .....

Signature of participant.....Date.....

Would you like to receive a copy of the findings of the research? Please tick YES ☐ NO ☐

I have explained this project and the implications of participation in it to this volunteer and I believe that the consent is informed and that he/she understands the implications of participation.

Name of investigator .....

Signature of investigator .....Date.....

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UNIVERSITY OF TASMANIA

School of Psychology

STATEMENT OF INFORMED CONSENT (12-15 years-ADD/ADHD)

Chief Investigator: Prof. Jeffery J. Summers *Co-Supervisor:* A/Prof. Clive Skilbeck
PhD Candidate: Bruno A. Cayoun

Title of investigation

The Dynamics of Bimanual Coordination in Attention Deficit Hyperactivity Disorder (ADHD)

I have read and understood the 'Information Sheet'. The type and possible effects of the study have been explained to me.

I understand that the study involves two sessions lasting up to 50 minutes with the following procedures:

- Attaching small metal disks to the index fingertips
- Making circling movements with the hands at differing speed while, at times, changing the direction of the circling movements as quickly as possible when a green light flashes and stopping and changing the direction if a red light flashes.
- Pressing the correct button on a box as fast as possible when a signal appears on either side of a computer screen while, at times, pressing a different button on a different box when a short sound appears.
- Being without any medication 6 hours prior to the test.

I understand that I can become tired during these exercises.

I understand that all results of the research will not be given to anyone but me or my parents if we wish to have them.

I am satisfied with the way my questions have been answered.

I agree that the results of the research may be published provided that no one can know that I participated in it.

I agree to participate in this study and understand that I can stop participating to it at any time without being disapproved.

Name of participant .....

Signature of participant.....Date .....

Would you like to receive a copy of the findings of the research? Please tick YES ☐ NO ☐

I have explained this project and the implications of participation in it to this volunteer and I believe that the consent is informed and that he/she understands the implications of participation.

Name of investigator .....

Signature of investigator .....Date.....

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Appendix B.1

ADHD Rating Scale-IV and scoring sheets

ADHD RATING SCALE–IV: SCHOOL VERSION

Child's name_____ Sex: M F Age_____ Grade_____
Completed by: _____

Circle the number that *best describes* this student's school behavior over the past 6 months (or since the beginning of the school year).

	Never or rarely	Sometimes	Often	Very often
1. Fails to give close attention to details or makes careless mistakes in schoolwork.	0	1	2	3
2. Fidgets with hands or feet or squirms in seat.	0	1	2	3
3. Has difficulty sustaining attention in tasks or play activities.	0	1	2	3
4. Leaves seat in classroom or in other situations in which remaining seated is expected.	0	1	2	3
5. Does not seem to listen when spoken to directly.	0	1	2	3
6. Runs about or climbs excessively in situations in which it is inappropriate.	0	1	2	3
7. Does not follow through on instructions and fails to finish work.	0	1	2	3
8. Has difficulty playing or engaging in leisure activities quietly.	0	1	2	3
9. Has difficulty organizing tasks and activities.	0	1	2	3
10. Is "on the go" or acts as if "driven by a motor."	0	1	2	3
11. Avoids tasks (e.g., schoolwork, homework) that require sustained mental effort.	0	1	2	3
12. Talks excessively.	0	1	2	3
13. Loses things necessary for tasks or activities.	0	1	2	3
14. Blurts out answers before questions have been completed.	0	1	2	3
15. Is easily distracted.	0	1	2	3
16. Has difficulty awaiting turn.	0	1	2	3
17. Is forgetful in daily activities.	0	1	2	3
18. Interrupts or intrudes on others.	0	1	2	3

ADHD RATING SCALE–IV: SCHOOL VERSION
SCORING SHEET FOR BOYS

Child's name_____ Date_____ Age_____

%ile	HI 5–7	HI 8–10	HI 11–13	HI 14–18	IA 5–7	IA 8–10	IA 11–13	IA 14–18	Total 5–7	Total 8–10	Total 11–13	Total 14–18	%ile
99+	27	27	27	25	27	27	27	27	52	54	54	52	99+
99	27	27	27	25	27	27	27	27	51	53	53	51	99
98	27	27	25	21	26	27	27	27	51	53	49	44	98
97	27	26	23	21	24	26	27	25	50	51	44	43	97
96	25	26	21	21	24	26	25	24	48	50	42	39	96
95	24	26	20	20	23	25	25	23	46	50	40	39	95
94	23	25	18	19	23	25	24	22	44	48	39	35	94
93	22	25	18	17	22	25	24	21	41	46	38	34	93
92	21	24	18	16	22	24	23	21	40	45	37	33	92
91	21	23	17	14	21	24	23	20	40	45	36	32	91
90	20	22	17	13	21	24	23	20	39	44	36	31	90
89	20	21	16	12	20	24	22	19	38	42	34	30	89
88	19	21	16	12	20	24	21	18	38	41	33	29	88
87	18	20	16	12	19	23	20	18	37	41	33	28	87
86	18	19	15	11	18	22	20	18	37	40	32	28	86
85	17	19	14	10	18	22	19	17	35	39	32	27	85
84	17	18	14	10	17	21	19	17	34	38	31	26	84
80	16	16	12	8	16	19	17	15	30	34	28	23	80
75	14	13	10	7	15	17	16	12	28	30	25	20	75
50	6	5	3	1	7	9	8	7	13	15	12	9	50
25	1	2	1	0	2	2	2	2	4	5	3	2	25
10	0	0	0	0	0	0	0	0	0	1	0	0	10
1	0	0	0	0	0	0	0	0	0	0	0	0	1

Note. HI, Hyperactivity–Impulsivity; IA, Inattention.

ADHD RATING SCALE–IV: HOME VERSION

Child's name_____ Sex: M F Age_____ Grade_____

Completed by: Mother_____ Father_____ Guardian_____ Grandparent_____

Circle the number that *best describes* your child's home behavior over the past 6 months.

	Never or rarely	Sometimes	Often	Very often
1. Fails to give close attention to details or makes careless mistakes in schoolwork.	0	1	2	3
2. Fidgets with hands or feet or squirms in seat.	0	1	2	3
3. Has difficulty sustaining attention in tasks or play activities.	0	1	2	3
4. Leaves seat in classroom or in other situations in which remaining seated is expected.	0	1	2	3
5. Does not seem to listen when spoken to directly.	0	1	2	3
6. Runs about or climbs excessively in situations in which it is inappropriate.	0	1	2	3
7. Does not follow through on instructions and fails to finish work.	0	1	2	3
8. Has difficulty playing or engaging in leisure activities quietly.	0	1	2	3
9. Has difficulty organizing tasks and activities.	0	1	2	3
10. Is "on the go" or acts as if "driven by a motor."	0	1	2	3
11. Avoids tasks (e.g., schoolwork, homework) that require sustained mental effort.	0	1	2	3
12. Talks excessively.	0	1	2	3
13. Loses things necessary for tasks or activities.	0	1	2	3
14. Blurts out answers before questions have been completed.	0	1	2	3
15. Is easily distracted.	0	1	2	3
16. Has difficulty awaiting turn.	0	1	2	3
17. Is forgetful in daily activities.	0	1	2	3
18. Interrupts or intrudes on others.	0	1	2	3

ADHD RATING SCALE–IV: HOME VERSION
SCORING SHEET FOR BOYS

Child's name_____ Date_____ Age_____

%ile	HI 5–7	HI 8–10	HI 11–13	HI 14–18	IA 5–7	IA 8–10	IA 11–13	IA 14–18	Total 5–7	Total 8–10	Total 11–13	Total 14–18	%ile
99+	26	25	25	19	24	26	27	25	43	49	51	41	99+
99	25	24	24	18	23	25	26	24	42	48	50	40	99
98	22	21	21	16	20	22	24	23	40	42	47	36	98
97	21	18	18	16	20	19	22	19	37	37	38	32	97
96	19	17	18	15	18	18	21	18	36	34	37	30	96
95	17	17	18	13	16	17	20	17	34	31	35	28	95
94	17	15	18	12	15	16	19	16	33	29	34	27	94
93	17	15	16	11	15	15	18	15	30	27	34	27	93
92	16	14	16	11	14	15	18	14	30	26	33	26	92
91	16	14	15	11	13	14	18	14	29	26	32	25	91
90	15	13	14	10	13	14	18	14	29	25	31	23	90
89	14	13	13	10	12	14	17	13	28	24	30	21	89
88	14	12	12	10	12	13	17	12	27	24	30	21	88
87	13	11	11	9	12	13	16	12	25	23	28	20	87
86	13	11	10	9	12	12	16	11	22	23	26	20	86
85	12	10	10	8	11	12	14	11	22	22	23	19	85
84	12	10	9	8	11	12	14	10	21	21	22	18	84
80	11	9	8	7	9	11	10	9	19	20	19	16	80
75	9	8	7	6	8	9	9	8	18	17	14	13	75
50	5	4	3	2	5	6	5	4	10	10	7	7	50
25	3	2	1	0	2	3	2	1	6	5	4	3	25
10	1	0	0	0	0	0	1	0	2	1	1	0	10
1	0	0	0	0	0	0	0	0	0	0	0	0	1

Note. HI, Hyperactivity–Impulsivity; IA, Inattention.

Appendix B.2

Edinburgh Handedness Inventory

EDINBURGH HANDEDNESS INVENTORY

NAME: _____

AGE: _____ YEARS: _____ MONTHS: _____

SEX: _____

Please indicate your preference in the use of hands in the following activities by putting + in the appropriate column. Where the preference is so strong that you would never try to use the other hand unless absolutely forced to, put ++. If, in any case you are really indifferent put + in both columns.

Some of the activities require the use of both hands. In these cases the part of the task, or object, for which hand preference is wanted is indicated in brackets.

Please try to answer all the questions, and only leave a blank if you have no experience at all of the object.

		Left	Right
[1]	Writing		
[2]	Drawing		
[3]	Throwing		
[4]	Scissors		
[5]	Toothbrush		
[6]	Knife (without fork)		
[7]	Spoon		
[8]	Broom (upper hand)		
[9]	Striking match (match)		
[10]	Opening box (lid)		
(i)	Which foot do you prefer to kick with?		
(ii)	Which eye do you use when only using one?		

Appendix B.3

Developmental Coordination Disorder Questionnaire and scoring sheet

COORDINATION QUESTIONNAIRE
(DCDQ)

Name of child:_____Person completing questionnaire:_____

Today's date:_____Relationship to child:_____

Most of the motor skills that this questionnaire asks about are ones which improve each year, as a child grows and develops. For this reason, it will make it easier for you to answer the questions if you think about other children who are the same age as your child. Please compare the degree of coordination your child has with other children of the same age when answering the questions. Circle the number that best describes your child.

Not at all like your child	**A bit like your child**	**Moderately like your child**	**Quite a bit like your child**	**Extremely like your child**
1	**2**	**3**	**4**	**5**

1. *Throws a ball* in a controlled and accurate fashion, compared to other children the same age as your child.

   1 2 3 4 5

2. *Catches* a small *ball* (e.g., tennis ball size) thrown from a distance of 6 to 8 feet, as well as other children the same age.

   1 2 3 4 5

3. *Hits* an approaching *ball* or *birdie* with a bat or racquet as accurately as other children the same age as your child.

   1 2 3 4 5

4. *Jumps* easily *over* obstacles found in garden or play environment.

   1 2 3 4 5

5. *Runs* easily *and* smoothly, and *stops* with control.

   1 2 3 4 5

6. If your child has a *plan* to do a motor *activity*, he/she can organize his/her body to follow the plan and effectively complete the task (e.g., building a cardboard or cushion "fort," moving on playground equipment, building a house or a structure with blocks, or using craft materials).

   1 2 3 4 5

7. Printing or *writing* in class is *fast* enough to keep up with the rest of the children in the class.

   1 2 3 4 5

8. Printing or *writing* letters, numbers and words is *legible*, precise, and accurate.

   1 2 3 4 5

	Not at all like your child 1	A bit like your child 2	Moderately like your child 3	Quite a bit like your child 4	Extremely like your child 5
9. Uses appropriate *effort* or tension when printing or writing (no excessive *pressure* or tightness of grasp, writing not too heavy or dark, or too light).	1	2	3	4	5
10. *Cuts* out a magazine picture accurately and easily, compared to other children the same age as your child.	1	2	3	4	5
11. Your child's performance in individual sports (such as swimming, running, skiing, skating) is better than in *team sports* (such as soccer, hockey, baseball).	1	2	3	4	5
12. Your child is disinterested in or tends to *avoid* participating in *sports* requiring good motor skills.	1	2	3	4	5
13. Learned to *ride a bike* later than his/her friends.	1	2	3	4	5
14. May have difficulty *learning* new motor *skills*, although may perform them well once they are learned (e.g., skating, skiing, swimming).	1	2	3	4	5
15. Your child could be described as a "*bull in* a *china* shop."	1	2	3	4	5
16. Is slow and *awkward* in tidying up, putting on shoes, tying shoes, dressing, etc.	1	2	3	4	5
17. *Fatigues easily*, and appears to slouch and "fall out" of chair if required to sit for long periods.	1	2	3	4	5

Coordination Questionnaire (DCDQ) Name: _____

Score Sheet

	Control During Movement	Fine Motor/ Handwriting	Gross Motor/ Planning	General Coordination
1. Throws ball				
2. Catches ball				
3. Hits ball/birdie				
4. Jumps over				
5. Runs and stops				
6. Plan activity				
7. Writing fast				
8. Writing legibly				
9. Effort & pressure				
10. Cuts				
11. Team sports				
12. Avoid sports				
13. Ride a bike				
14. Learning skills				
15. Bull in china				
16. Awkward				
17. Fatigues easily				

For Questions #11 to #17:
1 = 5
2 = 4
3 = 3
4 = 2
5 = 1
[shaded boxes] reverse the scoring as shown here

TOTAL _____ **/ 30** + _____ **/ 20** + _____ **/ 20** + _____ **/ 15** = _____ **/ 85 TOTAL**

Control during Movement | Fine Motor/ Handwriting | Gross Motor/ Planning | General Coordination

0-48 (0-10th percentile) indication of DCD
49-57 (11-25th percentile) suspect DCD
58-85 (26-100th percentile) probably not DCD