The development of rapid online control in children with and without Developmental Coordination Disorder

Submitted by

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This thesis is dedicated to my beautiful

and devoted wife, Kristy.

Persisting with me through this PhD is worthy of

an award in itself.

...and to all those wonderful children

who took part in this research.

Statement of Sources

This thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No other person's work has been used without due acknowledgement in the main text of the thesis. The nature of any other assistance received in the pursuit of the research and preparation of the thesis and the extent of collaborations with another person or persons have also been acknowledged. This thesis has not been submitted for the award of any degree or diploma in any other tertiary institution. All research procedures reported in the thesis received the approval of the relevant Ethics/Safety Committees (where required).

Signed:

Scott Ruddock

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List of Acronyms

Acronym	Meaning
ADHD	Attention Deficit Hyperactivity Disorder
AE	Anticipatory Error
AJE	Anti-jump Error
AMT*diff*	Anti-jump Movement Time Difference (non-jump and anti-jump)
AJMT*diff*	Anti-jump Movement Time Difference (jump and anti-jump)
BIC	Bayesian Information Criterion
CN	Cognitive Neuroscience
CSD	Cohort Sequential Design
CTE	Centre Touch Error
CO-OP	Cognitive Orientation to Daily Occupational Performance
COVAT	Covert Orienting of Visual-Spatial Attention
DAMP	Deficits in Attention, Motor Control, and Perception
DCD	Developmental Coordination Disorder
DJRT	Double Jump Reaching Task
DSM	Diagnostic and Statistical Manual
DS	Dynamical Systems
DSST	Double-Step Saccade Task
EF	Executive Function
FA	Fractional Anisotropy
GC	Growth Connectomics
GCM	Growth Curve Modelling
IMD	Internal Modelling Deficit
IP	Information Processing

Acronym	Meaning
IS	Interactive Specialization
MABC	Movement Assessment Battery for Children
MAND	McCarron Assessment of Neuromuscular Development
MI	Motor Imagery
MRI	Magnetic Resonance Imaging
MS	Milliseconds
MT	Movement Time
MT*diff*	Movement Time Difference (non-jump and jump)
NTT	Neuromotor Training Task
PAT	Prism Adaptation Test
PCT	Post Correction Time
PCT-AJ	Post Correction Time – Anti-jump
PFC	Prefrontal Cortex
PPC	Posterior Parietal Cortex
RMANOVA	Repeated Measures ANOVA
ROC	Rapid Online Control
RT	Reaction Time
TDC	Typically Developing Children
ToC	Time of Correction
ToC2	Second Time of Correction
ToC*diff*	Time of Correction Difference
TDE	Touch Down Error
VGPT	Visually Guided Pointing Task
WMNs	White Matter Networks

Acronym	Meaning
WM	Working Memory

Overview of Thesis

The work presented here was part a large longitudinal project. The overall aim of this research was to better understand the development of movement skill in children and the nexus between action systems and cognition. This thesis presents my contribution to the broader project. Using experimental and longitudinal methods, I examined the motor and cognitive trajectories of a large group of children, a proportion of whom had poor motor skills (termed Developmental Coordination Disorder—DCD). In doing so, I gained a firm impression of those motor control processes that might explain both typical and atypical motor development and the unfolding relationship between motor and cognitive systems, specifically that between executive systems and networks supporting online motor control.

This thesis is comprised of three sections. Section 1 provides a literature review of research of rapid online control (ROC) and its development in children, and a methodology chapter that describes the main paradigm and measures for examining ROC—the double jump reaching task. Section 2 presents three studies that examined how children's motor and executive systems interact with each other across normative and atypical development. To conclude, Section 3 reviews the data from the three studies with focus on implications for theory and clinical practice. Figure A illustrates the progression of the thesis chapters.

Section 1

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- Neuro-cognitive accounts of DCD and introduction to *interactive specialization*
- Review of ROC research

Chapter 2 – Methodology
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- Participants, design and data analytic approach for Studies 1, 2, and 3

Section 2

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Section 3

Chapter 6 – General Discussion
- Results of this thesis support unique developmental patterns in typical development and DCD, explained by the framework of *interactive specialization*

Figure A. Diagram depicting thesis sections and progression of chapters.

ABSTRACT

The online control of manual actions is critical for the development of functional skills in children, not the least because demands on behaviour and complexity of the environment increase with age. When unexpected changes occur during the course of action, rapid online corrections are necessary to ensure that movement parameters (like force and timing) can be quickly updated. Developmentally, the motor network supporting online control is thought to mature rapidly over childhood; however, cross-sectional research suggests that the trajectory of change is not linear because the mode of control undergoes reorganisation during middle childhood. At the same time, development of frontal executive systems (particularly inhibition) may influence the way children enlist motor functions like online (predictive) control. Maturational theories that once considered these systems to be unitary in their development are now being challenged by a more parsimonious neuro-behavioural hypothesis—*interactive specialization*; this suggests behaviour can be strengthened and supported by the interaction of separate but overlapping neural networks.

A growing body of research indicates that online control processes may be disrupted for children with motor coordination problems (aka Developmental Coordination Disorder; DCD). As well, it has been widely reported that these children show problems related to executive function including tasks that involve response inhibition. It is argued here that deficits in predictive online control may be exacerbated under task conditions that require concurrent inhibitory control as when one is required to withhold a response to a compelling cue and move to an alternate location. However, there is not a clear picture of developmental change in the ability to couple motor and executive systems, nor of differences in growth patterns between typically developing children (TDC) and children with DCD. The purpose of my research was to address this knowledge gap by conducting cross-sectional and longitudinal studies of development to examine the unfolding interaction between online and

executive systems in healthy and atypically developing children. Specifically, I examined how TDC and DCD groups corrected their arm movement mid-flight during a step-perturbation paradigm, and how a concurrent inhibitory load constrained their responses to a target shift.

A total of 196 primary children aged between 6 and 12 years were recruited for a two-year longitudinal study. Children were assessed as either TDC or DCD using research criteria at the commencement of testing. Motor ability was assessed using the McCarron Assessment of Neuromuscular Developmental (MAND), while online motor control was tested on a double-jump reaching task (DJRT). To assess the ability to couple online and inhibitory control, a modified 'anti-reach' version of the DJRT was used where children were instructed to touch a location contralateral to that of a cued target.

In Study 1, the coupling of online and inhibitory systems was assessed in a cross-sectional analysis of TDC. Children were allocated into three age bands: younger (6-7 years), mid-aged (8-9 years), and older (10-12 years) while online control was compared between groups as a function of trial type (non-jump, jump, anti-jump). It was predicted that online control would be implemented efficiently in TDC by 9 years of age, but adding an inhibitory load to the DJRT would constrain performance, particularly around middle childhood. Results showed that there were similar movement times across all age groups when trial constraints where low (non-jump). However, when a target perturbation was applied at movement onset (jump condition), children in the younger group showed disproportionately slower movement time compared with both mid-aged and older children, as well as slower corrections of reach trajectory. On anti-jump trials which enlist the use of inhibitory control, younger children continued to show delayed changes in trajectory and slower movement times compared with older children. Importantly, the performance of mid-aged children on anti-jump trials deviated from that of older children; the effect of the added inhibitory load was between that of younger and older children. Taken together, these results indicate that by middle childhood, online adjustments to jump trials can be implemented efficiently and to a level as that seen in older children. However, when demands were imposed on executive systems (as per anti-jump trials), performance of the mid-aged children was compromised relative to older children. This pattern of performance suggests that maturational changes in the development of executive networks during middle childhood may constrain the flexibility with which online control can be implemented, particularly when inhibitory demands are imposed on a reaching task.

The coupling of online control and inhibitory systems was then compared cross-sectionally between DCD and TDC groups in Study 2. Children were divided into the same age three groups (young, mid-age, older) as per Study 1 and classified also according to motor ability (TDC or DCD). It was predicted that children with DCD would be slower to adjust online corrections than TDC and that adding an inhibitory load to the DJRT would further constrain an already compromised online motor control system. It was found that movement times were similar between skill groups under simple task constraints (non-jump); however, on perturbation (jump) trials the DCD group were significantly slower than controls and corrected their reach trajectories later. Critically, the DCD group was further disadvantaged by anti-jump trials where inhibitory control was required, particularly for younger and mid-age children; movement and correction times were further delayed. This was also shown on measures of the difference in movement time between jump and anti-jump trials (AJMT*diff*), and the interval between the first (automatic) corrective movement and the second (inhibitory) correction for anti-jump trials (i.e. ToC*diff*). However, the effect of group appeared to dissipate with age such that older children with DCD were less disadvantaged than mid-aged, and did not differ significantly from older TDC. Taken together, the anti-reach data indicates that the coupling of online control and inhibitory systems may not be well developed in younger and mid-aged children with DCD, but show signs of improvement in older children (10-12 years) with DCD, indeed to a level similar to that of their age-matched peers. Whether these intriguing cross-sectional results would be mirrored in longitudinal modelling was the motivation for Study 3.

In Study 3 I modelled the coupling of inhibitory and online motor control coupled in TDC and DCD groups using a longitudinal design—specifically, a cohort sequential design. A group of 196 children (111 girls and 85 boys) aged between 6 and 12 years participated in the study. Children were classified as TDC/DCD according to research criteria and performance on the MAND. Using a cohort sequential design, both TDC and DCD groups were divided into 13 age cohorts, each separated by 6 months, and assessed at 6-month intervals over two years (5 time points in total). The critical measures of coupling on the DJRT were AJMT*diff* and ToC*diff*. Results showed that performance on the DJRT was slower in children with DCD relative to TDC. Furthermore, for the TDC group, model comparison using growth curve analysis revealed that a quadratic trend was the most appropriate fit with evidence of rapid improvement in anti-reach performance up until middle childhood (around 8-9 years), followed by a more gradual rate of improvement into late childhood and early adolescence. In contrast, for the DCD group, a linear function provided the best to fit on the key metrics, with a slower rate of improvement than controls. Under the framework of *interactive specialization*, these data suggest that while dorsal motor streams that support rapid online control are functioning well by mid-childhood in TDC, the ability to integrate fronto-inhibitory and predictive control require a period of re-organisation during middle childhood, followed by a steady but more gradual progression into older childhood. For children with DCD, this process of coupling is more gradual and protracted from younger childhood, with little evidence of a critical re-organisation during middle childhood; this pattern fits with the hypothesis of a maturational lag in the development of motor-cognitive networks in DCD. Combined cognitive and motor control issues in children appear to be an important risk factor in the development of goal-directed action and skill. These results have important implications for therapists and health professionals when designing treatment systems for DCD.

RESEARCH INTO DEVELOPMENTAL COORDINATION DISORDER

1.1. Overview

In this first chapter, I provide a review of research investigating Developmental Coordination Disorder (DCD) from a cognitive neuroscience perspective. First, I discuss DCD as a diagnostic entity and highlight key symptoms that health professionals assess when making clinical judgements or recommendations for treatment. Competing theoretical accounts of DCD are then discussed, with particular focus on the cognitive neuroscience approach which offers a principled way to understand the developmental precursors and neurocognitive underpinnings of DCD. In particular, converging evidence supports the view that deficits in both motor control (particularly predictive modelling) and executive function are present in children with DCD. This is evident from studies using paradigms that assess motor imagery, covert orienting of attention, force control, online control during reaching, response inhibition, executive attention, working memory, and others (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). Understanding the neuro-cognitive mechanisms that govern motor behaviour in typically and atypically developing children is critical in formulating a theory of DCD, which ultimately informs the design of effective interventions.

One aspect of motor control/performance that may be critical in models of DCD is rapid online control (ROC). Online control is integral to fast and efficient action. A useful and well-validated paradigm for assessing ROC is the *double-jump reaching task* (DJRT) where a growing body of research evidence (e.g., Hyde & Wilson, 2011a, 2011b, 2013) suggests compromise in children with DCD, and perhaps delay in maturation of fronto-parietal networks (Wilson et al., 2013). However, as external demands on action and behaviour increase with age and with brain maturation, action systems fall increasingly under top-down control and must therefore be integrated with other control systems, particularly executive function. When placed in context of neuro-development, cognitive control needs to be coupled with more posterior perceptual-motor systems (those that process and respond to sensory information), to help orchestrate progressively more complex actions and motor routines. For example, a basic reaching movement within peripersonal space extends to open environments where the action space is shared with other children and objects.

Currently, we know little about the time course over which cognitive and motor control systems are coupled in child development. To help bridge this knowledge gap, I draw on a contemporary neuro-behavioural theory of development, *interactive specialization* (Johnson, 2005, 2011). This theory views brain-behaviour relationships as more dynamic and intrinsically interactive, rather than modular. That is, emerging behaviour can be supported by several cortical regions, each with their own developmental timescales. The literature review concludes with a critique of the cognitive neuroscience framework for investigating the control of goal-directed reaching in healthy and atypically developing children, and how executive control processes influence and interact with online motor control systems at different stages of child development. These matters are taken up in the empirical studies presented in Chapters 3, 4 and 5.

1.2 An Introduction to Developmental Coordination Disorder

For the vast majority of children, learning to move and interact with their environment becomes a very seamless and adaptive process, requiring little conscious effort (Dewey, Kaplan, Crawford, & Wilson, 2002). During development, children acquire a vast array of motor abilities (e.g. reaching, grasping, graphomotor, walking, balancing, etc.) which require varying degree of gross and/or fine motor coordination (Geuze, Jongmans, Schoemaker, & Smits-Engelsman, 2001). However, for some children, skills are not readily learned, even with substantial practice, which can have a detrimental impact upon not only on activities of daily living but also on their psychosocial development and engagement in community activities (Angulo-Barroso & Tiernan, 2008; Engel-Yeger, Hanna-Kassis, & Rosenblum, 2015).

Even though motor clumsiness has been examined in the developmental literature since near the turn of the 20th century (Orton, 1937), only recently (in the last 40 years) has research and science begun to highlight the impact of motor difficulties on the broader development of children. The presence of physical awkwardness or clumsiness in children is commonly referred to as Developmental Coordination Disorder, or DCD (American Psychiatric Association, 2013), and in 1987 was included as a distinct entity in the Diagnostic and Statistical Manual of Mental Disorders III-R (American Psychiatric Association, 1987). A brief sojourn into the history of the condition reveals that poor motor skill in children has been labelled variously as *clumsy child syndrome* (Gubbay, 1975; Henderson & Hall, 1982; Losse et al., 1991), *developmental dyspraxia* (Dewey, 1995), *minimal brain damage* (Forsstrom & Von Hofsten, 1982), *physically awkward* (Marchiori, Wall, & Bedingfield, 1987), *perceptuo-motor dysfunction* (Laszlo, Bairstow, Bartrip, & Rolfe, 1988) and *deficits in attention, motor control, and perception* (DAMP; Gillberg, 2003). The wide range of terms has tended to confuse efforts to conceptualise disorders of motor learning under the one umbrella and comparison between studies. However, an increasing focus on motor development in recent decades has seen consensus around the choice of label (DCD), with concomitant advances in the development of theory and treatment (Polatajko, Fox, & Missiuna, 1995). The way DCD is identified and diagnosed is taken up for discussion next.

1.2.1 Diagnostic Criteria for DCD

Two prominent systems exist for identifying motor clumsiness in children: the more frequently used Diagnostic and Statistical Manual IV enlisting the DCD classification (DSM-IV; American Psychiatric Association, 2000), and the World Health Organization's International Classification System enlisting the SDDMF label or *specific developmental* *disorder of motor function* (ICD-10; World Health Organization, 2001). While there are some qualitative differences between the two classification systems, it is generally agreed that both systems are more similar than different (Sugden & Wade, 2013).

The Diagnostic and Statistical Manual IV (DSM-IV; American Psychiatric Association, 2000) classifies DCD as a failure to meet adequate motor milestones in the absence of any physical or neurological structural abnormalities, developmental delays, or intellectual deficiencies. Importantly, the motor problems are severe enough to interfere with activities of daily living and/or academic achievement. Only very recently has DSM-IV criteria been superseded by the DSM-5 (American Psychiatric Association, 2013). In both the DSM-IV and DSM-5, four categories (as listed in Table 1.1) should be addressed for a diagnosis of DCD to be offered.

Table 1.1

Comparison of Diagnostic Criteria between the Diagnostic and Statistical Manual-IV and the Diagnostic and Statistical Manual 5

Criterion	DSM-IV	DSM 5
A	Performance in daily activities that require motor coordination is substantially below that expected given the person's chronological age and measured intelligence. This may be manifested by marked delays in achieving motor milestones (e.g., walking, crawling, sitting), dropping things, "clumsiness," poor performance in sports, or poor handwriting.	The acquisition and execution of coordinated motor skills is substantially below that expected given the individual's chronological age and opportunity for skill learning and use. Difficulties are manifested as clumsiness (e.g., dropping or bumping into objects) as well as slowness and inaccuracy of performance of motor skills (e.g., catching an object, using scissors or cutlery, handwriting, riding a bike, or participating in sports).
B	The disturbance in Criterion A significantly interferes with academic achievement or activities of daily living.	The motor skills deficit in Criterion A significantly and persistently interferes with activities of daily living appropriate to chronological age (e.g., self-care and self-maintenance) and impacts academic/school productivity, prevocational and vocational activities, leisure, and play.
C	The disturbance is not due to a general medical condition (e.g., cerebral palsy, hemiplegia, or muscular dystrophy) and does not meet criteria for a Pervasive Developmental Disorder.	Onset of symptoms is in the early developmental period.
D	If Mental Retardation is present, the motor difficulties are in excess of those usually associated with it.	The motor skills deficits are not better explained by intellectual disability (intellectual developmental disorder) or visual impairment and are not attributable to a neurological condition affecting movement (e.g., cerebral palsy, muscular dystrophy, degenerative disorder).

Note. DMS = Diagnostic and Statistical Manual

A criticism of DSM-IV criteria has been that the description of some of features listed in Criterion A and B are difficult to operationalise (Geuze et al., 2001). Terms such as ‘daily activities’ and ‘marked delays’ may be interpreted in a number of different ways (Henderson & Barnett, 1998), potentially leading to arbitrary research classifications of motor impairment. In addition, Criterion C from DSM-IV, which excludes children from a diagnosis of DCD if they suffer from a medical condition or pervasive developmental disorder, now does not automatically exclude such children under DSM 5 criteria.

The DCD research community has addressed issues of diagnosis through the Leeds Consensus Meetings which produced guidelines (i.e. Sugden, Chambers, & Utley, 2006) that reinforced reference to DSM criteria. More recently, a comprehensive set of clinical and intervention guidelines (Blank, Smith-Engelsman, Polatajko, & Wilson, 2012) was developed based on systematic and meta-analytic research (Wilson et al., 2013). These guidelines, in addition to DSM-5 criteria, are sourced when assessing children for DCD (e.g., Caravale, Baldi, Gasparini, & Wilson, 2014; Parmar, Kwan, Rodriguez, Missiuna, & Cairney, 2014).

While diagnostic revisions and associated guidelines continue to shape our knowledge around DCD, one of the major problems with diagnosis based on any criteria is that it often fails to capture the range of difficulties children with DCD endure (Cairney, 2015). In the following section, I describe the expression of DCD and associated features.

1.2.2 Prevalence, Symptoms and Presentation of DCD

Generally, DCD is identified when age approximate skills are not achieved, detected both at home and, more often, in the school environment where tasks involving motor activities (e.g. physical education) are visible against a backdrop of peer performance (Kirby, Sugden, & Edwards, 2010; Sugden & Wade, 2013). Prevalence rates do vary between countries, often a function of the motor screening measure used and the particular normative sample (Niemeijer, van Waelvelde, & Smits-Engelsman, 2015), and there tends to be twice the number of boys diagnosed than girls (Henderson & Hall, 1982; Kadesjo & Gillberg, 1999). However, there is general consensus that approximately 6% of school-aged children suffer from coordination problems (Gibbs, Appleton, & Appleton, 2007; Lingam, Hunt, Golding, Jongmans, & Emond, 2009; Mandich & Polatajko, 2003; Zwicker, Missiuna, Harris, & Boyd, 2012b). This is not to imply that coordination difficulties somehow begin and end within this age bracket; recent research into adults with DCD (Tal-Saban, Ornoy, & Parush, 2014a, 2014b; Tal-Saban, Zarka, Grotto, Ornoy, & Parush, 2012) highlight the persistence of the disorder and associated social and emotional problems, reinforcing earlier views that children and adolescents do not necessarily grow out of DCD.

In terms of symptom expression, children often display motor skill problems across a number of activities or domains. Motor performance issues extend to different activities and may include problems dressing (Chambers, Sugden, & Sinani, 2005), an inability to catch a ball, poor penmanship (Smits-Engelsman, Niemeijer, & van Galen, 2001), unsteadiness in their posture and gait (Chen, Tsai, & Wu, 2014; Geuze, 2005; Hamilton, 2002), and so on. Children with DCD have also been found to be more obese than typically developing children (Zhu et al., 2014) and less physically fit (Hiraga, Rocha, de Castro Ferracioli, Gama, & Pellegrini, 2014; Lifshitz et al., 2014).

Due to the heterogeneous nature of presenting symptoms, diagnosis of DCD is a constant challenge in both research and clinical settings; however, what seems to be apparent is that the motor learning difficulties are also associated with difficulties in other areas of a child's life.

1.2.3 Psychosocial Consequences of the Disorder

The problems of DCD are not just confined to observable motor difficulties but to a range of negative consequences in the social, psychological and academic domains. For instance, participation in social activities may be adversely affected (Chen & Cohn, 2003;

Sylvestre, Nadeau, Charron, Larose, & Lepage, 2013), there is an increased risk for children to show motor clumsiness if they come from a family with a low socio-economic background (Lingam et al., 2009), there are problems linked to psychosocial functioning (Cummins, Piek, & Dyck, 2005), while language and emotional difficulties may also be present (Green, Baird, & Sugden, 2006; King-Dowling, Missiuna, Rodriguez, Greenway, & Cairney, 2015).

Additionally, they may also exhibit more symptoms from a mental illness such as depression (Campbell, Missiuna, & Vaillancourt, 2012) and anxiety (Missiuna et al., 2014); however, the link between DCD and some of the consequences mentioned above is often mediated by other factors. For example,Wagner, Bös, Jascenoka, Jekauc, and Petermann (2012) report that the relationship between DCD and internalising and externalising behaviours may be due to problems from friendship networks.

In the school environment, children with coordination problems have demonstrated lower academic ability than age-matched peers (Watson & Knott, 2006), particularly in reading (Dewey et al., 2002), writing (Cheng, Chen, Tsai, Shen, & Cherng, 2011) and arithmetic (Pieters, Desoete, Van Waelvelde, Vanderswalmen, & Roeyers, 2012). Additionally, teacher (Faught et al., 2008) and parent (Bodnarchuk & Eaton, 2004) appraisals of children's motor abilities further suggest that problems linked to DCD can be just as debilitating as the disorder's primary features. In short, the wider implications of DCD are reported across a range of studies.

1.3 Categories of DCD Research

The number of studies conducted on DCD has grown considerably over the last 15-20 years. By way of illustration, the meta-analytic review of Wilson and McKenzie (1998) which spanned 22 years included 50 performance based studies whereas the most recent meta-analysis spanning 14 contained over 129 (see Wilson et al., 2013). DCD research can be divided into three distinct categories: (i) descriptive studies that examine key characteristics and presentation of the disorder; (ii) studies which assess the efficacy of intervention programs and (iii) aetiological accounts that aim to identify causal/underlying factors of motor deficits. My main focus is the latter. However, a brief overview of each category is needed to place modern research in context and to highlight current directions.

1.3.1 Descriptive Research

As the name suggests, descriptive research attempts to define the core characteristics, presentation and associated features of DCD. Unlike aetiological research, it is not focused on identification of the underlying mechanisms that explain motor clumsiness. The range of studies included in this category is quite broad, based on simple correlational and longitudinal research and/or group comparisons. For instance, some research investigates prevalence estimates (dos Santos & Vieira, 2013; Lingam et al., 2009; Tsiotra et al., 2006) and prognosis (Missiuna, Moll, King, King, & Law, 2007). Other research reviews current issues of terminology, classification, and intervention (Zwicker et al., 2012b), while some work focus on a specific area such as psychosocial implications (Piek, Dworcan, Barrett, & Coleman, 2000; Skinner & Piek, 2001) or levels of participation in physical activity (Green et al., 2011).

Researchers have also examined co-occurring developmental disorders that are frequently diagnosed with DCD such as attention deficit hyperactivity disorder (ADHD; Gillberg et al., 2004; Kaiser, Schoemaker, Albaret, & Geuze, 2015; McLeod, Langevin, Goodyear, & Dewey, 2014; Missiuna et al., 2014), or language and learning difficulties (Cheng et al., 2011; Flapper & Schoemaker, 2013); the weight of evidence across studies suggests that co-occurring features are the norm rather than the exception (Sugden & Wade, 2013). Furthermore, there is research which suggests that there are sub-groups that exist within DCD (Tsai, Wilson, & Wu, 2008; Vaivre-Douret et al., 2011; Visser, 2003). Taken together, the above studies are just some that provide health professionals with valuable information to help advance interventions and offer support to children who suffer from motor difficulties; even though it may not be entirely clear which direction remediation should follow. This knowledge forms a base for continued research that explores the aetiology of clumsy behaviour and can help shape intervention programmes.

1.3.2 Intervention Research

The areas of focus for intervention studies is somewhat diverse, possibly due to the heterogeneity of symptoms noted within DCD groups, the sub-types that may exist or the guiding assumptions made about the aetiology of the disorder (Wilson, 2005), all potentially resulting in a lack of consensus about how to structure remediation. That said, the methods used in treatment programmes can be divided into two broad categories: task-oriented approaches and process-oriented approaches (Ferguson, Jelsma, Jelsma, & Smits-Engelsman, 2013; Smits-Engelsman et al., 2013; Sugden, 2007).

Process-oriented interventions are based on the premise that motor problems can be addressed by targeting the underlying process or function required for action (Smits-Engelsman et al., 2013), like kinaesthesis, for example. The assumption underlying therapy is that, by addressing putative processes, remediation will extend to the associated behaviour and lead to an improvement in skill performance. Examples of this approach include kinaesthetic training, sensory integration therapy and perceptuo-motor approaches.

By comparison, task-oriented interventions are informed by current motor learning principles and the notion of performance specificity (Smits-Engelsman et al., 2013). Drawing on an ecological framework that suggests movement is a function of the interaction between child, task, and environment, emphasis is placed on learning specific tasks (e.g. ball catching, handwriting), often through use of or problem-solving strategies. Programs that show promise in this area include the cognitive orientation to daily occupational performance (CO-OP; Banks, Rodger, & Polatajko, 2008; Taylor, Fayed, & Mandich, 2007) and neuro-motor training tasks (Ferguson et al., 2013; Niemeijer, Smits-Engelsman, & Schoemaker, 2007). The systematic review from Smits-Engelsman and colleagues (2013) showed that task-oriented interventions yielded much stronger effects (dw=0.89) than process-oriented program effects (dw=0.12) for DCD. They conclude that process-oriented have limited efficacy, over and above incidental learning. However, by the authors' own admission, only a small number of studies in the review conducted follow-up assessments and most others did not adequately describe the precise nature of the intervention design. These are critical factors that convey important information to clinicians wishing to integrate empirical evidence into best possible practice methods.

Even though there is a growing body of research in DCD that showcases the range of interventions that exist, there appears to be no gold standard that clinicians can turn to for effective remediation. That said, it is generally agreed that engaging children in any type of intervention is a more desirable option than leaving symptoms untreated, particularly when children's coordination problems can persist into adolescence and adulthood (Cousins & Smyth, 2003; Kirby, Edwards, & Sugden, 2011; Kirby, Sugden, Beveridge, Edwards, & Edwards, 2008). As more knowledge is gained about the varied expression and prognosis of DCD, clinicians and researchers are better able to identify movement difficulties in children and create empirically validated treatment programs. However, without a detailed understanding of the aetiology of DCD, such programs may not be well targeted to those children who need treatment. Several cogent theories have developed to explain the causal mechanisms associated with DCD, which directs the focus of experimental research on DCD and typically developing children. The main theoretical accounts are evaluated in the following section.

1.3.3 Recent Aetiological Perspectives of DCD

1.3.3.1 Information processing. One key argument about the aetiology of DCD is that no single theory of motor control can explain comprehensively all the deficits associated with the disorder (Shumway-Cook & Woollacott, 2011; Zoia, Barnett, Wilson, & Hill, 2006). From a historical perspective, the information processing (IP) account tended to dominate DCD research between 1980 to the mid-1990's (Wilson, 2005). Using a computer metaphor for motor action, the IP approach assumes incoming sensory information is processed through a number of sequential stages (or levels of processing), culminating in the programming and execution of a motor response. That is, information is processed in a serial fashion via sensori-perceptual operations, response planning, and motor execution functions (Savelsbergh, Davids, Van der Kamp, & Bennett, 2003). The main goal is to isolate disruptions to particular perceptual (e.g., visuospatial processing) and/or cognitive processes (e.g. attention, memory, and executive function) that might underlie the issues in overt performance that define DCD (Hill & Barnett, 2011; Rostoft & Sigmundsson, 2004).

Reference to the IP approach has remained attractive to researchers for pragmatic reasons in that it provides a framework for investigating specific mechanisms (e.g. working memory, inhibitory control, and processing speed) using an experimental approach. Based on the factor-addition logic of Sternberg, Sergeant and others, this approach lends itself to detailed chronometric and kinematic methods, which have dominated the research landscape until recently. For example, using a method of differential loading, Alloway and Temple (2007) showed that children with DCD were more impaired on verbal and visuospatial memory tests, suggesting a link between memory and motor learning in DCD.

As a way of synthesising the research, a comprehensive meta-analytic paper by Wilson and McKenzie (1998) examined 50 IP-based studies between 1963 and 1996. The authors identified 374 effect sizes based on 983 DCD and 987 control children, and found that the greatest deficit to be in visual-spatial processing, regardless of whether a motor component was involved. Other deficits were also noted in kinaesthetic and cross-modal processing. While the results of the study strongly suggested perceptual processes are associated with motor control difficulties, the investigators cautioned that the presence of such deficits could not be taken as evidence of causation. For example, deficits in kinaesthetic processing may arise as a negative consequence of low participation in sport and physical activity since children with DCD tend to avoid learning new motor skills (Engel-Yeger, Hanna-Kassis, & Rosenblum, 2012). Notwithstanding this cautionary tale, aspects of visuospatial processing have been linked causally to DCD in experimental work (Wilson et al., 2013).

Since the Wilson and McKenzie (1998) review, the IP perspective has been challenged on a number of fronts. First, the approach overemphasises the linear nature of information processing from stimulus to response and ignores evidence for parallel processing under tight temporal and spatial task demands (Wade, Johnson, & Mally, 2005). Parallel processing is necessary to negotiate multiple objects and events in the environment while orchestrating a movement or sequence of movements in real time, otherwise adaptive and flexible movement is not possible. In addition, output signals to the effector systems do not always emanate *top down* (Magill, 2010). Instead, control can be exerted on the system as a direct consequence of environmental signals or cues, rather than from a control centre. For instance, a fast looming object may trigger postural and other adjustments to avoid collision. This (*bottom up*) example shows how an automatic reaction, directed by low level sensori-perceptual processes, can influence motor behaviour.

Taken together, these challenges have weakened the strength of the IP account. Over time, such criticisms have led to a paradigm shift of sorts toward ecological and cognitive neuroscience perspectives on motor behaviour.

1.3.3.2 Beyond information processing: Insights into cognitive neuroscience.

More recently, motor control and learning has been influenced considerably by two pivotal approaches: cognitive neuroscience (CN) and dynamical systems. Cognitive neuroscience is a multi-disciplinary approach that models thought and behaviour in terms of the interplay between underlying neurocognitive systems (Miyashita & Farah, 2001). In the case of motor behaviour, control is implemented by multiple, interactive networks rather than a serial flow of information codes through different processing stages (Roy, 2008; Shumway-Cook & Woollacott, 2011; Wilson et al., 2013). Wilson and Butson (2007) suggest that the CN approach is an integrative one, drawing on a range of methodologies such as neuropsychological case studies, neuroimaging techniques (e.g. fMRI, MRI, and PET), neurophysiological techniques like EEG, brain lesion studies and animal models. The use of these techniques, coupled with experimental methods drawn from cognitive psychology, form a modern approach to examine the underlying mechanisms of motor clumsiness.

A criticism aimed at the use of neuroimaging studies suggests that actions performed in a recreated magnetic environment does little to simulate real-world constraints that impact upon the movement under investigation (Sanes & Donoghue, 2000). In response, Fuchs and colleagues (2000) argue that the scientific pursuit should focus on knowing which experimental paradigms "...afford the best entry point for understanding brain-behaviour relations" (p. 375). Comments like this reflect a desire to understand atypical motor development by using converging methodologies. At a functional level, paradigms that examine the interaction of action and the CNS between DCD and control children will add more to the current body of DCD knowledge. From a CN perspective, several promising new hypotheses have emerged to explain DCD. Perhaps the two leading accounts are the *internal modelling deficit* (IMD) hypothesis, focusing mainly on predictive motor control, and the motor timing (or cerebellar) hypotheses.

1.3.3.2.1 *Internal modelling and the IMD hypothesis*. One theory that has gained converging support concerns the way children learn to create an internal (or feedforward) representation of an intended movement. Modern computational accounts of motor control suggest that two processes are crucial for goal-directed action: forward (or predictive) modelling and inverse modelling (Desmurget & Grafton, 2003). Predictive models use a copy of the motor command (i.e., efference copy) to the *plant* to estimate the state of the moving limb, while inverse models produce the motor command necessary for the desired goal state (Desmurget & Grafton, 2003; Miall & Wolpert, 1996; Wolpert, 1997; Wolpert, Diedrichsen, & Flanagan, 2011). The process of predictive modelling generates forward estimates of limb positioning based on the expected consequences of action (Shadmehr, Smith, & Krakauer, 2010). In this way, the motor system is afforded advantage by quickly and accurately accounting for changes in target-limb relationships should discrepancy arise. The ability to adjust movement in this way avoids delay associated with slower feedback corrections, which have been found to take up to 250 ms (Frith, Blakemore, & Wolpert, 2000).

This process is subserved by fronto-parietal and parieto-cerebellar loops. It has been observed, for example, that patients suffering lesions of the posterior parietal cortex (PPC) perform poorly on motor imagery tasks, that require the generation of internal motor representations (Sirigu et al., 1995; Sirigu et al., 2004), and rapid online control (Pisella et al., 2000). Pisella and colleagues (2000), for example, showed that the performance of patients was exceedingly slow and deliberate when implementing online adjustments to sudden changes in target position, unlike the fast automatic corrections of control subjects. Results were consistent with a deficit in predictive online control.

More specifically, it has been hypothesised that the motor problems shown by children with DCD are due to a deficit generating internal (predictive) models of action

(Wilson et al., 2013). Evidence is drawn from studies using paradigms that assess motor imagery (Williams, Thomas, Maruff, & Wilson, 2008; Williams, Wilson, Thomas, Maruff, & Butson, 2006; Wilson et al., 2004), covert orienting of attention (Wilson & Maruff, 1999; Wilson, 1997), force control (Pereira, Landgren, Gillberg, & Forssberg, 2001; Przysucha, Taylor, & Weber, 2008), response inhibition (Mandich, Buckolz, & Polatajko, 2002), and others. More recently, online control during reaching has been used to assess the integrity of predictive modelling and is described more fully in a section below.

1.3.3.2.1.1 *Motor imagery.* For children with DCD, there is converging evidence to support the IMD hypothesis (Wilson et al., 2013). This account provides a parsimonious framework for explaining the difficulty that these children have learning new skills and refining performance, even in the face of repeated practice. The first line of evidence comes from studies of motor imagery (Lewis, Vance, Maruff, Wilson, & Cairney, 2008; Noten, Wilson, Ruddock, & Steenbergen, 2014; Williams, Omizzolo, Galea, & Vance, 2013). Motor imagery, defined here as the internal simulation of motor action without overt movement (Hyde, Wilmut, Fuelscher, & Williams, 2013), is taken to reflect the internal representation of action and a marker for internal modelling, specifically. This view is based on experimental data showing that the same physiological and neural processes are activated in actual movement (Jeannerod, 1995; Jeannerod, 2001; Williams et al., 2013; Wilson, Maruff, Ives, & Currie, 2001). Investigations of the relationship between real and imagined movements have led researchers to hypothesise that motor imagery is the efference copy of an intended movement (Wilson et al., 2001).

In an earlier study using the visually guided pointing task (VGPT), results have revealed atypical performance in children with DCD when compared to age-matched control children and adults (Wilson et al., 2001). On the VGPT, participants must move their hand either physically or mentally between targets of varying size. Wilson and colleagues (2001) found that the movement time of the DCD group did not conform to Fitts' Law (Fitts, 1954) unlike the control group, and also to that of adults shown from previous research (Decety & Jeannerod, 1995). In addition, the imagined movement of children with DCD did not increase with the addition of weight, as it did for control children suggesting an impaired ability to generate predictive (forward) models of movement.

Later, Williams and colleagues (2006) compared DCD and healthy controls children on four imagery conditions: a single-hand rotation task with and without explicit imagery instructions, a whole-body imagery task, and an alphanumeric rotation task. For each condition, stimuli were presented a computer screen for 10 seconds and rotated in increments of 45^0 between 0^0 and 360^0. For example, in the single-hand rotation tasks participants decided if a hand presented was either a ‘right’ or ‘left’ hand. Overall, results across the four tasks suggested that children with DCD had difficulty utilising specific motor imagery instructions and performing egocentric transformations, supporting earlier work (Maruff, Wilson, Trebilcock, & Currie, 1999; Wilson et al., 2001) and the IMD hypothesis. Interestingly, the pattern of performance in DCD resembles that seen in patients suffering lesions to the PPC (Sirigu, Duhamel, Cohen, & Pillon, 1996). Taken together, this body of research indicates that children with DCD show impairment in generating forward (or predictive) models of motor control.

Of the main limitations of this work on motor imagery are the fact that studies adopt quite different task methodologies (e.g. distance estimation, size comparison, simulating actions) and the possibility that children adopt visual imagery strategies to solve mental rotation and imagined timing tasks. Stevens (2005) suggests two different neural modalities operate concurrently: (i) visual imagery mechanisms (subserved by the right hemisphere of the brain) interprets the location and size of an object in space, and (ii) motor imagery (left hemisphere) reconstructs elements of biomechanical processes such as muscle control and joint movement. The issue for many studies is that without access to brain imaging techniques, it is difficult to verify that motor cortical or other regions are being activated in DCD.

1.3.3.2.1.2 *Postural control.* Deficits of postural control have been reported in children with DCD (Chen et al., 2014; Inder & Sullivan, 2005; Jover, Schmitz, Centelles, Chabrol, & Assaiante, 2010; Kane & Barden, 2012). In a study by Przysucha and colleagues (2008), postural sway was measured in two phases of movement (according to dual-component theories of motor control): feedforward and feedback stages based on the time to reach peak velocity. Briefly, dual-component models propose that sensory feedback is precluded from the initial stages of movement (i.e., until peak velocity), assumed to be under direction of the motor command. The second phase engages predictive feedback-based control by using sensory feedback to adjust the moving limb and improve target accuracy (Sarlegna & Mutha, 2014). Przysucha and colleagues found that leaning sway was poorer in children with DCD than controls. That is, analysis of time taken in the corrective movement phase showed that the DCD group spent 54% of time under feedback control compared with controls who took 78%. The feedback phase is a more efficient online strategy to adjust postural leaning as it integrates incoming signals into the nervous system with respect to body and limb position. Problems with this mode of control suggest that children with DCD may experience difficulty using predictive-based systems to maintain steady posture.

Recently, Jover and colleagues (2010) assessed anticipatory postural control on a load lifting task between children with DCD and matched controls. Participants extended their arms out to a horizontal position with a load (i.e. weight) attached to the forearm. Arm position was held following weight unloading during two conditions: imposed or voluntary load removal. Maintaining a stable posture in the latter condition is dependent on the ability of the nervous system to anticipate and adjust for the motor consequences of load removal.

This process is inferred from decreased elbow flexion and reduced EMG activity in the flexor muscles (prior to load removal). Even though children with DCD were able to compensate for weight unloading, they showed poorer arm stabilisation after voluntary load removal which suggested problems with anticipatory (predictive) control. Furthermore, the DCD group showed delayed inhibition of flexor muscles while no relationship was found between their inhibition and arm stabilisation. For control children however, earlier flexor inhibition was correlated with improved arm stabilisation suggesting more efficient use of predictive control strategies to maintain arm stability.

1.3.3.2.1.3 *Grip force.* Some researchers have inferred deficits of predictive control in DCD on the basis of problems using grip force modulation (e.g., Hill & Wing, 1999; Pereira, Eliasson, & Forssberg, 2000; Pereira et al., 2001). Pereira and colleagues (2001) compared 20 boys with DCD with age-matched control children on a lifting task which involved repetitive grasp and lift movements of a small object. This was to ensure that appropriate force was used to grasp the object while preventing excessive force being used. Success on the task is underscored by the ability of the nervous system to estimate the variable force and load associated with the speed and duration of movement according to the object's weight. In other words, faster movements performed with a heavier object require additional grip force to hold the object in place. Pereira and colleagues found that the DCD group had higher grip forces and safety margins than the control group and suggested disruption generating the predictive model to accurately anticipate the impending movement.

To conclude, while there is good evidence across paradigms to support the IMD hypothesis, it is recognised that not all children with DCD show deficits in motor imagery, postural control, and grip force. Other plausible theories of DCD and its underlying mechanisms exist.

1.3.3.2.2 *The cerebellar-motor timing account.* Deficits of motor timing have been widely observed in DCD (Wilson et al., 2013) and have been linked to some disruption at the level of the cerebellum, and its reciprocal connections to motor and sensory cortex. The role of the cerebellum is seen to act as part of a larger distributed system for both motor and non-motor control processes within the central nervous system (Cantin, Polatajko, Thach, & Jaglal, 2007; Mariën, Van Dun, & Verhoeven, 2014; Salman, 2002). More specifically, the cerebellum is involved in the coordination of muscle movements in the execution of action and postural balance by acting as an adaptive controller (Barlow, 2002; Herzfeld & Shadmehr, 2013; Shadmehr & Krakauer, 2008; Wolpert, Miall, & Kawato, 1998). In response to environmental signals, this adaptive controller is a means for implementing rapid changes based on discrepancies between planned and actual movement (ala internal modelling). More specifically, the cerebellum is thought to be a 'somatic discrepancy detector' (Blakemore & Sirigu, 2003). That is, unexpected mechanical perturbations and other unusual somatic events during the course of a movement are identified and corrected by cerebellar structures (e.g., climbing fibres), in association with the PPC (Mariën et al., 2014). Deficits associated with the neural networks within this system often impact rhythmic motor behaviours, which has become a focal point for experimental researchers.

One paradigm that has been adopted widely to test atypical motor control involving the cerebellum is synchronised tapping to a metronomic beat; problems maintaining rhythm on tasks is suggestive of cerebellar impairment (Ivry & Keele, 1989). Typically, participants are required to maintain a steady rhythm by tapping their finger in unison with a stimulus beat and continue tapping for a period of time after the stimulus beat is removed. Studies have repeatedly shown that children with DCD have problems maintaining stable rhythm patterns across motor tasks (De Castro Ferracioli, Hiraga, & Pellegrini, 2014; Lundy-Ekman, Ivry, Keele, & Woollocott, 1991; Mackenzie et al., 2008; Piek & Skinner, 1999). For example, using Wing-Kristofferson (1973) timekeeper model, Williams and colleagues (1992) showed that that timing control in a 'clumsy' group of children was more variable than controls on a uni-manual continuous tapping task, suggesting that a difference in rhythm control was due to dysfunction of a central time-keeping mechanism.

In another study, Lundy-Ekman and colleagues (1991) assessed clumsy children, who showed soft neurological signs of cerebellar dysfunction and soft neurological signs of basal ganglia damage, with age-matched controls. When children performed a continuous tapping task, a double-dissociation between the clumsy groups was found. Children in the cerebellar group displayed increased inter-tap interval and force variability, unlike the children in the basal ganglia group who demonstrated performance within normal range. Conversely, the basal ganglia group displayed increased force variance when compared to the cerebellar group. This double-dissociation led Lundy-Ekman and colleagues to infer that central timing and force control are regulated by different neural systems, and that deficits in the cerebellar group are due to an impaired central timing mechanism. In sum, these deficits in timing suggest that the cerebellum is implicated in DCD. Specifically, regulation of the relationship between agonist and antagonist bursts of muscle activation may be compromised.

Not all studies show clear evidence of a timing deficit in DCD, however. Cantin and colleagues (2007) used a Prism Adaptation Test (PAT; Martin, Keating, Goodkin, Bastian, & Thach, 1996) to assess cerebellar function in TDC and children with DCD. A PAT requires participants to perform goal directed movements (e.g., throwing a ball at a target), first with normal vision (an initial stage) and then with an undetectable visual displacement to a peripheral location by wearing prism glasses. Vision is then restored to normal conditions (a recovery phase) to complete the assessment. In the first stage of the PAT, participants generate an internal (predictive) model representing the relationship between visuo-motor and proprioceptive-motor frames of reference (Redding, Rossetti, & Wallace, 2005; Redding &

Wallace, 2004). Undetected visual displacement results in conflict between the expected consequences of the motor plan (according to the predictive model) and that indicated by sensory consequences of the action. In other words, wearing prism glasses shifts the frames of reference, necessitating a change to the internal model over repeated learning trials. Following visual displacement, initial trials tend to be less accurate but become successively better as the error signal is used to update the predictive and inverse models to account for the change in limb-target relationship. This process is inferred by comparing accuracy levels in the prism stage to those prior to wearing the glasses. Similarly, successful integration of the predictive and inverse models is seen from ‘after-effects’ once prism glasses are removed and vision returns to normal. Throwing a ball during this final phase of the assessment also shows poorer initial accuracy, this time toward the opposite direction of the prism displacement. Results from Cantin and colleagues showed that overall, the DCD group were more variable and less accurate than the control group throwing a ball at a target, but found that some children with DCD obtained normal scores on the PAT by adapting to the visual displacement. The behavioural data here neither confirm nor refute a cerebellar deficit in children with DCD but some researchers have questioned whether such paradigms can in fact isolate a specific cerebellar (or other) deficit (Wade et al., 2005). Importantly however, cerebellar patients show either impaired or absent motor adaptation during PATs (Martin et al., 1996; Morton & Bastian, 2004), providing evidence that the cerebellum may in fact play an important role in predictive models.

1.3.3.2.3 *Summary.* From converging approaches representative of the CN perspective, deficits in the internal (predictive) modelling of movement and timing control are two pivotal theories that help explain atypical motor development or DCD. Notably, evidence of dissociation in the pattern of performance between object-based and motor imagery tasks provides strong support for the IMD account. On balance, there is good support for cerebellar dysfunction in DCD, evident from motor timing and PAT deficits. Combined, the CN approach is a principled method to the investigation of underlying mechanisms associated with DCD. Increased used of neuroimaging and related methods has already refined our understanding, however studies to date have been limited in sample size and the fidelity of task design. With a focus on regions-of-interest and graph theoretic approaches, future neuroimaging studies will strengthen theory development in DCD research.

1.3.3.4 Dynamical systems approach to understanding DCD. Dynamical systems (DS) emerged as a reaction against the logic and assumptions of IP theories. Drawn from an ecological model (Gibson, 1976), DS emphasises the dynamic interplay between biological systems and their environment. The impetus to move is not top-down, but rather emerges from the interaction between the individual performer, the environment, and the nature of the task at hand. A key argument is that motor control is not prescribed from within the brain in pre-planned form. Rather, movement is an emergent property of the (individual) physical system itself in its interaction with the immediate environment (Geuze et al., 2001). Visual and other sensory inputs from the outside world are intrinsically meaningful to the mobile performer who utilises this information directly when organising a motor response. This is encapsulated by the notion of affordance and the process of *perceptual-motor coupling* (Gibson, 1976).

Dynamical systems contends that a plan created by a central command centre cannot account for the potentially infinite number of combinations (or degrees of freedom) that exist in the control of muscles units, tendons, and joints, even for the most simple action (Bernstein, 1967) like reaching for a book. The IP approach would assume a single, unique stored representation for every possible movement, which according to DS theory creates an unmanageable load on memory and response selection. The DS approach is particularly concerned with the system’s ability to extract information on invariant features of the environment and the movement space as a direct consequence of self-motion, as well as the ability to form movement synergies that reduce the degrees of freedom problem to a manageable set of kinematic and kinetic rules (Kelso, 1984; Savelsbergh et al., 2003). For example, in a seminal study of infants, Thelen, Fisher, and Ridley-Johnson (1984) found that the stepping reflex (which declines after two months of age) returns when infants are immersed upright in water. This showed that the stepping pattern was influenced by factors other than neural maturation, but rather environmental constraints. This example underlines the point that changes to observed movement patterns may potentially be too complex to be explained by brain-related mechanisms alone.

From a DS perspective, researchers have examined the control parameters associated with shifts in movement patterns or coordination dynamics in children with DCD. For example, changes seen in phase transitions, particularly those associated with the development of stable movement patterns, has been a focal point of research. Volman and Geuze (1998b) tested the stability of rhythmic (in-phase and anti-phase) finger movements in children with DCD using a perturbation paradigm. Here, a mechanical break attached to the index finger was applied during rhythmic flexion-extension movements. Volman and Geuze found deficits in children with DCD in the ability to produce rhythmic finger coordination patterns compared with controls, and noted that they required more time to restore their initial tapping rhythm after perturbation. In a related study, Volman and Geuze (1998a) measured visuo-motor coupling of finger flexions-extensions performed under in-phase and anti-phase conditions. Again, children with DCD were shown to have significantly less stable index finger coordination patterns for the anti-phase coordination patterns than matched controls. The researchers suggested that results could not be explained by a central timing mechanism as such a model was unable to account for complex coordination properties such as stability loss or phase transitions, and that these processes are not subserved by corresponding neural networks or structures. Ironically, it is likely that this deficit has some basis in the function of cerebellum (Mariën et al., 2014; Miall & King, 2008).

Inter-limb coupling has also been examined in DCD from a DS perspective. Whitall and colleagues (2006) measured the stability and coordination of hand-foot patterns of 10 children with DCD and matched controls. The task involved marching and clapping at the same time to an auditory beat, presented at four different frequencies (0.8, 1.2, 1.6 and 2.0 Hz). To assess participant's ability to coordinate their limbs, the researchers measured the time interval between a participant's foot strike-hand clap and the beat. By calculating the mean relative phase and variability of relative phase of the movement, they found that children with DCD had significantly greater trouble controlling coordinated hand and foot patterns in response to auditory changes.

In another study of inter-limb coupling, Volman, Laroy, and Jongmans (2006) tested 10 children with DCD across three in-phase and anti-phase tapping conditions: hand to hand, hand to foot (same body side), and hand to foot (opposite body side). Stability of coordinated movements was measured by the variability of the relative phase between the limbs under a condition performed at a preferred rate (steady state), and the point where a loss of pattern stability was observed. The researchers observed difficulties in rhythmic hand-foot patterns in DCD, shown from less stable patterns across all three limb combinations and in hand-foot combinations more than hand-hand combinations Coordination and control of inter-limb dynamics has also been strongly implicated in DCD in a recent meta-analytic review (Wilson et al., 2013), and is relevant to activities of daily living (e.g. running, locomotor transitions, intercepting objects while moving) - tasks which children with DCD frequently find difficult (e.g. Zoia et al., 2006).

While the DS approach has provided a more ecological and holistic perspective on motor coordination in DCD, the approach is not without its critics. Dynamical systems theory does tend to neglect the role of the nervous system in directing action (Shumway-Cook & Woollacott, 2011). In addition, most task paradigms (e.g., rhythmic finger tapping) have low ecological validity, ironically. In general, the research focus and outcomes are very descriptive, providing mathematical models to fit the dynamic relationship between physical units (the limbs) and external events, and inter-joint/limb coordination. As such, the underlying mechanisms of DCD are often bypassed in attempts to merely describe the dynamics of the motor action itself.

1.3.3.5 Integrative approaches. The reality now is that many researchers use a hybrid or integrative approach when framing research hypotheses and imposing methodologies to answer their questions (Elders et al., 2009; Smits-Engelman, Westenberg, & Duysens, 2008). What unites researchers here is the quest to understand atypical motor development by examining control processes, their neural bases, and factoring in the learning and developmental history of the child. This broad-based approach has informed the study of graphomotor control (Rosenblum & Livneh-Zirinski, 2008), force control during lifting (Law, Lo, Chow, & Cheing, 2011; Pereira et al., 2001), the effect of task constraints on target-directed reaching (Huh, Williams, & Burke, 1998), and measures of postural control under external perturbation (Geuze, 2005; Jover et al., 2010), all of which can provide unique windows into the development of movement skill in children with DCD. A broad theory that reflects the contemporary approach to child development, and is relevant to the main research aims of my thesis, is *interactive specialization*.

1.3.3.5.1 *Interactive specialization: An integrative model of neuro-behavioural development.* Recent modelling in the cognitive neurosciences has challenged traditional conceptualisations of neural development. Maturational approaches, dominant for many decades, posit that when a given region or structure matures within the central nervous system, the cognitive function or behaviours seated in that region become operational

(Johnson, 2005). Hence, maturation is often considered in dichotomous terms: a region is either *immature* or *mature*, ergo a cognitive function is either operational or not. In its most traditional form, this process of development is thought to be driven predominantly by endogenous factors, genetic and biochemical (Casey, Getz, & Galvan, 2008). Consequently, researchers have been able to predict the stage in development that a behaviour or cognitive mechanism will be expressed based largely on an individual's age. In the case of online control, for example, adult-like performance should emerge at around 8-9 years of age as fronto-parietal cortices reach a more advanced level of maturity (Wilson & Hyde, 2013) - this interaction between neural systems in relation to online control and executive systems is taken up for discussion later in this review.

Whilst the maturational approach provides an intuitively appealing and parsimonious account of development, it fails to account for a number of empirical and clinical observations (for a comprehensive review see Johnson, 2011). Critically, a purely maturational approach is incompatible with evidence which shows that brain development is experience-dependent, interactive, and mediated by endogenous factors, all of which shape the structure and function of the central nervous system, particularly in the first three decades of life (Barnea-Goraly et al., 2005; Casey, Tottenham, Liston, & Durston, 2005; Durston et al., 2006). In particular, the idea of *interactive specialization* helps link different lines of evidence together under the one theoretical umbrella. The broad hypothesis of *interactive specialization* posits that some regions of the cortex, while unfolding at a relatively slow rate, can still modulate the activity of other areas, influencing the tenor of cognitive processing. In other words, the emergence of a new behaviour is the result of weighted activity from several brain regions whose modular architecture and rate of maturation may differ in complexity and timescale (Johnson, 2011). New cognitive processes and behaviours thus arise as a result of changes to multiple regions rather than site-specific effects. This interaction (or coupling) between brain regions offers a general framework of *interactive specialization* and has provided researchers with a new focus on development.

1.3.3.5 Conclusion. Discussion of the above approaches has shed light on some of the different aetiological accounts of DCD. Accounts of IP, CN, and DS all offer some insight to the way DCD problems are expressed. Yet at the same time, there are also limitations associated with each account which highlight the need for a more unified aetiology of DCD, assessed through the use of carefully designed experimental work.

While there are many approaches to understanding the causes of DCD, the cognitive neuroscience account provided is the most promising for a number of reasons. First, more broadly, this approach has been successfully adopted for understanding the mechanisms that subserve motor development and disorder. Second, in the context of DCD, there is strong data in support of the view that delays in a variety of neuro-cognitive systems might be impaired in DCD. Last, and most importantly, it lends itself well to the development of intervention programs. Of the neuro-computational accounts that may explain DCD, predictive modelling offers the most promising account by virtue of the fact that it has received supportive evidence across a variety of tasks - most recently those of online control.

With this in mind, Wilson and colleagues (2013) conducted a meta-analysis of DCD research that examined experimental data of motor control and performance mechanisms. The researchers identified 1785 effect sizes across 129 studies and found that across all measures, there was a moderate-to-large effect size suggestive of a generalised performance deficit in DCD. Notably however, several areas were more noticeable. These included predictive control, coordination and timing movements, posture, gait, ball catching and executive function. Importantly, predictive control appears to be a fundamentally disrupted process and suggests that children with DCD struggle to form internal models (Wilson et al., 2013). What was unclear from the meta-analysis was how pronounced deficits across other systems such as executive function might influence the predictive control.

As a means to unravel the motor control and learning issues in DCD, I provide next an overview of ROC and evidence used to assess online motor control, drawn from double-step paradigms. Using a neuro-computational framework, I highlight the promise ROC holds in helping to clarify the nature of one of the more sturdy aetiology accounts of DCD: a deficit in predictive control (aka *internal modelling deficit*; IMD) and its integration with developing executive systems.

1.4 Predictive Online Control is Vital to the Acquisition of Movement Skill in Children

1.4.1 What is Rapid Online Control?

The ability to fluently adapt an on-going movement following unexpected environmental events requires a well-tuned and functional neuro-motor system. Accordingly, in recent decades the integrity of this process has been used as an important indicator of the maturation and cohesion of the broader control systems. Online control is a fundamental process involved with functional motors skills. It involves the ability to correct or update movement parameters in response to unexpected environmental consequences, requiring continuous integration of feedforward and feedback processing (Shadmehr et al., 2010), particularly in the case of upper-limb re-direction. Current neuro-computational models consider fluid reaching as being controlled by a broader, more integrative system of which ROC is part of.

Rapid online control is viable to the extent that neural signals can estimate the future location of a moving limb. It is supported through an internal (forward) model which incorporates information from the spatial estimates of body position and compares incoming sensory information prior to and during the course of action (Jeannerod, 1997; Wolpert, 1997). Once visual and proprioceptive signals become available to the nervous system they are compared with those predicted by the forward model. In cases where there is mismatch between expected and actual consequences of action, an error signal is generated and fed back to the controller with the on-going motor command, thus allowing for rapid updating of limb position (Desmurget & Grafton, 2000). Interestingly, the speed at which such corrections occur are often within 100 ms (Castiello, Paulignan, & Jeannerod, 1991), much faster than sensory feedback. Hence, predictive models are considered crucial to the development of online motor control by anticipating the sensory consequences of movement and engaging rapid corrective actions with minimal processing delay to ensure stability within the motor system (Gaveau et al., 2014).

Importantly, visual perturbation studies (discussed below) show that older children implement earlier changes in reach trajectory in response to visual displacements than younger children, suggestive of an ability to generate a more refined forward (internal) model. As the developing child learns the relationship between their own motor output and the resulting effects on their moving limbs, they become better at predicting the consequences of their movement. However, for some children with DCD, the ability to generate predictive estimates (*viz* internal models) may be impaired, evident from performance on a double-step paradigm.

1.4.2 Use of Double-Jump Paradigms to Assess Online Control

One of the key methods used in experimental research to assess ROC has been through target displacement paradigms, specifically a double-jump reaching task (DJRT). In this paradigm, the task commences with a reaching movement from a home base position toward a one of three central targets, located at the coordinates of -20^0, 0^0, 20^0 in a straight line from home base. For most trials, the centre target is stationary but on a small number of trials, it moves laterally at movement onset. Here, participants are required to correct their reach unexpectedly from the initially cued target to the new target. The DJRT assesses online control by engaging the participant to change their reach trajectory in flight to a perturbed target based on forward modelling. A dynamic movement error signal is computed by comparing the updated location of the target with a predicted estimate of the movement endpoint, thought to be subserved by PPC (Desmurget & Grafton, 2003; Desmurget & Sirigu, 2009). Where vision of the moving limb is reduced, the participant updates their movement as it occurs, based on the predictive estimate of limb position (Desmurget & Grafton, 2000; Wolpert et al., 2011). An error signal (*efference* copy) is generated and compared with the existing motor command to incorporate the target shift and new spatial coordinates into the system (Izawa & Shadmehr, 2011). Using chronometric and kinematic markers, the integrity of ROC is inferred from the ability of the participant to compensate for the target displacement by adjusting their arm reach mid-flight.

1.4.2.1 Online control in typically developing children. To date, there have been a limited number of studies investigating ROC in healthy children, although early research (e.g. Bard, Hay, & Fleury, 1990; Chicoine, Lassonde, & Proteau, 1992) has suggested non-linear developments in reaching ability occurs after approximately 5-6 years of age. To better understand how ROC develops over childhood, Wilson and Hyde (2013) conducted a cross-sectional study of children aged between 6-12 years on a DJRT, comparing the performance of younger (6-7 years), mid-age (8-9 years), and older children (10-12 years) to that of healthy adults. Movement time and time to correction (i.e., the point in the movement cycle where a change in reach is initiated toward a new location) were used as key metrics of online control performance. As predicted, results showed that adults were more efficient at implementing online control than children. Importantly, younger children were disadvantaged by perturbed trials, evidenced by slower movement and correction times in comparison with mid-age and older children, who were comparable with their performance on the DJRT. These findings suggest that the capacity to use predictive models of limb position during online corrections develops quickly in a non-linear manner during younger childhood, with steady improvements continuing through middle and late childhood.

1.4.2.2 Research investigating online control in children with DCD. The importance of online control to motor behaviour is not only supported by studies showing rapid improvement through the primary school period (e.g., Wilson & Hyde, 2013), but also from evidence of atypical motor development. In children with DCD, performance on tasks of online control has been found to be generally slower and less accurate than TDC (see next section). The underlying processes associated with this pattern of behaviour (i.e., a deficit with predictive control) are becoming clearer due to the focus of research using double-jump paradigms. However, prior to the relative recent introduction of the double-step paradigms to the investigation of online control in DCD, other experimental work has highlighted a possible deficit in the ability to account for unexpected changes in the environment.

An early study that examined oculomotor control in children with DCD was carried out using a double-step saccade task (DSST) (Katschmarsky, Cairney, Maruff, Wilson, & Currie, 2001). For the DSST, two targets were presented: one target for 140 ms immediately followed by a second for 100 ms. Children were required to generate sequential saccades, shifting eye movement from the first to the second target; however, the presentation of the second target was extinguished before the first saccade creating dissonance between the location of the second target and the necessary oculomotor program to reach it. To successfully complete the task, a forward (internal) model is required to estimate the point of the second saccadic shift from the first. For the DCD group, results showed that dysmetria occurred on the second saccade. Interpreted using a computational framework, this deficit was suggested to reflect a decreased ability to engage a forward model to program saccade sequences. However, the study did not involve a motor component where mechanisms for correcting online movement are required; hence, inferences about the integrity of predictive modelling is restricted to the domain of oculomotor planning rather than limb movement.

A more recent visual perturbation study that assessed performance on a sequential reaching task was conducted by Wilmut, Wann, and Brown (2006). They examined the ability of children with DCD and healthy control children to couple hand-eye movements on a pointing task. Here, participants were required to reach for targets in three conditions: (i) a reach to a target location; (ii) a ‘double touch’ reach for two targets presented in sequential order; and (iii) a ‘double off’ reach where participants again reached sequentially for two targets but were extinguished shortly after movement onset. Results showed no group differences on single-target movements. Similarly, no differences were found on single-target movements on the double-step tasks, however the DCD group were slower moving to the second target. Based on this pattern it was suggested that children with DCD over-utilised a ‘look-then-move’ strategy when making sequential movements by waiting longer for the eye to meet the target and then initiate movement. Increased foveation prior to movement onset in children with DCD was thought to interfere with use of the efference copy (a copy of the motor command) which was said to become less accurate when foveation time increased, suggestive of a problem engaging a feedforward mode of control (Adams, Lust, Wilson, & Steenbergen, 2014). However, the task of Wilmut and colleagues (2006) did not directly assess the ability of children with DCD to make online corrections. As participants were required to first touch the initial target and then the second target on sequential trials, they were able to complete the first motor command then generate a subsequent one rather than updating the ongoing motor command as would be required for online control.

Taken together, these earlier studies provided some empirical support for the oft noted research finding that children with DCD are less able to account for unexpected environmental changes. However, as noted, neither the studies from Katschmarsky and colleagues (2001) or Wilmut and colleagues (2006) sought to directly measure online control per se. Hence, we must be circumspect when inferring the integrity of this important system. In acknowledging these limitations (and that from the DSST), with the view of specifically clarifying the nature of ROC in DCD by using a traditional double-jump paradigm, Hyde and Wilson recently investigated the ability of children with DCD to engage in online control of reaching across a series of studies (Hyde & Wilson, 2011a, 2011b, 2013). This body of research, and its implications, is discussed next.

1.4.2.3 Children with DCD show problems with ROC adjusting reaching movements in response to visual perturbations. The first study to specifically investigate online control of reaching in DCD using a double jump task was Plumb and colleagues (2008). Interestingly, this study actually reported that online control was preserved in children with DCD. However, due to task complexity, the DCD and control groups performed reaching movements under vastly different constraints, limiting the validity of group comparisons. Specifically, healthy children were required to complete the task while standing and with the use of a hand-held stylus to reach for and press targets. However, on account that the DCD group had difficulty standing and holding the apparatus, they completed the task sitting down.

Since this initial investigation, Hyde and Wilson conducted a series of controlled studies of online control in DCD using the DJRT, each suggesting that the ability to fluently correct reaching movements mid-flight may be compromised in school aged children with DCD. Initially, Hyde and Wilson (2011a) adopted a chronometric approach to investigate the performance of children with DCD on the DJRT. In their study, TDC and DCD groups were compared on reaction time (RT), movement time (MT), and response errors when children were instructed to reach for one of 3 possible targets on a screen (as described earlier). For 80% of trials, movement occurred from the home base target to the centre target (*non-jump* trial). On the remaining 20% of trials, the centre target *jumped* at movement onset from home base to either left or right target location (*jump* trial). Importantly, this study showed that MT was longer for the DCD group on jump trials relative to non-jump. Critically, non-jump reaching is thought to place limited demands on the online control (and hence predictive modelling systems) since the target remains stationary. Alternatively, on jump trials, demands on online control systems are greater since the unexpected target perturbation results in mismatch between the expected and actual sensory consequences of action. Accordingly, the observed increase in MT select to jump trials shown by the DCD group was suggested to indicate a problem with online control. This deficit was interpreted to occur due to a problem generating the error signal which would ordinarily arise when the discrepancy between the predicted and actual location of the hand has been detected. In short, the researchers suggested that compromised speed performing online corrections was the result of a reduced ability to update predictive (internal) models during a corrective movement.

While the use of chronometric data in Hyde and Wilson's (2011a) initial study provided broad evidence that a deficit in online control was present in children with DCD, in the absence of kinematic data, they were unable to further examine the control processes that underpinned this deficit. While they were able to determine that children with DCD experienced difficulties completing jump trials, they were unable to determine whether these occurred up to the point of trajectory correction (i.e. when predictive control is greatest) or after (where predictive demands are reduced). To address this, Hyde and Wilson (2011b) conducted a follow-up study using the same DJRT paradigm as their first study with the inclusion of kinematic analysis. Most importantly, they measured the point in the movement cycle where the reaching limb deviated from the central cue to a peripheral target on 'jump' trials. This 'time of correction (ToC)' value is often used to indicate the point in reaching where information about target perturbation (i.e. the error signal) has been successfully integrated with the on-going motor command (Shadmehr & Krakauer, 2008). While the authors replicated their earlier chronometric data, which showed that MT was greater, the researchers also found that children with DCD were significantly slower to adjust their reach trajectory on jump trials. This data was taken as evidence that the deficit in jump trials performance was indeed likely to arise due to difficulties engaging the predictive modelling system. Notably, the performance from the DCD group was similar to that of patients with lesions to the parietal cortex (Gréa et al., 2002) which the authors suggest is evidence of developmental delay, particularly of parieto-cerebellar axis. Taken together, these data suggested that the issue of jump trial performance within the DCD group was due to a reduced ability to correct their online reach trajectory where demands on predictive control are high. This confirmed that poor reaching (and hence online control) as shown in the earlier study was indeed likely to reflect impairment with predictive modelling.

Finally, to clarify whether the poor online control shown by children with DCD was likely to reflect a developmental delay or neurological deficit (from typical neuro-cognitive development), Hyde and Wilson (2013) compared DJRT performance between three groups: (i) children with DCD (8-12 year olds); (ii) age-matched controls; and (iii) a younger control group (5-7 year olds). Performance of the DCD group was found to be comparable to the younger, typically developing group, evident from similar ToC values and MT difference scores (the time between non-jump and jump trials – larger difference scores suggest a reduced ability to complete online corrections). Hyde and Wilson suggested that the pattern of reaching between the DCD and younger control group is characteristic of immature predictive modelling systems where neural transmission between the PPC and the cerebellum is undeveloped.

1.4.2.4 Summary. Research using visual perturbation paradigms has provided converging evidence that suggests online control is impaired in DCD. Additionally, there also appear to be differences in the expression of ROC in TDC and children with DCD. Across normative development, there is rapid improvement during younger childhood years (6-7 years) on online control studies, (where predictive modelling systems become better at estimating unexpected changes), followed by more progressive refinements into adolescence. Importantly, for children with poor motor skills (i.e., DCD), evidence from double-jump perturbation studies suggests a reduced ability to engage in ROC. From a computational perspective these have been interpreted as reflecting an impaired ability to implement forward (internal) models. In the case of the DJRT, increased movement and correction times on target displacement trials indicates a problem adjusting limb position relative to target shift. Interpreted using computational modelling, the ability to perform online corrections is viable only to the extent that changes in spatial coordinates during movement can be efficiently integrated (using a dynamic error signal) into the on-going motor command (Desmurget & Grafton, 2000).

In sum, as a window into the predictive modelling system, evidence from DJRT provides compelling evidence that predictive modelling may be compromised in children with DCD. However, as *interactive specialization* theory would propose we need to consider the expression of motor systems in the context of the development of other cognitive systems. In the case of DCD, a putative deficit in predictive modelling is best understood in the context of the development of other systems. As I discuss below, motor systems and executive control are correlated in typical development and children with poor motor skills show deficits in executive processes. Taken together, this suggests that the expression of control systems, such as predictive modelling, may be constrained or influenced by executive systems in typically and atypically developing children.

1.5 Executive Function in Children with and without DCD: Implications for Adaptive Motor Control and Skill Learning

The development of executive function (EF) enables children to expand the temporal limits over which behaviour can be organised. Current models posit that EF comprise a set of separable yet overlapping processes including attention, working memory, and inhibition (Best & Miller, 2010; Diamond, 2013). Constituents of EF serve to bias information processing efficiency, enabling the user to respond more flexibility to new situations (Diamond, 2013). In the case of inhibitory control, the ability to suppress a dominant, habitual or pre-potent response is generally seen to mature within the first 8 years of life (Best & Miller, 2010). Indications of developing inhibitory control involve improvement in reaction time and reduction of inattention and perseveration errors on Stoop measures, for example (Gerstadt, Hong, & Diamond, 1994). These changes correspond to neural maturation; increased myelination followed by synaptic pruning in PFC regions contribute to better cognitive control during the early stages of childhood (between 5-8 years old) (Bunge & Wright, 2007; Casey et al., 2005; Johnson, 2005). By middle childhood, there emerges a more fine-tuned ability to retain information in working memory, for example, and to withhold a compelling (inhibitory) response (Bunge & Wright, 2007). The consolidation of EF during a critical time of development appears to coincide with the changes seen in behavioural measure of online motor control where rapid improvements are seen during younger and middle childhood (Wilson & Hyde, 2013). Evidence of changes to children’s EF systems is shown in diffusion imaging tensor MRI measurements of white matter networks (WMNs) which show that areas of the prefrontal cortex, corpus callosum, basal ganglia and ventral-visual pathways are correlated with age (Barnea-Goraly et al., 2005). That is, connectivity between key motor and cognitive systems increased across childhood; these same regions which interact and support behaviour for more voluntary control over action (Johnson, 2005). Impairment of executive function in atypical development, as may be the case for children with DCD (discussed below), would reciprocally constrain online motor control.

In typical development, studies investigating the relationship between motor ability and inhibitory control (e.g., Stroop task performance) show strong associations in both younger and older children (Livesey, Keen, Rouse, & White, 2006; Piek, Dyck, Francis, & Conwell, 2007). In atypical motor development (DCD), problems of inhibitory control have been reported across studies. Early evidence comes from visuospatial attention studies using a covert orienting of visual-spatial attention (COVAT) paradigm (Wilson & Maruff, 1999; Wilson, Maruff, & McKenzie, 1997). During this task, participants provide a response to stimuli in one of two possible locations; spatial cues were shown prior that directed attention to the stimulus location (valid cue) or away from it (invalid cue). When an invalid cue was presented, participants were required to shift (or disengage) their attention away from the invalid location and toward the correct target, as measured using an increase in reaction time. By presenting two types of spatial cues: (i) endogenous which automatically direct attention and (ii) exogenous which engage voluntary attentional shifts, results from both studies showed that children with DCD were significantly slower to direct their attention after invalid endogenous cues (but not exogenous cues) than matched controls. These results were suggested by the authors that a deficit of shifting attention may be present in children with DCD.

A later study from Mandich, Buckolz, and Polatajko (2003) found similar results on a COVAT task but offered an alternate explanation suggesting that the behaviour may represent a reduced ability to inhibit attention from an invalidly cued location. This level of impairment in children with DCD been subsequently shown from further COVAT paradigms (Tsai, 2009; C.-L. Tsai, Y.-K. Yu, Y.-C. Chen, & S.-K. Wu, 2009), while data from adult studies have implicated this dysfunction in frontal-parietal regions (Posner, Rothbart, &

Sheese, 2007) indicating that this network may underlie problems preventing voluntary attention from an invalid location in children with DCD.

To further corroborate a deficit of inhibitory control, deficits have also been shown on tasks where a motor response is required to be suppressed. For example, on the ‘Simon Task’, children with DCD were found to have more trouble preventing a manual response when presented with a visual stimulus, relative to TDC (Mandich et al., 2002). This pattern of impairment has been observed in basal ganglia and frontal networks (Bari & Robbins, 2013)

Accordingly, it is likely that the development of executive functions places demands on the expression of motor systems, such as predictive modelling. However to date, no studies have investigated this important principle in typical or atypical development. In the case of DCD, understanding how cognitive systems, such as executive control, might constrain predictive modelling is particularly important if we are to better understand how a deficit in predictive model might contribute to poor motor control in DCD. The nature of this dynamic relationship can be explained by *interactive specialization* which suggests that unfolding neural systems interact and support each other during critical periods of child development.

1.5.1 Interactive Specialization Offers a Parsimonious Way to Explain the Interaction between ROC and Executive Systems

The hypothesis of *interactive specialization* can explain how developing executive systems may influence online control in children. Briefly, IS theory emphasises the role of interacting neuro-cognitive systems on development; separable neural networks (whose activity becomes more coordinated with time and experience) combine to support flexible and efficient behaviour (Johnson, 2005). That is, frontal systems that play an important role in motor sequencing, planning and control (Diamond, 2013) may also support many of the executive processes crucial for flexible online control. For example, increases in task requirements that occur when an individual is forced to unexpectedly and rapidly adjust their reaching places greater demand on limited capacity visuo-spatial working memory stores (Wilson et al., 2013). The implication here is that when ROC and EF need to be reciprocally adopted for complex movement, we might see problems with coupling of these two processes as the nervous system learns and adapts to the emerging behaviour.

At an experimental level, a way to assess executive and online motor systems together would be to introduce an inhibitory load on double-jump paradigms. By modifying a traditional DJRT where online corrections are needed, an ‘anti-reach’ task could be administered that requires the individual to reach to a hemi-space opposite that of a compelling (displaced) visual target. Successful completion of the task would rely on the ability to suppress an automatic correction drawn toward the visual (yet invalid) cue and purposefully redirect the hand to a contralateral target location. By imposing a load on executive stores, the time taken to engage the hand would assess the ability to engage frontal modulation during online corrections. At a broader level, an understanding of how online control and executive systems are coupled would provide important information about the causal basis of motor dysfunction in DCD, particularly when deficits have been found across both systems separately.

1.5.2 Conclusion

Interactive specialization is a useful framework to explain the degree that executive control might constrain the development of motor systems, using online control as an excellent marker of predictive modelling. Not only should the hypothesis of IS clarify the nature of ROC in children with DCD, but it may also inform existing cognitive neuroscientific accounts of DCD; specifically a deficit in predictive modelling. While I have presented a case based on current neurodevelopmental theory and data that the development of ROC is likely constrained by fronto-executive control systems - and to varying degrees in

TDC and children with DCD - the theory is yet to be validated empirically. Accordingly, the focus of research in this thesis was to understand how emerging executive systems impact online control across the primary school years. This matter of investigation comprised the broad focus of the studies presented in Chapters 3, 4 and 5.

1.6 Summary of Chapter 1

Developmental Coordination Disorder a serious childhood learning disorder that is characterised by deficits across a range of fine and gross motor skills. Children with motor control problems frequently show below average performance in scholastic ability and/or everyday activities, which tend to persist into adulthood. With a prevalence rate of approximately 6%, research to understand the developmental precursors of DCD is important in an effort to avoid some of its negative consequences, as well as providing empirically validated theory for health professionals to develop appropriate interventions. This chapter reviewed broad categories of DCD research (and motor control in general), followed by key aetiological accounts of information processing, cognitive neuroscientific and dynamical systems.

In particular, theories based on a cognitive neuroscience framework lead the way to identify the underlying mechanisms of DCD. Notably, impaired predictive control (*viz* IMD hypothesis) is drawn from evidence of motor imagery, force control and visual perturbation studies, although a deficit in cerebellar motor-timing may also explain problems linked to DCD. While each account offers a relative degree of empirical validity, there are limitations to the research in terms of explaining the aetiology of motor control problems seen in DCD and hence, suggest a need for further experimental work. Importantly, I argued that a computational modelling account of ROC was useful to clarify the nature of predictive control in children, tested through carefully designed double-jump studies.

While ROC appears to be crucial to fluid movement in motor development, and may be compromised in children with DCD, its development is best understood within the context of other neuro-cognitive systems, namely executive function. Importantly, there is a need to assess how motor and cognitive systems interact across development, particularly when deficits of ROC and EF have been reported in children with DCD. By presenting a neuro-behavioural account of *interactive specialization*, I argue that this parsimonious framework will help extend previous ROC research and explain two main lines of investigation in this thesis: (i) how executive systems influence the expression of online motor control in children's typical and atypical motor development; and (ii) how these two systems develop over childhood. At an experimental level, the use of a double-jump paradigm will provide valuable data about the interaction of these co-occurring systems. The matters of how ROC and EF are operationalised and assessed are presented in Chapter 2.

METHODOLOGY

2.1 Overview

In Chapter 1 I provided a review of research that has been central in building knowledge of rapid online control and its development in children. In this chapter, I first outline the general cognitive neuroscience approach to the study of motor control in children and present the pivotal research hypotheses that are the focus of this thesis. From this theoretical framework, I then describe the main research paradigm for examining online control—the double jump reaching paradigm—including the operationally defined behavioural measures of ROC. Finally, I describe the cross-sectional experimental designs used for Studies 1 and 2, with multi-factorial analysis, and the longitudinal design for Study 3 that incorporates statistical modelling using growth curve analysis.

2.1.1 Cognitive Neuroscience Approach to the Investigation of Motor Control

From a neurocomputational perspective, the notion of *internal modelling* has become a critical concept in explaining the process of motor control and learning. As described in Chapter 1, internal modelling comprises two complementary processes: forward (or predictive) modelling and inverse modelling. The process of predictive modelling involves the generation of forward estimates of limb and body position based on the expected sensory consequences of movement. To the extent that the consequences of movement can be predicted accurately in real time or online, the motor system is afforded a significant advantage, especially under dynamic conditions. The ability to model movements in this way reduces the load on slower feedback-based corrections which can take up to 250 ms (Frith et al., 2000). One method for understanding the integrity of online control (*viz* predictive control) is the double-jump reaching paradigm. Work using this paradigm has revealed that an interactive neural network underpins the ability to implement rapid online corrections.

2.1.2 The Double-jump Paradigm is a Valid and Reliable Method to Assess Online Motor Control in Children

Visual perturbation paradigms have been shown to be a valid and reliable method for investigating rapid online control and the integrity of predictive modelling, whether using behavioural, neurophysiological or a combination of outcome data (e.g. Hyde & Wilson, 2011a; Katchmarsky et al., 2001). At the level of behavioural analysis, performance on the double-jump reaching task (DJRT) can be analysed using chronometric and kinematic outcome measures. For this task, visual targets presented on a touchscreen or similar device are displaced at or shortly after lift off from a home target position. Under conditions where vision of the moving limb is prevented or greatly reduced, the participant must change their reach trajectory 'mid-flight'. Critically, the speed and efficiency of this correction is based on a predictive (or forward) estimate of limb motion and its changing position with respect to the target (Desmurget & Grafton, 2000). A dynamic movement error signal is computed by comparing the updated location of the target with a predicted estimate of the effector endpoint, a process thought to be subserved by the PPC and its network connections (Gaveau et al., 2014; Gréa et al., 2002). Motion analysis technologies now provide highly accurate measures of limb kinematics that describe the processes by which this online control occurs.

Using this paradigm, it has been shown that online control develops gradually over childhood, and that for children with DCD, this mode of control is delayed in development. However, the model of typical and atypical motor development in limited to the extent that we do not understand how online control is coupled to cognitive systems developing in parallel, and what best describes the pattern of change with age, based on longitudinal data. These gaps in our understanding informed several hypotheses that were the focus of this thesis.

2.2 Main Rapid Online Control Hypotheses

The broad hypotheses for each completed study are listed below.

2.2.1 Hypotheses for Study 1

1. Rapid online control (assessed by chronometric and kinematic measures described below) would be implemented efficiently in most children from 9 years of age.

2. The ability of online control in younger (6-7 years) and mid-age children (8-9 years) would be reduced when tasks demand higher levels of executive (inhibitory) control; flexible performance under these same demands (i.e., successful and time efficient anti-reaching) would manifest in most children by 10-12 years of age.

2.2.2 Hypotheses for Study 2

3. The integrity of internal modelling (*viz* rapid online control) would be: (a) significantly lower in children with DCD compared with age-matched children with typical levels of movement skill, and (b) children with DCD would show further impairments when an inhibitory constraint is added by way of an anti-reach movement.

2.2.3 Hypotheses for Study 3

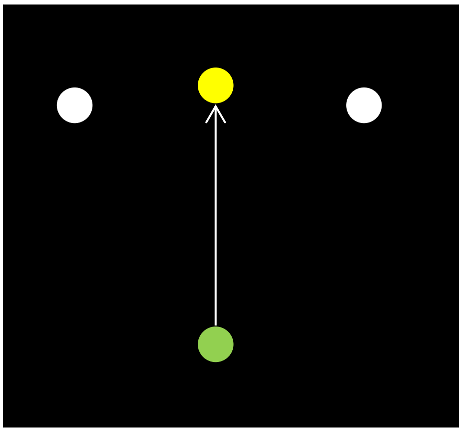
4. Longitudinal data from a two year project would confirm that (a) a quadratic trend provides the best fit to growth curve models of ROC over childhood, interpreted via an *interactive specialization* framework, and (b) children with DCD would display a generalised maturational delay on key metrics that measure the ability to couple online motor and executive systems.

2.3 The Double Jump Reaching Task: Conditions, Key Metrics, Power Analysis and Justification of Sample Size

To test the hypotheses listed above, a double-jump reaching paradigm was used. The DJRT was programmed using Virtools™ software (3DVIA, 2010) and run on a quad-core Dell Precision laptop computer. The computer was connected to a 42-inch touchscreen display, mounted in portrait view at 10 degrees from the horizontal plane on a height adjustable table. Children stood in front of the screen with their hand resting next to the monitor. The stimulus display consisted of a green home base and three possible yellow target locations, presented against a black background. The home base consisted of circular target, 2.5cm in diameter, positioned at the midline of the screen, and 5cm from the nearest edge. The three target locations were positioned in a semi-circular formation near the middle of the screen, located at the coordinates of -20º, 0º, 20º with respect to the home base target (see Figure 2.1). Each target location was positioned within peripersonal space as their distance from the home base was scaled to arm length based on age norms: young children, 25cm; mid-age children, 28cm; and older children, 30cm (Gerver, Drayer, & Schaafsma, 1989). Each trial began with the finger held stationary on the home target. The imperative stimulus consisted of a doubling in luminance of the central target, and simultaneous extinction of the home base.

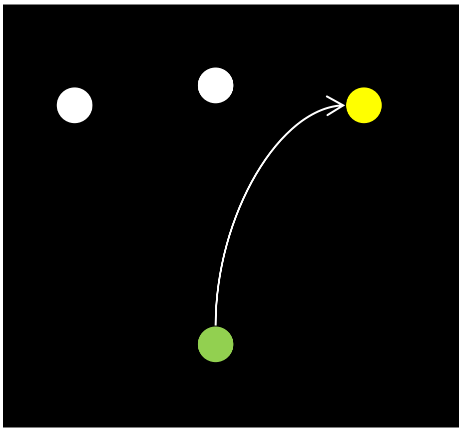
Condition A (standard jump trials)

Non-jump trial



The central target remains lit until touchdown.

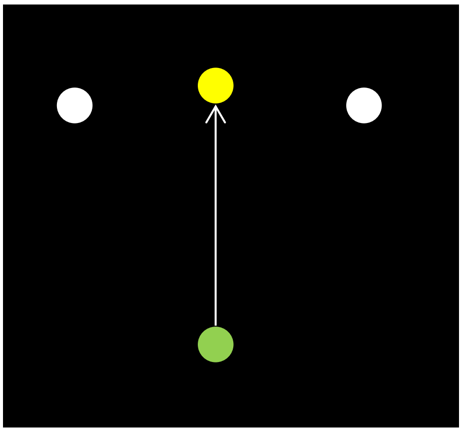
Jump trial



Target displacement occurs to either peripheral location at finger lift off

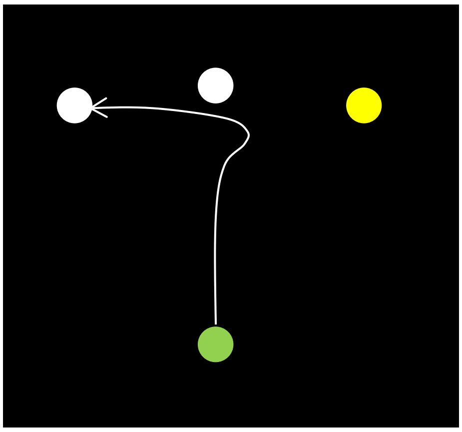
Condition B (with anti-jump trials)

Non-jump trial



The centre target remains illuminated until finger touchdown.

Anti-jump trial



Reach to the contralateral location is required.

Figure 2.1. Schematic overview of the double jump reaching task showing trial types across jump and anti-jump conditions.

For the standard DJRT used to assess online control, participants were instructed to reach and touch the illuminated target as quickly and as accurately as possible with their dominant hand index finger. On 80% of trials the centre target remained lit (*non-jump* trial). For the remaining trials (20%), the centre target was first illuminated, but at the point of lift off from the home base, it was extinguished and a lateral target was presented (*jump* trial). A ratio of 80-20 trials was used to prevent participants from anticipating the frequency of perturbed trials. Practice trials were offered to participants prior to the task to ensure all children were able to perform the task with a relative degree of proficiency.

For the inhibitory DJRT used to assess coupling between online and inhibitory control (Day & Lyon, 2000), the same stimulus display and event sequences were used. However, when target jumps occurred, participants were instructed to reach and touch the target location on the opposite side to that of the illuminated target (*anti-jump* trial). Both conditions comprised two blocks of 40 trials administered with 32 non-jump trials and 8 perturbed trials per block, yielding 80 trials in total. Each peripheral target was programmed to 'jump' pseudo randomly for a total of 16 times per task condition (or 8 times per block). Randomisation of jump and non-jump trials prevented anticipatory responses. The order of presentation of jump and anti-jump conditions was counterbalanced over participants to prevent possible order effects. Motion was tracked in real time using the ultrasonic Zebris™ CMS system (Noraxon, 2010), sampling at 200 Hz. The system was clamped to the table and positioned at a height of 1 meter above the middle of the screen. The acoustic sensor (which weighed less than 5 grams) was placed on the back of the child's index finger to record kinematic movement and did not impede task performance.

2.3.1 Measurement Variables on the DJRT

Performance was measured both chronometrically [Response Time (RT) and Movement Time (MT)] and kinematically [Time of Correction (ToC) and Post Correction

Time (PCT)]. RT was measured as the latency between stimulus presentation and finger lift off from the home base. MT was measured as the time interval between lift off to the successful touch of one of the three target locations. For the standard jump condition, the efficiency of rapid online control was measured as the difference in MT between jump and non-jump trials (MT_{diff}). With respect to kinematic variables, efficiency of online control was measured by two independent raters who identified the first corrective movement toward the cued location (or time of correction - ToC); using visual plots of movement trajectory, this was determined by finding the point at which the hand deviated from a direct path from the central target (i.e. ToC) toward a peripheral location. Agreement of ToC ratings occurred within 2 frames (i.e., less than 10ms); any values that occurred outside of this range (less than 1%) were deferred to a third rater for consensus. The time of the deceleration phase of the movement (PCT) was defined as the point where movement correction on perturbed trials occurred to successful finger touchdown on the touchscreen.

For the anti-jump condition, the coupling between executive (inhibitory) function and online control was defined operationally using three metrics: the first was the difference in MT between jump and anti-jump trials ($AJMT_{diff}$); second, the ability to rapidly initiate a second, more purposive, corrective movement (on anti-jump trials) toward the side of visual space opposite that of the cued location (Time of Correction 2 - ToC2); third, the time difference between ToC and ToC2 (ToC_{diff}). The latter two kinematic measures reflect conscious inhibitory control after the initial (automatic) hand deviation occurred toward the cued target.

Performance was examined as a function of age, condition, and motor ability using a combination of experimental, cross-sectional, and cross-sequential longitudinal designs. These enabled tracking of developmental trends in online motor control and how emerging executive systems might modulate these control systems with age.

2.3.2 Power Analysis and Justification of Sample Size

The number of participants recruited for the three studies is based on several factors: (i) optimising statistical power to detect group differences, (ii) the increased probability of a Type-I error given the repeated number of analyses that were conducted in Studies 1 and 2, (iii) the possibility of an attrition rate between 15-20% during data collection, and (iv) experience in identifying and recruiting children who met research criteria and guidelines for DCD (Blank et al., 2012; Geuze et al., 2001).

In recent research investigating online control, effect sizes (Cohen's *d*) of between 0.6 and 0.9 have been reported for children with DCD (Hyde & Wilson, 2011a, 2011b). In addition, earlier cross-sectional research has revealed similar effect sizes when younger, mid-aged and older children were compared on measures of predictive control (e.g. Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009). With Type I error at $p < 0.01$, it has been found that at least 10-12 participants per group provided sufficient power (≥ .80) to detect differences on performance measures that operationally define the internal modelling of movement or online control, more specifically (e.g. Katchmarsky et al., 2001).

2.4 Test Instruments, Procedure and Data Analytic Approach

2.4.1 Test Instruments

Movement skill was assessed in all children using the MAND. The MAND is a well validated motor test and has been found to have a strong relationship with other commonly used motor tests in the area of DCD research: the Movement Assessment Battery for Children (r_S = .86) and the Bruininks-Oseretsky Test of Motor Proficiency (r_S = .83) (Tan, Parker, & Larkin, 2001). The MAND has good norms for both children and adolescents (Hands, Larkin, & Rose, 2013; Piek, Baynam, & Barrett, 2006), and is suited to repeated assessment. A score below the 15th percentile was selected as a criterion to identify children with DCD. This was based on recommendations that identify this cut-point to detect movement difficulties on a standardised motor test (Blank et al., 2012; Geuze et al., 2001). Measures of dispersion of MAND NDI scores (taken at baseline) for the total sample are as follows: M = 91.97, SD = 15.72; minimum: 40 maximum; 131; range: 91; quartile 1: 83; quartile 2: 92; quartile 3: 102.75; inter-quartile range: 19.75. Online control was assessed using the DJRT paradigm as described above.

2.4.2 Procedural Notes

The DJRT experiment was easy to comprehend by children, quick to administer (15 minutes in total), and enjoyable to perform. Pilot work showed that while younger children (6-7 years) found the task challenging, they understood it and were able to repeat back task instructions. Motor screening was administered during the same session as the DJRT. In total, testing and screening time took approximately 45 minutes per child. Rest breaks were provided at appropriate intervals to reduce fatigue and boredom. For Study 3 (longitudinal investigation), all children assessed in Study 1 were re-assessed at 6-monthly intervals over the course of two years and were measured on the DJRT and MAND at each time point.

2.4.3 Data Analytic Approach

2.4.3.1 Use of ANOVA. The use of within subjects repeated measures ANOVA (RMANOVA) analyses holds a number of advantages. For example, the same participants are used for each of the experimental conditions. This is in contrast to independent groups design, in which there are separate groups of participants for different experimental conditions – each participant is often exposed to just one of the conditions (Field, 2013). This means that experiments can be conducted with fewer participants. In addition, a source of between-subjects variability is removed from the error term when generating and testing the significance of F. In other words, using the same participants across all trial conditions minimises the influence of individual differences that could occur when different people are tested within levels of each factor, for example; variables like age and IQ can be held constant (Field, 2013).

2.4.3.2 Limitations of repeated-measures designs. While there are numerous advantages to RMANOVA, it does require a balanced design where there is no missing data across experimental conditions (Field, 2013). Where data is missing for a given participant, all their contributions to data across cells are removed from the analysis, leading to a loss of statistical power. One assumption that is particularly difficult to meet is that for sphericity (or homogeneity of variance-covariance matrices); use of multivariate tests like Wilks lambda can circumvent this issue. A common threat to internal validity is practice/order effects; however, counter-balancing task presentation can circumvent this possibility, as was the case in my study. Fatigue can be an issue during performance under repeated assessments or conditions. However, adoption of adequate rest intervals and spacing of tests, as used in the current project, can prevent this issue.

2.5 Participants, Design and Data Analyses for Studies 1, 2, and 3

2.5.1 Study 1: Cross-sectional Investigation of Rapid Online Control in TDC (Hypothesis 1 and 2)

2.5.1.1 Participants. A total of 196 children aged between 6 and 12 years were recruited from mainstream state, catholic and private schools for the duration of the two year research project. For Study 1, 129 children, who represented a broad cross-section of movement skill, were included. There were 56 boys and 73 girls divided into three age-groups: young (6-7 years), mid-aged (8-9 years), and older (10-12 years) children. All children included in the sample were assessed for motor proficiency using the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997). Children who scored below the 20^{th} percentile (Hyde & Wilson, 2013) were excluded from Study 1. Parents and teachers also completed a brief developmental questionnaire (see Appendix H).

Exclusion criteria were a current or past history of neurological disease (including head injury), serious medical condition (e.g., asthma, visual impairment, epilepsy, etc.), intellectual disability, or other major developmental disorder (i.e., Autism Spectrum Disorder, Dyslexia, Specific Language Impairment).

2.5.1.2 Analyses for study 1. Prior to running each analysis, data was inspected for outliers and removed if greater or less than three standard deviations from mean values. Tests of assumptions (i.e. homogeneity, normality) were conducted for each analysis. To minimise the chance of Type 1 errors given inflated family-wise error rates, alpha adjustments were made on a notional basis. However, it is important to reach a stable compromise between power and Type 1 error; for this reason, alpha levels were never set below the 0.01 level (Howell, 2011). For 2-way ANOVA, tests of simple effects were used to isolate the locus of (predicted) interactions. For all analyses, an estimate of effect size (i.e., partial eta square) was used to temper the interpretation of significance tests, consistent with recent recommendations by the APA (American Psychiatric Association, 2013).

2.5.1.2.1 *1-Way ANOVA*. To isolate the difference within the 3 levels of the age group factor, RT, MT_{diff}, $AJMT_{diff}$, ToC2, and error variables [i.e. touch-down error (TDE), anticipation error (AE), centre touch error (CTE), anti-jump error)] were submitted to 1-way RMANOVA. Post-hoc testing with an alpha-adjusted correction rate was conducted to clarify the locus of group differences.

2.5.1.2.2 *2-Way ANOVA*. Analyses that involved 2 factors (i.e., Age and Trial Type) were assessed using 2-way RMANOVA. Mean MT [Age Group (young, mid-age, older) x Trial Type (jump, anti-jump)] assessed the interaction between groups on trials where inhibitory control was required or not. Time of correction (ToC) and PCT were assessed using 2-way RMANOVA [Age Group (3) x Trial Type (2)] to highlight kinematic changes to movement planning and online control.

2.5.2 Study 2: Cross-sectional Investigation of the Coupling between Online and Executive Control in Children with DCD (Hypothesis 3a and 3b)

2.5.2.1 Participants. Participants in Study 2 were selected from the same pool of children as those recruited for Study 1. Four additional participants joined the program at Time 2. They represented three age bands (young, mid-age, older) but were also classified according to their motor ability status (DCD or typically developing children; TDC). Overall, there were 87 TDC and 42 who were considered at risk for DCD. For inclusion in the TDC group, children scored above the 20th percentile on the MAND (Hyde & Wilson, 2013) and reported no intellectual, physical or developmental disability. Children in the DCD group met DSM-5 criteria (American Psychiatric Association, 2013) and research guidelines for the disorder as outlined by Geuze et al. (2001) and Hyde and Wilson (2011b): all demonstrated a level of movement skill below the 15th percentile on the MAND (Criterion A) (Piek et al., 2006), showed that their motor problems interfered with activities of daily living/educational performance (Criterion B), whose movement difficulties were evident by school age (Criterion C) and had no previous developmental or physical diagnosis (Criterion D). Importantly, the 15th percentile was used to maximise the chance of identifying children who were at risk for DCD within the context of a research setting.

2.5.2.2 Analyses for study 2. As per study 1, data inspection and assumption testing was first carried out. Simple main effects were used to tease out interactions. Effect sizes were added to place significance tests in better context. For the key analyses, MT was compared using 3-way RMANOVA [3(Age: young, mid-age, older) x 2(Skill Group: Control/DCD) x 3 (Trial Type: non-jump, jump, anti-jump). Two-way RMANOVA [3(Age) x 2(Skill Group)] was used on AJMT*diff* and ToC to assess the impact of inhibitory load on online corrections.

2.5.3 Study 3: Growth Curve Modelling Provides a Flexible and Efficient Means of Testing Developmental Trajectories (Hypotheses 4a and 4b)

2.5.3.1 Participants. Study 3 followed two groups of children (TDC and DCD), as assessed at Time 1 and for whom sufficient data was available over the duration of the project (see below for further detail). There was a total of 109 TDC and 62 children with DCD at Time 1, with a 17% attrition rate by Time 5. Both TDC and children with DCD were placed in their respective age cohort (13 in total separated by increments of six-month intervals which together spanned a 6-year period from 6- to 12-years of age) at the time of commencement in the study. During recruitment, the ratio of girls to boys was higher for girls (60:40). When participants exited the study, usually when a child graduated from primary to secondary school, more boys left the study than girls. There was a higher number of children classified to the DCD group than expected, possibly due to (a) the 15th percentile on the MAND used to identify children with DCD and (b) several schools were randomly selected from lower socioeconomic areas; research has linked children from low socioeconomic families with coordination difficulties, although this relationship may be moderated by risk factors such as poor diet (Montgomery, 2010) and limited access to facilities required for participation in physical activity.

2.5.3.2 Data analysis. Growth curve modelling (GCM) offers a number of major advantages over traditional methods of analysing longitudinal data (like ANOVA mentioned above): (i) measurement of change in ROC over time at both a population and individual level, consistent with developmental theory; (ii) flexibility in treatment of the time variable (i.e., each child does not have to contribute measures over the entire age range of interest); (iii) effective in handling missing/incomplete data; (iv) modelling can be generalised to non-normal data distributions; (v) suited to overlapping longitudinal designs; (iv) does not require equal spacing between test points; and (iiv) is robust to homogeneity of variance assumption (a requirement of ANOVA). Accelerated growth curve modelling, in particular, permits analysis of (predicted) non-linear developmental trajectories and possible sub-groups (Adolph & Robinson, 2011; Bryk & Raudenbush, 1992; Gaveau et al., 2014; Grammer, Coffman, Ornstein, & Morrison, 2013; Singer & Willett, 2003).

By using two waves of measurement per year, the statistical modelling provided a more robust representation of development over childhood. In general, multiple points of assessment over relatively brief time periods is recommended for developmental analyses, with accelerated designs preferred for modelling over wider age periods (Holmbeck, Bruno, & Jandasek, 2006; Watt, O'Connor, Stewart, Moon, & Terry, 2008). Each age cohort was measured five times over a two year period; hence, there was a one-year overlap between adjacent cohorts. The age spanned by the modelling was between 6 to 12 years; the oldest cohort was not re-tested upon entering secondary school at age 13. Online control metrics were assessed using accelerated growth curve modelling.

Growth curves were analysed at two main levels: Level 1 examined within-person (or individual) change using age as a predictor variable. This yields individual estimates for intercept and slope for the main outcome measures. All individual estimates were then combined for each age cohort. Cohort-specific trajectories were also plotted and inspected for overlap at relevant age points. Possible cohort interactions with different change trends were tested using convergence estimates. A common model was then tested under the assumption that members of all cohorts follow a single underlying developmental trajectory (Duncan, Duncan, & Strycker, 2006). Each outcome measure (i.e. AJMT*diff* and ToC*diff*) was tested for linear, quadratic, and cubic growth patterns in typically developing and DCD samples. Model parameters (i.e., age, cohort, age*cohort) were assessed in an unstructured covariance matrix, using a random effects approach to protect the model from high correlations that can arise from repeated measurements (Anderson, Oti, Lord, & Welch, 2009), and tested for their sequential effect to determine the most appropriate growth curve solution using *-2log likelihood* statistic. Fit and comparison between models was assessed using goodness of fit indices, specifically the Bayesian Information Criterion (BIC). This index is useful for making comparisons between models; smaller values on this index indicate a more parsimonious model, irrespective of the magnitude of the actual score.

2.6 Conclusion

This chapter presented a brief overview of the neuro-cognitive method to assess ROC using visual perturbation paradigms, and the hypotheses I proposed to test the development of ROC and executive function. More specifically, I described a DJRT and how it could be adapted to assess the coupling behaviour of ROC and inhibitory systems. This included key performance variables and their operational definition. Power and sample size were discussed which justified the minimum number of participants required for each of my studies. To conclude, this chapter outlined cross-sectional and longitudinal designs for each of my studies; benefits and limitations of using traditional statistical techniques (such as ANOVA) were presented and advanced growth curve modelling was proposed as an innovative way to assess developmental trajectories of control systems in longitudinal data. Accordingly, the first study of this thesis is presented in Chapter 3, aimed to clarify how online control is performed across the crucial primary school years of children (aged 6-12) and how adding an inhibitory load, by way of an anti-jump task, impacts the performance of online corrections.

CHAPTER 3

STUDY 1. EXECUTIVE SYSTEMS CONSTRAIN THE FLEXIBILITY OF ONLINE CONTROL IN CHILDREN DURING GOAL-DIRECTED REACHING

3.1 Introduction

3.1.1 Online Control is part of a broader Cognitive System that underlies Action Systems and is subject to changing constraints with Childhood Development

The ability to rapidly and seamlessly adjust arm movements in response to sudden or unexpected changes in the environment (i.e. *online control*) is crucial to flexible and efficient action. Current neuro-computational modelling holds that this form of control is dependent on an individual's ability to generate a predictive (forward) model of an intended movement and integrate it 'on the fly' with sensory feedback throughout the movement cycle (Desmurget & Grafton, 2000; Izawa & Shadmehr, 2011; Wolpert et al., 2011). In essence, this mechanism allows the nervous system to circumvent delays associated with basic sensory feedback processing. That is, if incongruence between the estimated (according to the predictive model) and actual consequences of movement is detected, rapid corrective mechanisms can be implemented within 100ms (Castiello, Bennett, & Chambers, 1998; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991), far too quickly to be accommodated by sensory processing alone. Thus, a system of predictive control, also referred to as an *internal feedback loop*, is critical for movement stability under dynamic conditions. From a neural perspective, these systems appear to be supported by finely tuned reciprocal connections between parieto-cerebellar cortices and upstream motor areas (Shadmehr & Krakauer, 2008). Surprisingly, little is known of its development.

Efficient online correction of reaching is a key indicator of a functional and mature motor system. Developmentally, the motor system matures rapidly over childhood; however, the trajectory does not appear to be linear (for a review see Elliott, Chua, & Helsen, 2001). Earlier work using a double-jump perturbation suggests a somewhat different trajectory with rapid development of online control after early childhood (6-7 years) , and then similar levels of proficiency when mid-aged (8-9 years) and older (10-12 years) children are compared

(Wilson & Hyde, 2013) Results showed that 5-7 year olds were significantly slower to adjust their reaching to visual perturbation than either mid-aged or older children while the latter two groups did not differ. Interestingly, online corrections occurred somewhat earlier in adults, manifest by a more efficient trajectory on jump trials, a pattern not seen in children of any age. Hence, the fast internal feedback loops that support very early and rapid changes in trajectory may not fully mature until adolescence or early adulthood (Farnè et al., 2003).

To date, there is little direct neurophysiological data on rapid online control (and predictive modelling) in children. However, adult data suggests a pivotal role for the parietal cortex, especially the posterior parietal cortex (PPC), in the ongoing representation of body schema, the dynamic mapping of limb-to-target relations, and the real-time integration of feedforward commands with sensory feedback. For visually-guided reaching, the PPC is thought to play a crucial role in state estimation, continuously integrating dynamic visual inflow with predictive estimates of limb position (Wolpert, Ghahramani, & Flanagan, 2001) and is also involved in processing the resultant error signal; for example, a spike in PPC activity occurs immediately after unexpected target displacement and is tuned to its direction (Reichenbach, Bresciani, Peer, Bulthoff, & Thielscher, 2011). This signal would be transferred to frontal motor centres, modulating the motor command as it unfolds and modifies the flight path of the hand, so to speak, with minimal lag.

Importantly, recent morphological evidence indicates that the cortical structures involved in goal-directed action and predictive control (principally the fronto-parietal axis), follow a protracted period of development (Johnson, 2005). Motor and perceptual centres do mature earlier than higher-cortical areas associated with cognitive control, and the pattern of activation tends to shift from diffuse to more focal with age across childhood (Casey et al., 2005). Importantly, the rapid improvement in online control we see after early childhood occurs after a period of rapid growth in white matter volume in parietal and frontal cortices.

This is followed by a period of neural sculpting during middle and later childhood; a combination of factors, both progressive (i.e. myelination) and regressive (e.g. synaptic pruning and/or grey matter loss) contribute to this, mediated by experience (Casey et al., 2005). A switch from diffuse to localised neural firing throughout this period plays an important role in neuro-cognitive development broadly. This process is underpinned by continued white matter maturation but also experience driven synaptic pruning through childhood (and into adolescence), contributing to improvements in cognitive and motor skills (e.g. Barnea-Goraly et al., 2005). These changes to pre-frontal cortices and their connectivity to other neo- and sub-cortical structures (e.g. visual pathways and cortico-thalamic and cortico-spinal tracts) support greater cognitive flexibility in children, and top-down modulation of what were previously more automatic processes in infants and young children. The ability to enlist inhibitory control in the face of compelling environmental cues is a case in point (Casey et al., 2005). I argue that prefrontal motor control processes that are supported by parieto-cerebellar pathways (e.g., rapid online control and motor adaptation) enable more behavioural flexibility under changing external conditions (Posner et al., 2007).

3.1.2 Interactive Specialization: Implications for the interplay between Online Control and Executive Function

The notion of interactive specialization posits that some regions of the cortex, while unfolding at a relatively slow rate, can still modulate the activity of other areas, influencing the tenor of cognitive processing (Johnson, 2005). In other words, the emergence of a new behaviour is the result of weighted activity from several brain regions whose modular architecture and rate of maturation may differ in complexity and timescale. Neuronal regions are initially ill-defined and are enlisted in response to a broad range of stimuli. With time and experience, cortical regions become more specialised, and shift from diffuse to more focal activation for a given class of stimuli (Durston et al., 2006). Importantly, functional activity of a given cortical region is determined by how it is coupled to other regions and their modulating effect. New cognitive processes and behaviours thus arise as a result of changes to multiple regions rather than site-specific effects.

In the context of action, frontal systems play an increasingly important role in the control of movement throughout development as environmental constraints become more complex or variable and demands on top-down control increase (Brocki & Bohlin, 2004). For example, increases in task complexity that occur when an individual is required to unexpectedly and rapidly adjust their reaching place demands on limited capacity working memory systems, subserved by a functional loop between the dorso-lateral prefrontal cortex and parietal cortex (Suchy, 2009). Moreover, the degree of coupling between anterior and posterior regions increases over childhood (Casey et al., 2008). Taken together, it is possible that the ability to enlist online control of movement under more complex task constraints (e.g. when executive control demands are higher) may be limited in younger children to the extent that the modulating effect of frontal executive functions is less well coupled to posterior visual-motor centres.

Perhaps the most significant transition in the development of executive function occurs between 4 and 8 years where cognitive flexibility expands concomitant to continued myelination and synaptic pruning of the prefrontal cortex (PFC) and its reciprocal connections downstream (Casey et al., 2008; Johnson, 2005). What is particularly interesting is the fact that at a time when specialised frontal functions are unfolding during middle childhood (but not necessarily consolidated) we also see evidence of different solutions to online control; for example, greater reliance on feedback control under some circumstances (e.g. Chicoine et al., 1992). That said, there is little direct evidence to test the hypothesis that children of middle childhood perform goal-directed reaching much like older children under simple task constraints, but may struggle when these constraints are heightened, enlisting greater frontal modulation.

Nonetheless, correlational data suggest a link between executive control and the development of movement skill, more generally. We know from behavioural studies that levels of inhibitory control (e.g., Stroop performance and initiation of anti-saccades) are correlated with movement skill in both younger (Livesey et al., 2006) and older (Piek et al., 2007) children. Similarly, we see that problems of inhibition are common in children with poor motor skills (Mandich et al., 2002; Wilmut, Brown, & Wann, 2007).

I suggest that the development of online control is likely to be constrained by the unfolding of fronto-executive systems. Hence, the aim of this study was to understand how executive control is enlisted in the context of movement that requires rapid online adjustments. Using a double-jump reaching task, I predicted that because mid-aged children are still developing a workable coupling between frontal and posterior (motor control) systems, they would show performance decrements under conditions of inhibitory load; this would result in slower online corrections, and a pattern of behaviour more akin to that observed in younger children.

3.2 Method

3.2.1 Participants

The sample was taken from a larger study in a longitudinal project. The sub-sample consisted of 129 children (56 boys and 73 girls) between the ages of 6 and 12 years. Children were divided into three age bands: young (6-7 years); mid-age (8-9 years); and older (10-12 years). Table 3.1 displays the descriptive data for age, gender, and handedness of each group. Parents completed a questionnaire to indicate if their child suffers from a previously diagnosed intellectual/developmental/learning disorder or serious medical condition (e.g. asthma, visual impairment, epilepsy, etc…), which was then corroborated by the child's classroom teacher. Five children were excluded from the study based on a previously diagnosed developmental disorder: one child reported motor control difficulties; one reported Autism Spectrum Disorder; one reported Dyslexia; and two reported Specific Language Impairment. No child reported intellectual disability; accordingly, since all children were recruited from mainstream primary schools, it was assumed that children included in the study were within normal IQ range (Hyde & Wilson, 2011a).

Table 3.1

Descriptive Statistics of Age Groups in the Double Jump Reaching Task

	Age		Gender		Handedness	
	M	*SD*	Male	Female	Right	Left
6-7 years (*n* = 38)	7.1	0.6	14	24	33	5
8-9 years (*n* = 50)	8.9	0.6	26	24	48	2
10-12 years (*n* = 41)	10.6	0.5	16	25	38	3

Note. *N* = 129.

3.2.2 Materials

The Double-Jump Reaching Task (DJRT) paradigm was used to assess online motor control. The VIRTOOLS Software Package (3DVIA, 2010) was used to develop the computer interactive display on a black Samsung 40” touch screen television (refer to Figure 3.3 for experimental set-up). The television was placed on top of a table with its screen facing up and was raised at a 10^0 angle from horizontal and positioned in portrait view when a child performed the task. The background of the monitor screen was black to match the frame of the TV and reduce contrast while the participant performed the task. The display consisted of a green ‘home base’ circle 2.5cm in diameter and positioned 5cm from the edge of the display. Three yellow targets were situated above the home base in the middle of the screen.

Target locations were positioned at -20^0, 0^0, 20^0 from the direction of the home base target. To account for age-related differences in arm reaching, the distance to the yellow targets were scaled according to arm length (taken from Gerver et al., 1989) across the three groups: young children, 25cm; mid-age children, 28cm; and older children, 30cm. Arm movement was captured using the Zebris CMS10 (Noraxon, 2010) system for 3D-motion analysis which sampled at 200Hz. It was placed one meter directly above the centre-point of the television. A small ultrasonic marker (7mm in diameter) was used to track arm movement. The marker was connected by cord from the Zebris to the child's dominant index finger and held in place by an adhesive pad that was stuck to the tip of the index finger nail.

3.2.3 Procedure

Principals from six randomly selected primary schools were contacted and invited to participate in the study. Information about the study was sent home via letter with children at each school, outlining the nature of the research to parents. The study was approved by relevant ethics committees. Informed consent was provided by each school principal and children were eligible to participate if their parent/guardian completed and returned an informed consent statement to the head researcher.

Hand preference was assessed using a two-step procedure: (i) children were asked which hand they liked to write with and (ii) children were handed a pen to write their name and observed which hand they used. All trials were performed using the dominant hand. To ensure the cord attached to the kinematic sensor on the child's index finger did not obscure hand movement and interfere with movement trajectory, the researcher secured cord slack away from the child. Before the commencement of the experiment, children were explained the nature of the task. The DJRT was performed in a quiet school classroom with low light to prevent visual feedback from the moving limb (Farnè et al., 2003). Children stood in front of the monitor and used their index finger to reach and touch the targets.

Two versions of the DJRT were administered during the testing session: a typical DJRT and an anti-jump DJRT. For the typical DJRT, the green ‘home base’ was first illuminated at the start of each trial. Children held their index finger stationary on this target until the ‘home base’ light was extinguished and a yellow target was simultaneously illuminated: a random delay of 500-1500ms minimised anticipatory effects. To direct visual attention to the same place on each trial, children were instructed to reach and touch in the middle of the target as *quickly and accurately as possible* until the light was extinguished. A successful trial was indicated with an auditory tone when the centre of the correct newly acquired target was pressed. For the majority of trials (80%), the initially illuminated target remained stationary until it was pressed (*non-jump* trial). However, for a small percentage of trials (i.e. remaining 20% of trials) the target jumped to either of the peripheral target location after finger lift-off (*jump* trial) from the home base. During these ‘jump’ trials, children were instructed to also *follow and press the middle of the target as quickly and accurately as possible.* Upon completion of each trial, children were instructed to return their finger to home base ready to repeat the next trial.

During the anti-jump DJRT, children performed a modified version of the first DJRT: similarly to the earlier version, for most trials (80%) the target remained stationary for the duration of movement, yet for a small percentage of trials (20%) the target ‘jumped’ laterally at movement onset. During the latter condition, children were instructed to reach to the target on the opposite side of the illuminated target (see Figure 3.3).

The order in which the two conditions were presented to children was randomised to account for potential learning effects. Within each condition, children were administered two blocks with each block containing 40 trials: 32 *non-jump* trials and 8 *jump*/*anti-jump* trials (four trials to the left and four to the right peripheral location). The sequence of trials was programed into the task so that non-jump, jump, and anti-jump trials occurred pseudo-randomly. At the end of each testing block, children were permitted a two minute interval to rest.

Before the task commenced, a researcher demonstrated the action required for the 3 trials; *non-jump*, *jump*, and *anti-jump*. Children were then given 10 practice trials (8 *non-jump* trials and 2 *jump/anti-jump* trials) to become familiar with the task. Where necessary, the researcher provided additional practice trials until he was satisfied that children understood the task.

3.2.4 Data Analysis

Chronometric measures taken were reaction time (RT), measured as the time between illumination of the central target and finger lift-off from 'home base', and movement time (MT), defined as the time taken between finger lift off from 'home base' to the moment the index finger successfully touched inside the yellow target. Only valid *non-jump*, *jump* and *anti-jump* trials (i.e. where a child successfully touched the centre of a yellow target) were included. Outliers were removed, defined as those values > +/- 2.5 *SDs* from the mean. An average of 19 (24%) non-jump trials and 2 (25%) jump/anti-jump trials were removed from the younger group, 18 (23%) and 2 (25%) respectively from the mid-age group, and 18 (23%) non-jump and 2 (25%) jump/anti-jump trials respectively from the older group. *Jump*- and *anti-jump* trials were collapsed over left and right target locations. Trials that incurred an error were removed from the data set. An error was defined by a trial where a child touched outside the boundary of the cued target (indicated by the target light remaining illuminated). Out of a possible 16 perturbed trials, a criterion of 8 successful jump/anti-jump trials per block was set as a minimum requirement to include the data in the analysis. Mean RT and MT were then calculated for each child. Mean RTs were compared between age groups using 1-way ANOVA. The pattern of mean MT was compared between groups using 2-way repeated measures ANOVA (3[Group] x 2 [Trial Type: Jump & Anti-Jump]). Movement time difference scores were also calculated between the average MT for *non-jump* and *jump* trials (MT_{diff}) and then between *non-jump* and *anti-jump* trials (AMT_{diff}). Each difference score was compared between age groups using 1-way ANOVA.

In addition, three kinematic variables were recorded. Kinematic data (i.e. ToC, ToC2, and PCT) were filtered post-task using a fourth order Butterworth filter with a cut off of 10Hz. For *jump*- and *anti-jump* trials, time of correction (ToC) represented the first detectable point at which the finger deviated from its straight movement path toward the centre yellow target when it changed direction toward a peripheral target (Hyde & Wilson, 2011b; Pisella et al., 2000; Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007). Similar to healthy adults who perform tasks that require inhibition of a prepotent response toward a cued stimulus, participants showed a tendency for the hand's 'automatic pilot' to initially reach toward the illuminated target on displacement trials of the 'anti-jump' DJRT, prior to re-directing their reach trajectory toward the opposite target location (Cameron, Cressman, Franks, & Chua, 2009). Hence, for anti-jump trials two ToC values (ToC and ToC2) were measured: the first trajectory correction away from the initial target to the illuminated target, and a second re-direction of the reach trajectory towards the opposite target location. Movement trajectories were plotted on a 2D Cartesian plane using MATLAB (Mathworks, 2010) computer software where ToC and ToC2 values were independently determined by two researchers to ensure reliability. ToC was analysed using a 2-way repeated measures ANOVA (3[Group: younger x mid-age x older children] x 2 [Trial Type: Jump & Anti-Jump]) to assess for an interaction effect between groups on trials where an inhibitory load is present or not while ToC2 was analysed using 1-way ANOVA. In addition, post-correction time (PCT) was recorded from the initial point of movement correction on both jump and anti-jump trials to successful finger touchdown on the touchscreen. This was analysed using 2-way repeated measures ANOVA. Kinematic data (i.e. ToC/ ToC2 and PCT) were filtered post-task using a fourth order Butterworth filter with a cut off of 10Hz. For each dependent variable outliers were removed if they were deemed -2.5 < or > 2.5+ *SD* from the mean score.

Four types of response errors were recorded for the DJRT: touch down error (TDE) occurred when children touched outside the boundaries of a yellow target; anticipatory error (AE) was recorded when lift-off from 'home base' occurred before the yellow central target was illuminated and/or when RT was less than 150ms (Wilson et al., 1997); centre touch error (CTE) was defined as a touch to the central target instead of a peripheral target during a jump trial; and anti-jump error (AJE) occurred when children pressed the incorrect (or cued target) during an anti-jump trial. 1-way ANOVA was also used to assess the mean difference between groups on each error variable (TDE, AE, CTE, & AJE). Preliminary analyses showed that site location and gender were not systematically related to performance on any measure. Measures of effect size (partial η^2) were used to interpret the magnitude of the effect.

3.3 Results

Table 3.2 displays the means and standard deviations of all outcome measures listed below.

Table 3.2

Descriptive Statistics for the Double Jump Reaching Task on Chronometric and Kinematic Variables

Age Group	Trial Type	RT (ms)		MT (ms)		ToC (ms)		ToC 2 (ms)		PCT (ms)		AE		TDE		CTE		AJE	
		M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
	Non-jump	554	75	469	74	_	_	_	_	_	_	2.85	2.07	5.21	3.36	_	_	_	_
6-7 Years	Jump	580	95	837	158	309	46	_	_	468	62	0.81	0.85	6.10	2.74	1.90	2.08	_	_
	Anti-jump	590	114	1236	238	319	39	619	99	549	112	0.54	0.71	5.14	2.96	0.60	1.58	1.36	2.01
	Non-jump	488	71	476	82	_	_	_	_	_	_	2.00	2.14	4.53	2.95	_	_	_	_
8-9 Years	Jump	511	87	727	92	292	45	_	_	433	63	0.44	0.60	3.89	2.53	0.81	1.17	_	_
	Anti-jump	480	85	1080	160	303	41	571	83	516	96	0.38	0.78	3.66	2.25	0.25	1.00	0.63	1.20
	Non-jump	455	60	434	79	_	_	_	_	_	_	2.26	2.36	4.11	2.93	_	_	_	_
10-12 Years	Jump	458	80	681	80	269	26	_	_	408	65	0.57	0.95	4.11	2.47	1.00	1.37	_	_
	Anti-jump	472	70	984	152	273	26	499	82	477	91	0.63	0.94	3.92	2.76	0.18	0.53	0.82	1.38

Note. RT = Reaction Time, MT = Movement Time, ToC = Time of Correction, ToC2 = Second Time of Correction, PCT = Post Correction Time, AE = Anticipatory Error, TDE = Touch Down Error, CTE = Centre Touch Error, AJE = Anti-Jump Error, ms = Milliseconds.

3.3.1 Reaction Time

Overall, there was a significant age effect, $F(2,92) = 24.29$, $p < .001$, partial $\eta^2 = .35$: RTs for older children (462 ms) were faster than 8-9 year-olds (508 ms) who, in turn, were faster than 6-7 year-olds (575 ms).

3.3.2 Movement Time

The mean MT (+/- SE) for each group is displayed in Figure 3.1. The 2-way ANOVA on mean MT showed a significant main effect for trial type, Wilks' $\Lambda = .08$, $F(2,99) = 609.76$, $p < .001$, partial $\eta^2 = .93$, and age group, $F(2,100) = 18.52$, $p < .001$, partial $\eta^2 = .27$. The interaction between age group and trial type was also significant, Wilks' $\Lambda = .77$, $F(4,198) = 6.91$, $p < .001$, partial $\eta^2 = .12$.

Tests of simple effects showed no differences between the three age groups on non-jump trials. For jump trials, 6-7 year olds (837 ms) were significantly slower than both 8-9 year-olds (727 ms), $p < .001$, partial $\eta^2 = .15$, and 10-12 year-olds (681 ms), $p < .001$, partial $\eta^2 = .28$, while the two older groups were not shown to differ, $p = .23$, partial $\eta^2 = .07$. On anti-jump trials, younger children (1235 ms) were significantly slower than 8-9 (1080 ms), $p = .003$, partial $\eta^2 = .13$ and 10-12 year olds (984 ms), $p < .001$, partial $\eta^2 = .28$. The difference between the two older groups was not significant, $p = .079$, partial $\eta^2 = .10$.

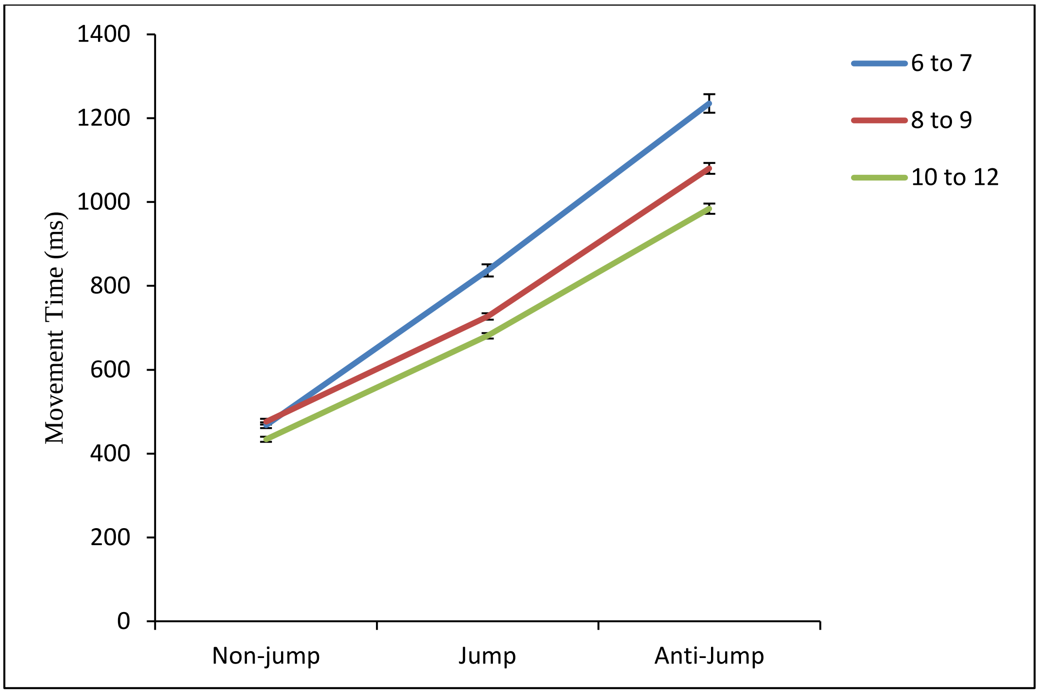


Figure 3.1. Mean movement time (MT +/- SE) values for age groups on the double-jump reaching task.

3.3.3 Movement Time Difference

The average MT_{diff} score between non-jump trials and jump trials was calculated and compared between the groups. One-way ANOVA revealed a significant effect for age group, $F(2,116) = 10.54$, $p < .001$, partial $\eta^2 = .15$. Post-hoc tests revealed that the MT_{diff} score for the youngest children (393 ms) was significantly longer than that for 8-9 year-olds (286 ms), $p = .002$, and 10-12 year-olds (253 ms), $p < .001$. The comparison between the two older groups was not significant, $p = .49$.

For the AMT_{diff} score between non-jump and anti-jump trials, 1-way ANOVA revealed a significant age group effect, $F(2,110) = 19.30$, $p < .001$, partial $\eta^2 = .26$. Follow-up tests revealed that the AMT_{diff} score of the youngest children (750 ms) was significantly greater than the 8-9 year-olds (611 ms), whose score, in turn, was greater than the 10-12 year-olds (524 ms), with each $p < .05$.

3.3.4 Time of Correction (ToC and ToC2)

The average ToC (+/- SE) for each group is displayed in Figure 3.2. The 2-way ANOVA on the mean ToC found no significant interaction between group and trial type, Wilks' Λ = .99, $F(2,98) = 0.34$, $p = .71$, partial $\eta^2 = .007$. Overall, children were faster to correct initial trajectory on standard jump trials (290 ms) than anti-jump trials (298 ms), Wilks' Λ = .95, $F(1,98) = 5.47$, $p = .021$, partial $\eta^2 = .05$. The main effect for age group was also significant, $F(2,98) = 12.75$, $p < .001$, partial $\eta^2 = .21$. Averaged over jump and anti-jump trials, older children (272 ms) were significantly faster to correct than 8-9 year-olds (298 ms) who, in turn, were faster than 6-7 year-olds (314 ms).

One-way ANOVA on the mean ToC2 showed an overall age effect, $F(2, 113) = 14.33$, $p < .001$, partial $\eta^2 = .20$. Post-hoc tests using Tukey's HSD indicated that older children (506 ms) were significantly faster than mid-aged (571 ms; p = 005, $\eta^2 = .12$) and younger children (618 ms; $p < .001$ $\eta^2 = .26$); the latter two groups were not shown to differ ($p = .06$, $\eta^2 = .06$).

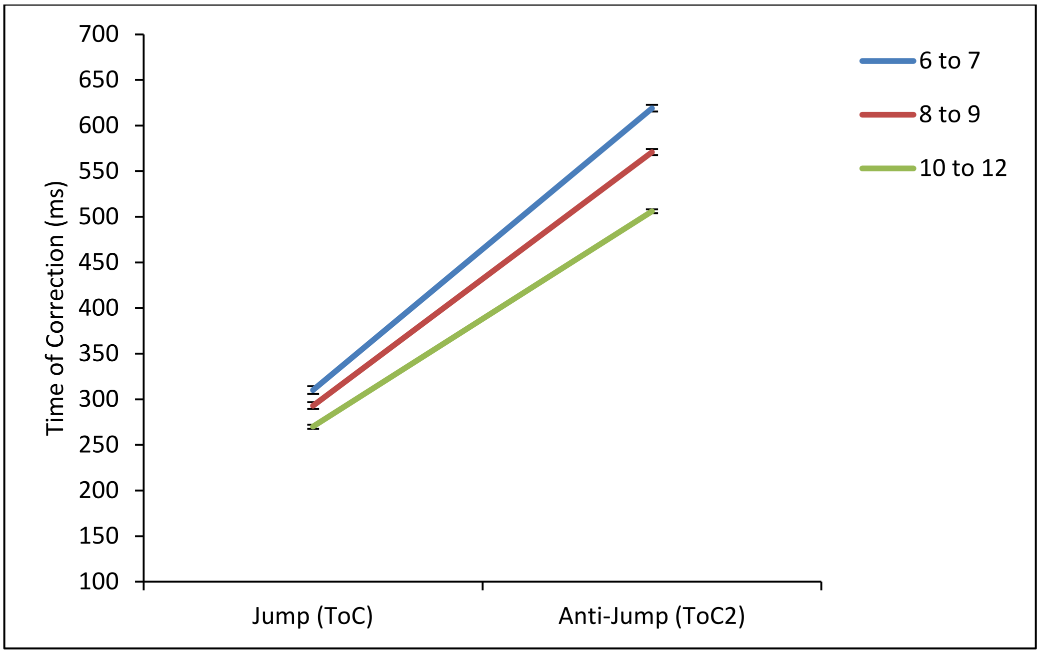


Figure 3.2. Mean time of correction on jump trial and second time of correction on anti-jump trial (ToC and ToC2 +/- SE) values for age groups on the double-jump reaching task.

3.3.5 Post Correction Time

A 2-way ANOVA showed no significant interaction between group and jump/anti-jump trials on PCT, Wilks' Λ = 1.00, $F(2,94) = 0.22$, $p = .80$, partial $\eta^2 = .005$. PCTs were faster on jump trials (431 ms) than anti-jump (509 ms), Wilks' Λ = .60, $F(1,94) = 62.78$, $p < .001$, partial $\eta^2 = .40$. The main effect for age group was significant, $F(2,94) = 6.73$, $p = .002$, partial $\eta^2 = .13$. Averaged over jump and anti-jump trials, 10-12 year-olds (443 ms) and 8-9 year-olds (475) did not differ significantly, while the former were faster than 6-7 year-olds (509 ms).

3.3.6 Errors

Overall, there was no difference between age groups on the mean number of AEs, $p = .19$: 6-7 year-olds (1.4), 8-9 year-olds (0.9), and 10-12 year-olds (1.2). For TDEs, there was a significant age effect: younger children committed more errors (5.5) than 8-9 year-olds (4.0) and 10-12 year-olds (4.0), $F(2,101) = 4.94$, $p = .009$, partial $\eta^2 = .09$. There was no difference between age groups on the number of CTEs, $p = .25$, partial $\eta^2 = .07$: 6-7 year-olds (1.3), 8-9 year-olds (0.5), and older children (0.6). Finally, a 1-way ANOVA on AJEs revealed no difference between age groups, $p = .45$, partial $\eta^2 = .04$: 6-7 year-olds (1.4), 8-9 year-olds (0.6), and older children (0.8).

3.4 Discussion

This study investigated how online control develops across childhood and the extent to which it is constrained by demands on (inhibitory) executive control in three different age-groups: 6-7 year olds (younger), 8-9 year olds (mid-age) and 10- 12 year olds (older). Consistent with my predictions, I found that the pattern of performance on non-jump trials was similar between age groups. However, when a target perturbation was applied at movement onset, children in the younger group showed disproportionately slower movement time compared to both mid-aged and older children, as well as slower reaching trajectory corrections. Furthermore, when I imposed the inhibitory demand (instructing children to move their arm to the side opposite the target perturbation, i.e., anti-jump trials), I found that younger children continued to show delayed changes in trajectory and slower movement times compared with older children; indeed, the group difference on MT increased from around 150 ms for jump trials to around 250 ms for anti-jump trials. Interestingly, the performance of mid-aged children was compromised relative to the older group on anti-jump trials, but regressed away from older children on anti-jump trials. This was evident on both movement time and a delay in the reaching trajectory away from the illuminated target towards the correct target. This pattern is broadly consistent with the hypothesis that the ability to enlist online control is not linear in development, but depends on the nature of the task constraints and associated load on executive control systems. I argue that the ability to utilise predictive control as a means of reducing the latency of online corrections is well developed by 8-9 years of age. However, in cases where rapid online control must be implemented under conditions of real-time inhibitory load (*viz* anti-jump conditions), then the performance of mid-aged children is somewhat constrained.By 10-12 years, children are better able to integrate the demands of both online and executive systems in the service of a goal-directed action. These findings are discussed in further detail below.

3.4.1 Non-jump Trials

As predicted, an age-effect on RT was observed. Specifically, older children tended to initiate movement more quickly than mid-age children and younger children. This finding accords with earlier developmental research where performance of typically developing primary-school aged children was compared on the double-step reaching task (Hyde & Wilson, 2013). Since the time taken to initiate reaching towards a prepotent visual target likely reflects information/neural processing efficiency (Wilson & McKenzie, 1998), this pattern of results supports developmental literature suggesting increased processing efficiency between the ages of 5 and 12 years, linked to white matter maturation among other factors (Barnea-Goraly et al., 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004).

The mean MT of each group was similar on non-jump. Simple, stimulus-driven movements of this type place minimal demands on online control (and hence predictive modelling). Computationally, since the target remains stationary throughout the movement; discrepancy, or error, between the expected (according to the predictive model) and actual consequences of action is minimal, assuming that the initial motor command is accurate (Desmurget & Grafton, 2000). Accordingly, in light of current accounts of motor control (i.e. Shadmehr et al., 2010), my results suggest that the ability to complete rudimentary movements within peri-personal space is well developed by 5 years of age (e.g. Chicoine et al., 1992). Importantly, the similar movement times observed across age-groups here on non-jumps highlights that the developmental differences I observed for jump and anti-jump reaching cannot be explained by general maturation of the motor system but rather by the unfolding of specific control systems (i.e. predictive modelling and executive functioning). This argument is taken up below.

3.4.2 Jump Trials

Like earlier studies (e.g. Castiello et al., 1998; Farnè et al., 2003; Hyde & Wilson, 2011a; Paulignan et al., 1991), MT increased from non-jump to jump trials. This is explained by the added processing demands in detecting target perturbation and then implementing a corrective shift in movement trajectory, which itself was longer in distance as the hand moved to the middle target and then redirected to a peripheral location. The additional time taken to implement the anti-jump movement can be attributed to the demands imposed on inhibitory processing and the associated requirement that children withhold the prepotent response to the cued location and then implement a movement to the opposite side.

Younger children were disadvantaged by target shifts relative to mid-aged and older children, as shown by the significant interaction between age and trial type on MT. Whereas there was significant difference between groups when the target remained stationary, younger children were slower to adjust on jump trials: MT*diff* scores were significantly longer for younger children (393 ms) compared with both mid-aged (286 ms) and older children (253 ms). This pattern replicates an earlier study by Hyde and Wilson (2013). The slower adjustments to target perturbation shown by younger children suggests that the process of motor prediction that supports rapid online control is less efficient in younger children but develops rapidly after the age of 6-7 years. Indeed, the performance of 8-9 year-olds was not significantly different to that of older children on standard jump trials, suggesting a more gradual trend in development from middle childhood. Analysis of kinematic variables further support this view: correction of the reaching trajectory occurred later for younger children

(309 ms) compared with both mid-aged (292 ms) and older children (269 ms), with the latter two groups not shown to differ significantly. Importantly, ToC reflects the stage in reaching where *internal* feedback signals are integrated with the motor command to initiate correction away from the initial direction of movement. Higher ToC suggest that this aspect of predictive control is not fully integrated into the motor system of younger children. Taken together, my results for jump performance supports a growing body of evidence suggesting that online control (i.e. predictive modelling) mechanisms undergo rapid developmental change between the ages of 6 and 8 years, with less marked change during the later stages of childhood (Casey et al., 2008; Casey et al., 2005; Johnson, 2005, 2011). Other data suggest that further changes occur after the age of 12 years and into early adulthood, although the exact trajectory is unknown (Hyde & Wilson, 2013).

3.4.3 Anti-jump Trials

Crucially, I observed significant group differences between mid-aged and older children on MT when an inhibitory load was imposed on the movement following target perturbation. This was shown by progressively smaller AMT*diff* scores with age: the difference in MT between non-jump and anti-jump trials was greater in 6-7 year-olds (750 ms) than 8-9 year olds (610 ms), whose score, in turn, was greater than the older children aged 10-12 years (524 ms). In contrast, no such difference between mid-aged and older children was observed on MT*diff* scores.

On the kinematic data, there was a tendency for children to perform a two-step correctional process: first an initial correction towards the illuminated target prior to re-directing their reach in a second stage towards the opposite target location. This pattern of performance is a stable characteristic of healthy adults when performing similar tasks (e.g. Cameron et al., 2009). The lack of condition effect when comparing this initial ToC measure on anti-jump trials to ToC values measured during jump trials suggests that the hand’s 'automatic pilot' is initially drawn to the illuminated target (Cameron et al., 2009; McIntosh, Mulroue, & Brockmole, 2010; Striemer, Yukovsky, & Goodale, 2010). Importantly, the second corrective movement (i.e. ToC2) indicates conscious and purposive inhibition of the nervous system's tendency to reach toward a prepotent (yet incorrect) target before re-directing the hand to the opposite (correct) target. My data confirms this pattern and showed that younger and mid-age children not only took longer to make the first automatic correction, but also took significantly longer (618 ms and 571 ms respectively) to inhibit their response from the cued location than older children (506 ms). In contrast on standard jump trials, children were merely required to correct their reaching toward the new stimulus location, the shifting target serving to bias trajectory in, at least, a spatially meaningful way. The pattern of performance for anti-jump trials supports the hypothesis that mid-aged children are less efficient at implementing online control when demands on inhibition are imposed, performing more like younger children than older.

This suggests a crucial transition in both executive control and motor systems during middle childhood, an age where motor control is thought to transition to a well-integrated system of feedback and feedforward mechanisms (Pellizzer & Hauert, 1996). During this same maturational period, frontal executive systems undergo a period of rapid growth and brain connectivity which sees executive systems exert more (top-down) control over behaviour (Durston et al., 2006). However, some theorists point to a lag period during which the child learns (implicitly) to harness or couple these emerging frontal networks to other systems (Johnson, 2011). In the case of adaptive online control, the child must learn to couple frontal executive systems to the more automatic online control systems of the dorsal stream. As such, we might expect to see a performance decrement in middle childhood when a task places demands on both systems; experience-dependent learning to that point in development is perhaps not sufficient to build an integrated network of top-down modulation.

Taken from the perspective of interactive specialization, maturation of different cortical zones can change how previously acquired cognitive functions are represented in the brain (Johnson, 2011). That is to say that the same behaviour could potentially be supported by different neural substrates at different ages during development. Developmental studies of children reveal that cognitive processes emerge at different points in time, each showing its own maturational trajectory (Anderson, 2002; Garon, Bryson, & Smith, 2008). In general, executive function develops rapidly during the primary school years and then continues at a slower pace during adolescence (Anderson, 2002). During this time, the emergence of complex processes such as set shifting, working memory and inhibition may take some time to be integrated efficiently with existing processes, perceptual-motor and other. The question here is to assess how inhibitory control becomes integrated into functional systems of motor control.

At a neural level, behavioural improvements in inhibition appear to be parallelled by refinements in the underlying brain activity in the PFC and in networks that include the PFC (Durston et al., 2006). We know that frontal systems reach a peak in synaptogenesis during early childhood, and that structural MRI shows a progressive increase in myelination along anterior-to-posterior pathways over childhood and adolescence, including reciprocal connections to the PPC (Bunge & Wright, 2007; Durston et al., 2006). Indeed, diffusion tensor imaging research also suggests that white matter development underlies an important role with mechanisms that shape cognition (Barnea-Goraly et al., 2005), and subcortical structures may play a role in rapid adjustments to target perturbations (Day & Brown, 2001). While these structural changes occur rapidly over early development, the degree of functional coupling that occurs along these networks appears to be more protracted. The online control system that supports (simple) goal-directed reaching is quite functional by early childhood, but undergoes significant change between 5 and 8 years. However, the difficulty that mid-aged children had with online adjustments under an inhibitory load supports the hypothesis that coupling between anterior and posterior systems takes some time to fully emerge. My data show that the coupling unfolds rapidly between middle and later childhood, while experience-driven learning continues to influence the development of motor and executive systems

In terms of attentional shifts to abrupt-onset cues, the consensus of opinion is that the process of engagement and disengagement is largely a motor preparatory process (Rizzolatti, Riggio, & Sheliga, 1994). More specifically, the putative disengagement process has been conceptualised as an aspect of inhibitory motor control (Mandich et al., 2003). As such, it could be argued that the effects I observed for the jump trials could involve aspects of motor inhibition. For anti-jump, the inhibitory demand is such that more controlled, frontal processing is required to counter the compelling effect of the cued target location on motor planning and, hence, hand trajectory. Further research is needed to disentangle these components of attention and motor control as a function of task complexity.

3.4.4 Limitations

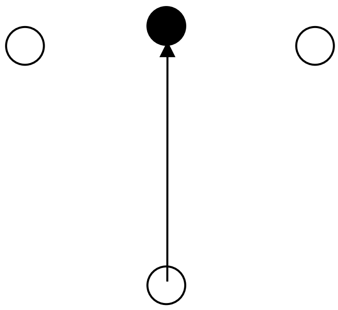
For repeated movements during which we experience error between the intended action and incoming sensory information (i.e. a target shift), it is possible that a memory representation builds up for the adjusted movements (Shadmehr et al., 2010). In other words, the repeated corrections to limb position could act as a training signal for the brain. This has been observed for actions involving mechanical perturbation of the moving limb: the motor memory associated with the effects of the perturbation may provide advance information for subsequent motor commands. However, when this logic is applied to the paradigm used in my study, it is unlikely that memory effects would accrue over repeated arm movements because there were only a limited number of jump/anti-jump trials within a given block, and those that did were interspersed randomly. Furthermore, I counterbalanced the order of jump and anti-jump conditions to ensure learning effects were minimised. In future, I could vary the probability of jumps and also compare early and late trials on my task to resolve memory-related effects from predictive control per se.

3.4.5 Conclusion

For some time now, the maturational viewpoint has been a widely adopted explanation of motor development in children. Maturational theories seek to interpret emerging sensory, motor and cognitive functions in terms of the development of particular regions of the brain, usually specific areas of cerebral cortex. Alternatively, under the assumption of interactive specialization, a new cognitive function or skill is acquired through the re-organisation of interactions of different brain structures and regions. My results are broadly consistent with this view as they show that age-related variation in the ability to implement rapid online is contingent on (frontal) inhibitory constraints. By middle childhood, online adjustments can be implemented as quickly as those seen in later childhood. However, when demands are imposed on executive systems (as per anti-jump trials) online corrections are slowed in mid-aged children relative to older. Rapid maturation of executive systems during this period may constrain the flexibility with which online control can be implemented. More precisely, the ability to modulate online control via the inhibitory system requires a more protracted period of development over childhood.

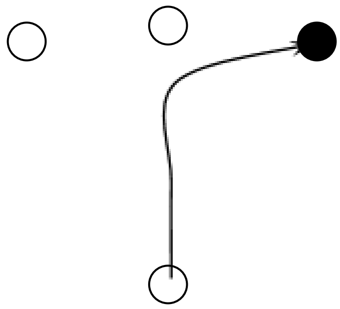
Condition A

Non-jump trial



The central target remains lit until touchdown.

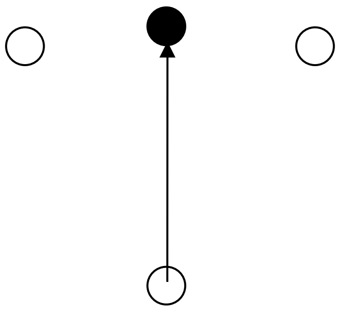
Jump trial



The central target displaces to either peripheral location at finger lift off.

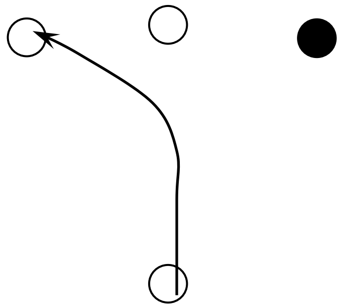
Condition B

Non-jump trial



The central target remains lit until touchdown.

Anti-jump trial



The central target displaces to either peripheral location at finger lift off. Then, the participant reaches to the target on the opposite side.

Figure 3.3. Experimental set-up of double jump reaching task for non-jump, jump, and anti-jump trials.

CHAPTER 4

STUDY 2. COUPLING ONLINE CONTROL AND INHIBITORY SYSTEMS IN CHILDREN WITH DEVELOPMENTAL COORDINATION DISORDER: GOAL-DIRECTED REACHING

4.1 Introduction

Deficits in motor prediction have been implicated as one possible cause of motor clumsiness in children with Developmental Coordination Disorder (DCD; Hyde & Wilson, 2013). A recent meta-analysis has shown deficits in studies as varied as target-directed reaching, grip force control, dynamic balance, and eye-movement control (Wilson et al., 2013). Also seen as part of the constellation of processing problems in DCD is poor executive control, evident across tasks of selection attention, working memory, and response inhibition. Of some importance in developmental terms is how predictive (online) control and executive function (EF) are coupled in the service of goal-directed action. This issue has also emerged as a focus in a recent developmental study (Gonzalez et al., 2014) with data showing that motor control and EF emerge along similar timelines and share overlapping neural networks (Pangelinan et al., 2011). In relation to the neurocognitive underpinnings of DCD, I enlisted a double-jump paradigm performed with and without inhibitory constraints.

The ability to correct one's movement in response to unexpected target or environmental changes (viz online control) is a critical part of efficient, goal-directed action. Recent neuro-cognitive models of human reaching propose that online control occurs by the action of *internal feedback loops* that generate forward estimates of the dynamics of limb position and egocentric location - a process referred to variously as (forward) internal modelling or predictive control (Ruddock et al., 2014). This system of rapid control is critical for movement stability because of processing delays associated with sensory feedback loops and general impedance of the motor plant (Wolpert & Flanagan, 2001). For visually-guided movements, adult studies have shown recruitment of reciprocal loops between premotor cortex, posterior parietal cortices (PPC), and cerebellum, with strong PPC-cerebellar activation under target perturbation (Gréa et al., 2002; Reichenbach et al., 2011; Reichenbach, Thielscher, Peer, Bülthoff, & Bresciani, 2014). Only recently has the nature of online control in children with and without motor difficulties been studied with renewed focus.

Available data suggest that the mechanisms linked to fast corrective processes undergo considerable change between 6 and 12 years of age (Bard et al., 1990; Van Braeckel et al., 2007; Wilson & Hyde, 2013).Younger children (5-7 years of age) are able to generate fast, ballistic movements but are slower to integrate online feedback when correcting their reaching mid-flight, resulting in reduced endpoint accuracy and/or inefficient timing. During middle childhood (around 8-9 years) there is earlier and greater use of sensory feedback (e.g. Chicoine et al., 1992) as both feedforward and feedback (predictive) control become better integrated, resulting in better online error correction. By 9 to 12 years, the system of predictive control is well developed, approaching adult levels (e.g. see Wilson & Hyde, 2013).

It is no coincidence that the developmental timescale over which online control unfolds coincides with periods of increased myelination and structural connectivity along fronto-parieto pathways (Casey et al., 2005; Lebel, Walker, Leemans, Phillips, & Beaulieu, 2008). Predictive control in particular is underpinned by maturation of reciprocal connections between frontal, parietal and cerebellar cortices, pathways that are sculpted by experience (Gaveau et al., 2014). In short, an interplay between external (i.e., experiential) and internal (e.g. neural myelination and synaptic pruning) factors support the fidelity of predictive control with development (Casey et al., 2008).

A unifying hypothesis in cognitive neuroscience that can shed light on the development of function in DCD is the notion of interactive specialization (Johnson, 2011). Here it is posited that behavioural competencies unfold through the interaction of several brain regions whose individual growth trajectories may differ in developmental time. For example, (automatic) online control is supported by fast dorsal motor systems (Pisella et al.,

2000) that forge reciprocal connections with frontal executive systems over the course of childhood, bestowing a degree of flexibility in action (i.e. Ruddock et al., 2014). However, this coupling between motor and executive systems is not well refined until later childhood. Using a target perturbation paradigm, I found that under an inhibitory load (or anti-reach condition), the ability to adjust movement trajectory was reduced in mid-aged children (8-9 years) relative to older children (10-12 years), despite the fact that online control per se was well developed by 9 years of age (Wilson & Hyde, 2013). I observed that the time taken to correct reach trajectories (in this case to the hemi-space opposite the target jump) increased in mid-aged children to an extent similar to that seen in younger children (6-7 years). I argued that while frontal systems are unfolding rapidly during the middle childhood period, there is lag in the coupling of these systems to more posterior perceptual-motor systems. Only by later childhood do we see evidence of more seamless integration of fronto-parietal systems, manifest as smooth and efficient reach trajectories and greater endpoint accuracy under not only double jump constraints but also anti-reach conditions (Wilson & Hyde, 2013).

4.1.1 The link between Executive Function and Online Control in Children with Developmental Coordination Disorder

Importantly, deficits in both executive and motor control systems are widely reported in children (Livesey et al., 2006; Michel, Roethlisberger, Neuenschwander, & Roebers, 2011; Piek et al., 2007) and adolescents (Rigoli, Piek, Kane, & Oosterlaan, 2012) with atypical motor development (or DCD), suggesting that the process of coupling between systems may be particularly problematic with development. A recent studies of goal-directed reaching has shown that children with DCD aged 8-12 years are disadvantaged by target perturbation, taking longer to correct movements on jump trials (Hyde & Wilson, 2011a). This pattern of performance is thought to reflect an underlying difficulty using predictive models of action. Additionally, Hyde and Wilson (2013) showed that the performance of children with DCD aged 8-12 years was not qualitatively different to younger typically developing children suggesting a neurodevelopmental delay in structures that underpin predictive control, particularly fronto-parietal and parieto-cerebellar loops. Other work using fMRI suggests possible disruption of top-down (or anterior) modulation of posterior networks for tasks requiring inhibition (Querne et al., 2008). Converging evidence of reduced executive function in DCD (Piek et al., 2007; Wilson et al., 2013) suggest a more generalised level of delay in these children.

Problems of inhibitory control are particularly common in DCD (Livesey et al., 2006; Michel et al., 2011). On the Simon Task, for example, a well-known neuropsychological choice reaction time test, children with DCD show difficulty inhibiting a manual response to a visual stimulus relative to controls (Mandich et al., 2002). On tasks of *voluntary* visuospatial attention, poor inhibitory control has also been identified (Mandich et al., 2003; C. L. Tsai, Y. K. Yu, Y. J. Chen, & S. K. Wu, 2009; Wilson & Maruff, 1999), inferred from a reduced ability to disengage visual attention from invalidly-cued locations (Mandich et al., 2003). This raises the possibility that children with DCD may be particularly disadvantaged when called to enlist inhibitory control in the context of a motor task requiring motor prediction.

Therefore, my main hypothesis here is that impaired coupling between frontal executive and more posterior visuo-motor regions associated with predictive control (and spatial updating) may be an important factor in DCD. Hence, the broad aim of my study was to examine whether poor online control in DCD is exacerbated when tasks demand higher levels of executive control, specifically response inhibition. Addressing this issue will also clarify the often cited observation that motor skill deficits in DCD are more pronounced under conditions of high cognitive load (Wilson et al., 2013). Specifically, children's ability to implement rapid online corrections was assessed on a double-jump perturbation paradigm under three task conditions: non-jump, jump, and anti-jump. In line with earlier studies of online control (Hyde & Wilson, 2011a, 2011b, 2013) I predicted that, overall, children with DCD would be slower to correct their reach trajectory mid-flight following an unexpected target shift than typically developing children. Moreover, I also predicted that their performance would be further compromised by the addition of an inhibitory load (*viz* anti-reach condition), manifest as slower movement time and delayed time to correction, but that the deficit would be less pronounced in older children in lieu of the developmental delay suggested by earlier work (Hyde & Wilson, 2013).

4.2 Method

4.2.1 Participants

The sample was drawn from a large longitudinal project and consisted of 129 children: 42 in the DCD group and 87 in the control group (refer to Table 4.1 for descriptive data).

Table 4.1

Descriptive Statistics of Developmental Coordination Disorder Group and Control Group Groups for the Double Jump Reaching Task

	Control					DCD				
	n	Sex		Age (years)		*n*	Sex		Age (years)	
		Girls	Boys	*M*	*SD*		Girls	Boys	*M*	*SD*
6-7	26	17	9	7.20	0.46	10	5	5	7.27	0.69
8-9	38	23	15	8.92	0.63	16	5	11	8.87	0.63
10-12	23	13	10	10.74	0.49	16	10	6	11.07	0.38

Note. N = 129.

Group selection involved a two-step process: (a) parents completed a medical and developmental history questionnaire and (b) children's motor proficiency was tested using the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997). On the MAND, children who scored less than the 15^{th} percentile (Noten et al., 2014; Piek et al., 2006) (Criterion A), whose difficulty learning motor skills was deemed to interfere with daily activities (Criterion B), and whose movement difficulties were evident by school age (Criterion C), were included in the DCD group. Children scoring above the 20^{th} percentile were placed into the control group (Hyde & Wilson, 2011a). Additionally, selection for the DCD group adhered to research criteria specified from the Diagnostic and Statistical Manual 5 (American Psychiatric Association, 2013). Children were excluded from the study if they reported a developmental, neurological and/or physical condition (Criterion D), which was confirmed by the child's school health officer. As children were recruited from mainstream primary schools and attending standard classes, intelligence was assumed to within the normal range (Geuze et al., 2001).

All children and parents gave their informed consent to participate in the study which was approved by institutional and government research ethics committees.

4.2.2 Instrumentation

A modified version of the Double-Jump Reaching Task (DJRT) was used to assess online motor control. VIRTOOLS Software Package (3DVIA, 2010) was presented on a black Samsung 40-inch touchscreen. The touchscreen was in portrait orientation on a table and elevated at 10^0 from horizontal. The background of the display was black to match the bezel of the TV, reducing contrast interference. The computerised display consisted of a circular 'home base', 2.5cm in diameter, positioned centrally 5cm from the near edge of the bezel. Three yellow targets were positioned at -20^0, 0^0, 20^0 from a vertical line, extending upward from the home base. All target distances were scaled according to three age groups: young children, 25cm; mid-age children, 28cm; and older children, 30cm (Gerver et al., 1989). Arm movement was recorded using the Zebris CMS10 (Noraxon, 2010) system for 3D-motion analysis with 200Hz sample rate. The motion tracking system was secured to the table and positioned at a height of one meter above the centre of the screen. A 7mm ultrasonic sensor/marker was attached by adhesive pad to the child’s dominant index finger tip and tethered with adhesive tape along the arm and then to the Zebris receiver.

4.2.3 Procedure

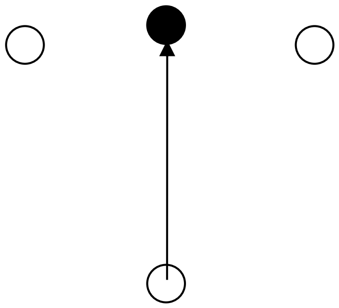
Hand preference was assessed by asking each child which hand children he/she wrote with, and then observing them as they wrote their name. The DJRT was performed in a quiet classroom under low lighting conditions to prevent visual feedback from the hand (Farnè et al., 2003) and the imposition of environmental distractors. At the beginning of the DJRT, the nature of the task was explained and the child was then directed to stand in front of the screen while the kinematic sensor was attached to the index finger of their dominant hand.

Testing was conducted in two blocks, with the order of conditions randomised: a typical ‘jump’ DJRT and modified ‘anti-jump’ DJRT. For the jump condition, children were instructed to place their index finger on the green home base at the beginning of each trial. The three possible target locations were indicated at the start of each trial, while individual targets per se were triggered on a trial-by-trial basis by a doubling in luminance. The finger was held stationary until the home base was extinguished and the middle yellow target doubled in luminance at the same time. A random delay of 500-1500 ms was programed across trials to ensure participants did not anticipate the change in target illumination. Children were instructed to *follow the target* and touch its centre as *quickly and accurately as possible*. A successful trial resulted in the newly acquired target light being extinguished while an auditory tone was emitted to reinforce to children that the trial was complete. On

80% of trials the middle target remained lit until touched (*non-jump* trial) while on 20% of trials the location of the target jumped at movement onset either to the left or right position (*jump* trial). At the end of each trial, children repositioned their finger back on home base in readiness for the next trial. The anti-jump condition was administered using the same procedure described for the jump condition. However, children were instructed to reach and touch the opposite side (*anti-jump* trial) when the target shifted to a peripheral location (refer to Figure 4.1).

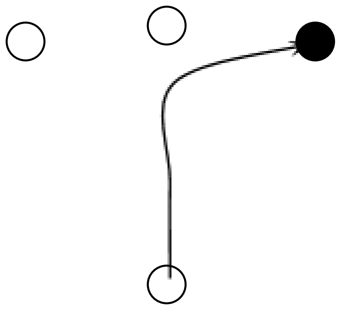
Block A

Non-jump trial



The central target remains lit until touchdown.

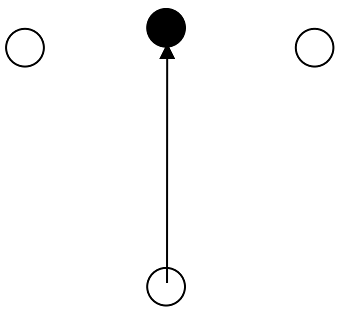
Jump trial



The central target jumps either left or right at finger lift off.

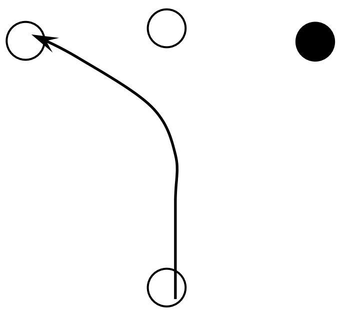
Block B

Non-jump trial



The central target remains lit until touchdown.

Anti-jump trial



The central cue jumps either left or right at lift off, while the child is instructed to reach and touch the opposite locations.

Figure 4.1. Experimental set-up for the double jump reaching task showing trial types over two blocks of trials

At the commencement of the first condition, the researcher modelled the action necessary for *non-jump*, *jump*, and *anti-jump* trials. Children were then given 10 practice trials to familiarise themselves with the nature of the task and permitted additional practice trials if task requirements were not met. Children performed two blocks within each condition; each block was of 40 trials (32 *non-jump* and 8 *jump*/*anti-jump*) which were interspersed pseudo-randomly across left and right target locations. At the end of the first condition, children were permitted a two minute rest before commencing the second condition. Total administration time of the task was 15 minutes.

4.2.4 Data Analysis

For each child, reaction time (RT) and movement time (MT) of the DJRT were recorded. Only successfully completed trials were included and outliers for all chromomeric and kinematic variables were excluded from analysis; outliers were defined as values > +/- 2.5 *SDs* from the mean (Ruddock et al., 2014). An average of 20 (14%) non-jump trials and 4 (25%) jump/anti-jump trials were removed from the DCD group, and 18 (13%) and 3 (19%) respectively from the control group. *Jump*- and *anti-reach* trials were aggregated over left and right target locations and eight successful *jump/anti-jump* trials per block was a minimum requirement for valid data inclusion (Ruddock et al., 2014). MT was compared between groups using 3-way repeated measures ANOVA (3 [Age] x 2 [Skill Group] x 3 [Trial]). RT was compared between groups using 2-way repeated measures ANOVA (3 [Age] x 2 [Skill Group]). I measured the impact of the inhibitory load on online control by calculating the difference in MT between anti-jump and jump trials ($AJMT_{diff}$). Specifically, using a 2-way ANOVA, I tested whether the effect of inhibitory load (as measured by $AJMT_{diff}$) varied as a function of the interaction between group and age.

Kinematic variables were time of correction (ToC) and time of correction 2 (ToC2; for anti-reach trials only which was the interval between the first movement correction and the point at which spatial trajectory changed toward the location opposite that of the target), and were filtered post-task using a fourth order Butterworth filter with a cut off of 10Hz. For jump trials, time of correction (ToC) was defined as the point at which the hand initiated a change in direction away from the centre target toward the left or right peripheral target (Hyde & Wilson, 2011b). On anti-jump trials, the critical deviation in trajectory occurs after an initial deviation toward the cued location (Cameron et al., 2009); this second correction (ToC2) reflects the implementation of inhibitory control as part of the corrected movement plan toward the location opposite the cued side. All participants demonstrated a tendency for the hand to be drawn first toward the illuminated target before (purposefully) redirecting movement to the opposite target location (Cameron et al., 2009). Finally, post correction time for anti-jump trials (PCT-AJ) was defined as the time taken after TOC2 to touch the location contralateral to the cue.

Movement trajectories were plotted on a 2D Cartesian plane using MATLAB (Mathworks, 2010) computer software and ToC and ToC2 values were determined by two independent raters (Ruddock et al., 2014). Time of correction was analysed using 2-way repeated measures ANOVA (2 [Age] x 2 [Skill Group]).

Error responses were also recorded on the DJRT. A touch down error (TDE) occurred when a participant touched outside of the yellow target boundary. Anticipation error (AE) was recorded when finger lift-off from ‘home base’ occurred before the yellow central target illuminated. Logically, this cannot vary as a function of cue type as there is no probability information available to predict this with any certainty. Centre touch error (CTE) was defined as a touch to the centre target instead of a peripheral target during a *jump*/*anti-ju*mp trial. Finally, an *anti-jump* error (AJE) occurred when the incorrect (i.e., cued target) was touched on anti-jump trials.

Initial analyses showed that both gender and site locations were not systematically related to performance on any measure. Partial η^2 was used to interpret the magnitude of the effect size.

4.3 Results

Table 4.2 displays the values for each variable across skill group and age.

Table 4.2

Descriptive Statistics of Variables on the Double Jump Reaching Task

Skill	Age	Trial	RT (ms)		MT (ms)		AJMT*diff* (ms)		ToC (ms)		ToC2 (ms)		PCT-AJ (ms)		TDE		AE		CTE		AJE	
			M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Control	6-7	N-J	572	93	504	88									7.96	7.28	3.58	2.73				
		J	583	84	855	157			307	51					5.32	3.19	1.08	1.26	2.73	2.97		
		A-J	573	94	1220	215	352	170	304	41	625	115	594	115	3.31	2.15	1.00	1.20	0.38	1.02	0.96	1.40
	8-9	N-J	473	100	497	93									5.00	5.16	1.66	1.73				
		J	470	71	733	95			286	36					3.26	2.67	0.76	1.60	1.55	2.29		
		A-J	486	76	989	140	248	102	272	40	497	81	488	75	3.08	2.16	0.53	0.65	0.53	0.95	0.79	1.23
	10-12	N-J	430	74	445	68									3.43	3.38	1.35	1.53				
		J	420	80	630	67			252	36					1.78	2.07	0.48	0.66	0.29	0.55		
		A-J	425	63	840	116	210	91	242	27	421	70	417	53	2.43	1.56	0.52	0.79	0.17	0.48	0.50	1.17
DCD	6-7	N-J	633	121	620	140									11.00	8.31	4.30	3.74				
		J	649	115	894	114			375	70					4.60	3.10	1.60	1.51	1.10	1.73		
		A-J	634	110	1393	139	499	166	361	38	691	94	707	117	3.80	2.10	1.70	1.16	0.50	0.85	1.00	1.49
	8-9	N-J	523	95	482	80									7.06	5.97	5.00	5.37				
		J	525	87	792	141			320	51					4.50	2.83	0.81	0.66	2.06	3.70		
		A-J	518	91	1135	175	359	128	309	53	566	87	564	108	3.25	1.65	0.88	1.03	0.24	0.44	1.29	1.40
	10-12	N-J	461	79	468	91									3.31	2.91	2.00	2.00				
		J	456	82	685	114			272	39					1.94	1.95	0.56	0.89	0.25	0.68		
		A-J	459	64	892	134	207	99	269	40	442	70	450	74	2.13	1.86	0.69	1.20	0.31	0.48	0.38	0.89

Note. MT = Movement Time, AJMT*diff* = Movement Time Difference between Anti-jump and Jump Trials, ToC = Time of Correction (jump trials), ToC2 = Time of Correction for Anti-Jump Trials, PCT-AJ = Post Correction Time Anti-Jump Trials, TDE = Touch Down Error, AE = Anticipation Error, CTE = Centre Touch Error, AJE = Anti-Jump Error, N-J = Non jump, J = Jump, A-J = Anti-Jump.

4.3.1 Reaction Time

As there were no significant effects involving trial type, mean RT was averaged over this factor. Two-way ANOVA showed a significant main effect for age, $F(2, 127) = 33.58$, $p < .001$, partial $\eta^2 = .35$, with younger children (607 ms) slower than mid-aged (499 ms) who were in turn slower than older (442 ms), $p < .05$. The main effect of group was also significant with controls (498 ms) faster than DCD (540 ms), $F(1, 127) = 10.39$, $p = .002$, partial $\eta^2 = .08$. The interaction between age and group was not significant, $F(2, 127) = 2.40$, $p = .10$, partial $\eta^2 = .04$.

4.3.2 Movement time

Mean MT (+/- SE) for age groups within DCD and control group are displayed in Figure 4.2. Three-way ANOVA on MT showed significant main effects for age, $F(2,123) = 54.63$, $p < .001$, partial $\eta^2 = .47$, skill group, $F(1,123) = 14.42$, $p < .001$, partial $\eta^2 = .11$, and trial, Wilks' $\Lambda = .08$, $F(2,122) = 754.88$, $p < .001$, partial $\eta^2 = .93$. The higher order 3-way interaction between these factors was also significant, Wilks' $\Lambda = .91$, $F(4,244) = 2.92$, $p = .022$, partial $\eta^2 = .05$. Simple interaction effects were therefore explored within each skill group.

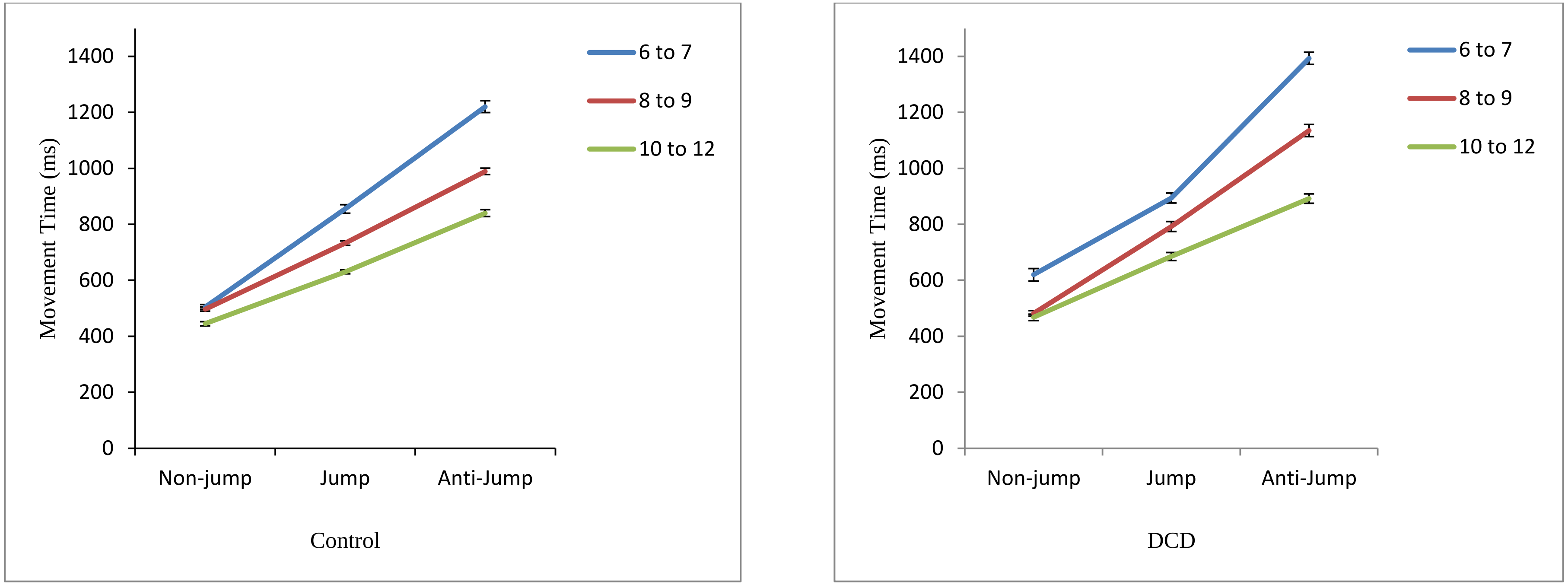


Figure 4.2. Mean movement time (MT +/- SE) values of young (6-7), mid-age (8-9) and older (10-12) children for DCD and control groups on the double-jump reaching task.

For the control group, there was a significant simple interaction between age group and trial, $F(4,166) = 12.80$, $p < .001$, partial $\eta^2 = .24$. Follow-up tests of the simple effect of age revealed the following: for non-jump trials, there was no significant difference between mid-aged and younger children, whereas both these groups were slower than the older children. For jump trials, younger children were slower than mid-aged who, in turn, were slower than older children (by around 105 ms). For anti-jump trials, younger children were slower than mid-aged (by around 230 ms) who, in turn, were slower than older children (by around 150 ms).

For the DCD group, the simple interaction between age and trial type was also significant, $F(4,76) = 8.67$, $p < .001$, partial $\eta^2 = .31$. For non-jump trials, mid-aged and older children with DCD were not shown to differ, unlike controls; both these groups were, in turn, faster than younger children. For jump and anti-jump trials, the pattern of differences between age groups was similar to that shown for controls; however, the mean difference between mid-aged and older children on anti-jump trials was very large at around 245 ms. Importantly, for older children on anti-jump trials there was no significant difference between skill groups whereas the same comparisons for mid-aged and younger children showed faster performance in controls.

I also examined the magnitude of group differences within each trial condition. For non-jump trials, the effect of group varied with age: there was no difference between mid-aged DCD and control children (partial $\eta^2 = .00$), and between older DCD and controls (0.05). However, younger children with DCD (630 ms) were significantly slower than younger controls (501 ms), partial $\eta^2 = .27$. For jump trials, the significant difference between DCD and controls (partial $\eta^2 = .05$) did not vary as a function of age: the simple interaction of group by age was not significant, $F(2, 132) < 1$. Finally, for anti-jump trials, the difference between DCD and control groups varied as a function of age: for younger children, partial η^2 = .20, for mid-age (0.17), and for older children (0.04).

4.3.3 Anti-Jump Movement Time Difference

The mean AJMT$_{diff}$ for DCD and control group is displayed in Figure 4.3.

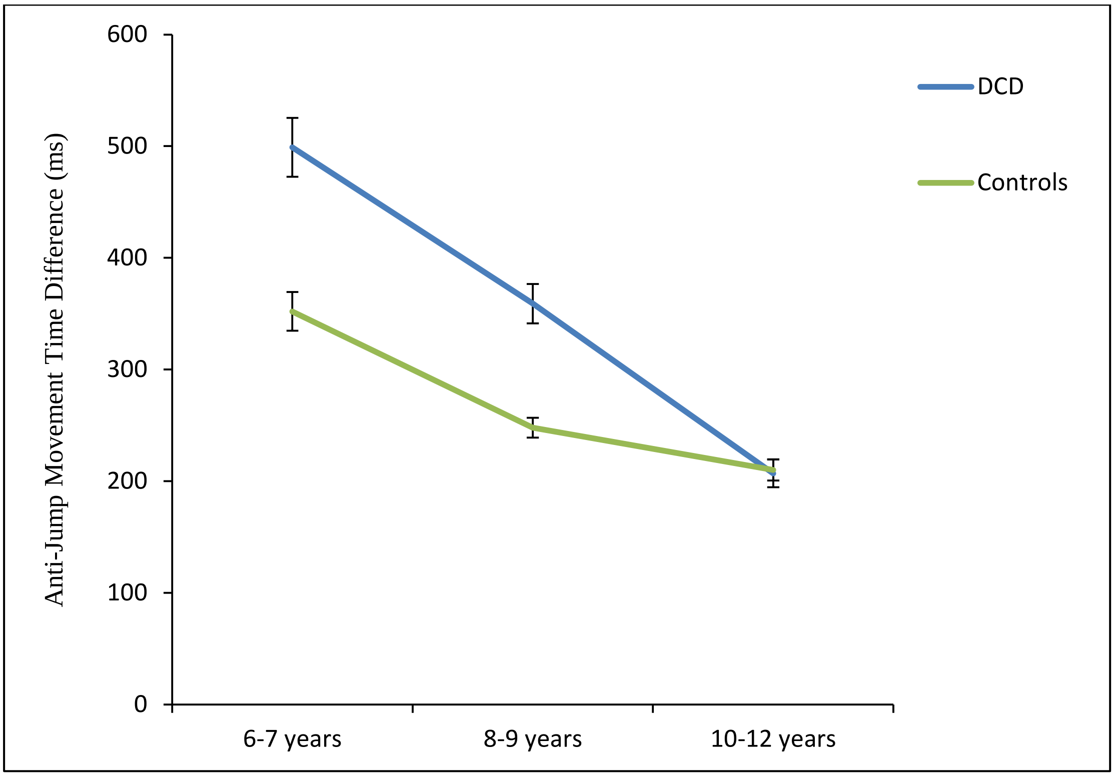


Figure 4.3. Mean anti-jump movement time difference (AJMTdiff +/- SE) values of young (6-7), mid-age (8-9) and older (10-12) children for DCD and control groups on the double-jump reaching task.

Three outliers (2 older controls and one mid-aged DCD) were removed from the 2-way ANOVA as values were greater than 2.5 *SDs* from the mean. Results showed a significant main effect for age group, $F(2,120) = 24.47$, $p < .001$, partial η^2 = .29, with values for younger children (395 ms) higher than that for both the mid-aged (280 ms) and older children (209 ms). The difference between mid-aged and older children was also significant. Overall, the DCD group (334 ms) were significantly higher than controls (269 ms), however the main effects were moderated by a significant interaction between age and group, $F(2,120) = 3.40$, $p = .037$, partial $\eta^2 = .05$. The simple effect for skill group was significant for younger children, $F(1, 35) = 6.89$, $p = .013$, partial $\eta^2 = .17$, mid-aged children, $F(1, 54) = 11.69$, $p = .001$, partial $\eta^2 = .18$, but not older, $F(1, 41) < 1$, partial $\eta^2 = .00$.

4.3.4 Time of Correction

4.3.4.1 ToC for jump trials. The average ToC (+/- SE) for DCD and control group is displayed in Figure 4.4.

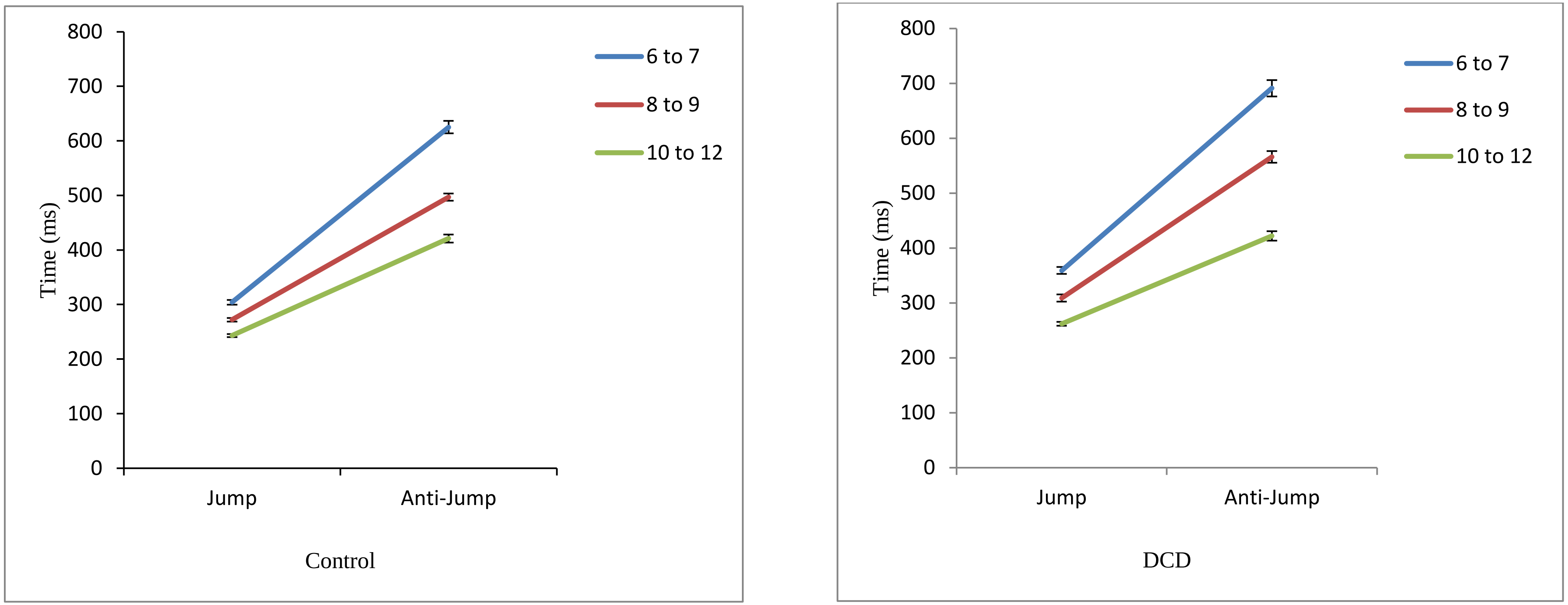


Figure 4.4. Mean time of correction (+/- SE) showing initial correction (ToC) and second correction (ToC2) on anti-jump trials for DCD and control group on the double-jump reaching task.

2-way ANOVA on mean ToC showed no significant interaction between skill group and age, $F(2,127) = 1.21$, partial $\eta^2 = .02$. The was a main effect for age group, $F(2,127) = 32.27$, $p < .001$, partial $\eta^2 = .34$ and skill group, $F(1,127) = 28.85$, $p < .001$, partial $\eta^2 = .19$. Younger children (321 ms) were slower to correct trajectory than mid-aged (283 ms), who in turn were slower than older (253 ms). Overall, children with DCD (307 ms) were slower than controls (274 ms).

4.3.4.2 ToC2 for anti-jump trials. For ToC2 on anti-jump trials, 2-way ANOVA showed no significant interaction between age and skill group, $F(2,124) < 1$, partial $\eta^2 = .01$. There was a main effect for age group, $F(2,124) = 53.51$, $p < .001$, partial $\eta^2 = .46$, and skill group, $F(1,124) = 9.31$, $p = .003$, partial $\eta^2 = .07$. Younger children (644 ms) were slower to make the second correction on anti-jump trials than mid-aged (519 ms), who in turn were slower than older (431 ms). Overall, children with DCD (550 ms) were slower than controls (516 ms).

4.3.5 Post Correction Time for Anti-Jump Trials

Two-way ANOVA revealed a significant effect for group, $F(1,129) = 19.64$, $p < .001$, partial $\eta^2 = .13$, and age, $F(2,129) = 50.42$, $p < .001$, partial $\eta^2 = .44$, while the interaction was not significant, $p = .18$. Older children (432 ms) had faster PCTs than mid-aged (514 ms), who were in turn faster than younger (628 ms). Children with DCD (555 ms) were slower to finish the post-correction phase than controls (502 ms).

4.3.6 Response Errors

Initial analyses on TDEs and AEs showed no effects involving trial type; hence, error variables were examined as a function of age and group.

4.3.6.1 Touch down errors. Two-way ANOVA showed no significant interaction between age and skill group, $F(2,124) <1$, partial $\eta^2 = .006$. A main effect for age was significant, *F*(2,124) = 3.92, *p* = .022, partial η^2 = .06; younger children (3.44) made significantly more TDE than older children (2.31) but not mid-age (3.15). There was no difference between mid-age and older children. There was no effect for group as DCD and control groups made 2.98 errors respectively, *F*(1,124) < 1, partial η^2 = .001.

4.3.6.2 Anticipation errors. Two-way ANOVA revealed no interaction between age and group, *F*(2,124) <1, partial η^2 = .01. There was a main effect for age, *F*(2,124) = 5.23, *p* = .005, partial η^2 = .08, and skill group, *F*(1,124) = 5.33, *p* = .023, partial η^2 = .04. On average, younger children (1.19) made significantly more AE than mid-age (0.65) and older children (0.59). There was no difference between mid-age and older children. The DCD group (1.02) made significantly more errors than controls (0.67).

4.3.6.3 Centre touch errors. For CTE, there was no 2-way interaction between age and group, *F*(2,125)< 1, partial η^2 = .02. There was no main effect for age, *F*(2,125)< 1, partial η^2 = .01: younger (0.42), mid-age (0.44) and older (0.23) children; and no effect for group: DCD (0.33) and controls (0.29), *F*(2,125)< 1, partial η^2 = .001.

4.3.6.4 Anti-jump errors. On AJE, there was no interaction between age and skill groups, *F*(2,125) < 1, partial η^2 = .01. There was a main effect for age, *F*(2,125) = 3.04, *p* = .05, partial η^2 = .05; younger children (mean of 0.97 out of 8 anti-jump trials) had significantly more AJE than older children (0.45) but not mid-age (0.95). The difference between mid-age and older children was also significant. There was no significant difference between DCD (0.88) and controls (0.76), *F*(2,125)< 1, partial η^2 = .003.

4.4 Discussion

The aim of the study was to examine the ability of children with DCD to implement online control when inhibitory constraints are superimposed on a reaching task. Using a double-jump paradigm, I confirmed that these children were significantly slower than non-

DCD to adjust their arm reaching movement on jump trials, evident by longer movement time and delayed time to initiate a corrective movement. Importantly, on anti-jump trials, children with DCD were further disadvantaged relative to controls, evident by larger $AJMT_{diff}$ scores and longer duration to implement a second corrective movement (i.e. ToC2) after their hand was first drawn to the cued location. However, this effect was moderated by age such that the anti-reach performance of older children with DCD approached that of their age-matched peers. These results support the hypothesis that children with DCD have particular difficulty coupling executive control (i.e., response inhibition) to online control during goal-directed action, particularly during younger and middle childhood. This deficit might explain the particular difficulty these children have with more complex tasks, both cognitively and from a motor control perspective. The implications of these findings are discussed below.

4.4.1 Chronometric Performance Measures

For reaction time, the non-significant effect for trial type (non-jump vs jump vs anti-jump) and its interactions were expected since the stimulus display up to the point of finger lift-off was identical for each condition. The DCD group was slower to initiate reaching than controls which is in line with recent studies of online control (Hyde & Wilson, 2011a, 2013) and is consistent with a recent meta-analysis (Wilson et al., 2013) that shows longer latencies when responding to externally cued stimuli. Reduced neural transmission times when responding to external events may underlie this issue.

For non-jump trials, only the younger children with DCD differed from their age-matched controls. This accords with earlier research showing that mid-aged and older children with DCD can complete simple goal-directed reaching within a comparable timeframe as typically developing children of the same age, at least where the need for online adjustments is minimal (Wilmut et al., 2006; Wilson & Hyde, 2013). What my data suggests is that younger children with DCD may be slower to implement even simple movements within peripersonal space. For control children, unlike Study 1 (Chapter 3) where MT was similar between age groups, mid-age and younger control children demonstrated significantly longer MTs than the older group.

For both DCD and control groups, movement time increased significantly from non-jump to jump trials. This accords with previous work (Castiello et al., 1998; Hyde & Wilson, 2011a) and reflects the added computation and implementation time involved when modulating movements in-flight to perceptible changes in target location. In a recent review of online control, Gaveau and colleagues (2014) have commented that increased MT is generally observed when target jumps are of sufficient extent to enlist more voluntary aspects of online control. By comparison, under conditions of saccadic suppression, fast online corrections to relatively small target jumps are performed automatically, without conscious awareness, and with no significant increase in MT relative to non-jump trials. In line with previous studies (e.g. Querne et al., 2008; Rigoli et al., 2012) performance deficits were manifest by longer movement times while group differences were not found on touch down, centre touch or anti-jump errors. The added (temporal) costs associated with using feedback-based control are likely to explain this effect, perhaps a function of reduced efficiency in processing visual information through fast dorsal stream channels (Wilson et al., 2013).

Overall, children with DCD were slower to correct movements in response to jump trials (TOC). Indeed, this effect was not moderated by age suggesting some residual deficit in online control per se over childhood. What is intriguing, however, is the differential effect between groups of the added inhibitory load, measured both chronometrically and kinematically. This finding is described in detail below and is the central focus for the remainder of the discussion.

4.4.2 Deficits in the Online Control of Reaching are Exacerbated with increased Inhibitory Demands

Movement times increased between jump- and anti-jump trials for both groups. For anti-jump trials, I saw two corrective movements in response to the (perceptible) shift in target location which account for the increase in MT over what is a longer trajectory length. The first correction occurs toward the compelling lateral cue and the second inhibiting movement away from the cued location and toward the contralateral target, equidistance from the midline. This bi-phasic correction has also been noted in studies of healthy adults (Pisella et al., 2000) and in my recent developmental work assessing children aged 7 to 12 years (Ruddock et al., 2014). The first correction is considered automatic in that the initial deviation is very difficult to withhold under task instructions that emphasise both speed and accuracy (Gaveau et al., 2014). The second correction is voluntary for what is an unfamiliar task. Results for $AJMT_{diff}$ suggest a specific impairment in younger children with DCD that may subside with age. Overall, the $AJMT_{diff}$ score (i.e., between jump and anti-jump trials) was larger for the DCD group compared with controls, but importantly its magnitude varied as a function of age. Only for younger and mid-aged children was the comparison between skill groups significant. Similar scores for older TDC and DCD groups indicate that they are taking a similar amount of additional time to complete anti-jump trials compared with jump trials.

This suggests a reduced capacity in DCD over this age period to integrate inhibitory and online control during the brief time course of goal-directed reaching. However, by older childhood this capacity in DCD may approach levels of typically developing children. Interestingly, while TOC and TOC2 were delayed in DCD as a whole, there was no moderation of this effect with age. Measures of MT appear to be more sensitive than kinematic measures to change with age and as a function of motor skill.

Finally, children with DCD as a whole were also slower to complete the post-correction phase on anti-jump trials. However, this effect did not decline as a function of age.

This suggests two possibilities: first, it could be taken as evidence that the early stages of online control (up to TOC) are not fully developed in younger and mid-aged children with DCD, or second, it may suggest that the process of implementing trajectory changes remains problematic in DCD over childhood. In lieu of the compelling results for $AJMT_{diff}$, I suggest that the former hypothesis is more likely.

Taken together, my results suggest that the online motor control difficulties of children with DCD are exacerbated when an inhibitory load is superimposed on a dynamic reaching task. Importantly, however, my cross-sectional data shows that by older childhood the level of efficiency in controlling anti-reach movements approaches that seen in typically developing children. I argue that in younger and mid-aged children with DCD, their slower anti-reach performance reflects an immature coupling between frontal and posterior control systems (likely PPC), delaying the voluntary adjustment of movement trajectories in real time. Evidence for improved coupling in older children can be attributed to a combination of neural maturation and experience-dependent plasticity in these same networks (Casey et al., 2008; Johnson, 2005). For example, Balsters, Whelan, Robertson, and Ramnani (2013) found that cerebellum Crus I and II are strongly connected with the prefrontal cortex (PFC) which may support the cognitive control of action systems. What remains to be seen is how particular forms of practice or intervention can alter these couplings over short and long timescales.

From a neural perspective, changes to EF appear to be mirrored by an increase in (sub)cortical structures tied closely to the PFC (Durston et al., 2006). When emerging networks come ‘online’ there is often a period of adjustment as new skills are adopted and refined (Johnson, 2011). With regards to performance on step-perturbation tasks, non-linear changes (i.e. more variability in performance) become apparent as the child learns to refine their motor skills in the pursuit of goal-directed action. The problems the younger- and mid-age DCD groups showed, in particular, when making online adjustments under an inhibitory load might be either the result of executive systems further containing an already impaired ability to redirect movement, or problems coupling multiple systems to more demanding action. Certainly, neuroimaging studies could help clarify the specific structures and regions at play here and shed light on how the two proposed systems interact.

4.4.3 Implications and Limitations

Comparison of the results from the current study to previous online control research may be limited due to several reasons. First, it may be difficult to directly assess data from mid-age children as the age groups defined here (i.e., 6-7, 8-9, and 10-12) are different from the criteria used in the study from Hyde and Wilson (2013) where younger children were grouped between 5-7 years. In addition, I used the 15^{th} percentile as a cut point to define the DCD group compared with the 10^{th} percentile used by Hyde and Wilson. The online deficit on jump trials was somewhat more pronounced in the earlier study, underlining the issue of severity in causal accounts of DCD. Finally, to provide a stronger test of the hypothesis that children with DCD have difficulty coupling online control and executive systems I suggest the use of a longitudinal design (c.f. the cross-sectional data presented here). This may provide a more comprehensive understanding into the developmental trajectory of these control systems, and their pattern of interaction over childhood.

4.4.4 Conclusion

Overall, results extend earlier work by showing that children with DCD have difficulty performing online adjustments and that this is compounded when inhibitory constraints are imposed on a reaching task. Importantly, however, the latter effect was reduced as a function of age. Whereas younger and mid-aged children with DCD were disadvantaged by anti-jump trials – as shown by MT and $AJMT_{diff}$ scores – older children were not relative to age-matched controls. This intriguing finding suggests that whatever is driving the poor motor skill performance of older children with DCD, it is not the ability to couple inhibitory function with online control. Before this age, however, immature coupling may compound the performance issues in DCD, particularly when motor tasks make demands on executive function. That is, the coupling between these systems may require a more protracted period of development in DCD before being functionally integrated. Longitudinal data is needed to unravel the changing pattern of interaction between these systems with age and their relationship to other aspects of executive function.

CHAPTER 5

STUDY 3. COUPLING OF ONLINE CONTROL AND INHIBITORY SYSTEMS IN CHILDREN WITH ATYPICAL MOTOR DEVELOPMENT: A GROWTH CURVE MODELLING STUDY

5.1 Introduction

Everyday tasks such as selecting a book from a shelf, dressing, or simply walking through a busy room are acquired easily by most children but certainly not all. Typically developing children (TDC) acquire motor skills quite seamlessly over the course of development, mainly by a process of visual modelling but also through verbal instruction and hands-on manipulation by a skilled adult or caregiver (Wilson et al., 2013). Changes in performance are shown by greater synergy between joints and muscle activations, and enhanced perceptual-motor coupling, measured on kinematic and kinetic markers. In general, there is a gradual transition from initial freezing of degrees of freedom to a more unconstrained exploration of movement space (Asmussen, Przysucha, & Dounskaia, 2014). With this transition, there is an enhanced ability to adapt movements to variability or complexity in the environment. For example, a basic running or catching action in a closed environment is translated to open conditions where the action space is shared with other children or objects.

One of the hallmarks of a healthy motor system in children is the ability to quickly update movement plans in the face of sudden changes (or perturbations) in the environment, like a moving object in the field of view or a physical force as when one’s arm is knocked in the act of reaching (Shadmehr et al., 2010). Neuro-computational models of human reaching posit that online motor control is critical for fluent and efficient movement. Underpinning online control are fast *internal feedback loops* which utilise predictive (or forward) estimates of limb position based on the expected sensory consequences of self-motion (Desmurget & Grafton, 2003). Once (actual) visual and proprioceptive signals become available to the nervous system at movement onset, they are compared with those predicted by a ‘forward’ model in real-time. Where discrepancies arise, error signals are generated and relayed back to the controller to be integrated with the unfolding motor command, allowing for rapid adjustments to limb dynamics should they be necessary (Desmurget & Grafton, 2000). Impressively, these corrections can occur within 100 milliseconds (ms) (Castiello et al., 1991) and support the stability of the motor system with minimal processing delay.

While the nature of rapid online control during reaching and its neurocognitive bases have been well studied in adult populations (e.g. Gaveau et al., 2014; Pisella et al., 2000), only recently has it been addressed in children. While this work is in its formative stage, it is becoming clear that mechanisms linked to fast corrective processes undergo considerable changes between the ages of 6 and 12 years (Bard et al., 1990; Van Braeckel et al., 2007). By 7 years of age, children are able to generate fast and accurate ballistic movements but are slower to integrate online feedback than older children, resulting in some inefficiency for more complex movements (Wilson & Hyde, 2013). At around 8-9 years of age, children are able to make earlier and greater use of sensory feedback (e.g. Chicoine et al., 1992) as both feedforward and feedback (predictive) control become better integrated, resulting in a steep improvement in their capacity to implement corrective actions. By 9-12 years, the nervous system is able to integrate predictive and sensory systems more smoothly, resulting in an adult-like ability to correct simple movements online (e.g. see Wilson & Hyde, 2013) while movement skills continue to develop into adolescence.

Research on the development of brain morphology provides important insights into the timescales over which perceptual-motor systems unfold. At a neural level, studies in healthy adults have implicated the posterior parietal cortices (PPC) in corrective hand movement during the course of goal-directed action (Gréa et al., 2002; Reichenbach et al., 2011; Reichenbach et al., 2014). In typically developing children, improvement in online control appears to coincide with patterns of neural maturation that include synaptogenesis, myelination, and formation of white matter networks (WMNs) (for reviews see Casey et al., 2005; Chen, Liu, Gross, & Beaulieu, 2013; Collin & Van Den Heuvel, 2013; Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013; Sripada, Kessler, & Angstadt, 2014; Ve´rtes & Bullmore, 2014). Of the various cortical and sub-cortical networks, peak periods of myelination and synaptic pruning are observed to occur last in frontal and parietal zones, shaped by both external (i.e., experiential learning) and internal/maturational growth factors (Casey et al., 2008). Similarly, development of dorsal attention and fronto-parietal WMNs is maximal during older childhood (10-13 years of age) (Sripada et al., 2014). This same fronto-parietal circuitry is critical to the control of goal-directed and target-directed motion (Gréa et al., 2002; Reichenbach et al., 2014).

The broad theory of *interactive specialization* provides a parsimonious explanation of how different neural systems unfold and interact over time (Johnson, 2011; Johnson, 2013). Traditional models of brain-behaviour posit a number of separable brain systems that support a narrow range of behaviours, each unfolding under specific maturational timelines. In the case of motor control, for instance, this implies that specific processes/behaviours develop according to localised neural regions. However, neural networks are far more dynamic in their interaction than this model would suggest. A more parsimonious account is that separate systems (with individual growth trajectories) can impact the development of each system through a process of *interactive specialization* (Johnson, 2005, 2011; Johnson, 2013). To this end, recent behavioural and neurophysiological evidence indicates that the emergence of new, or more refined behaviour, is often the result of several brain regions/networks whose growth trajectories may differ, but yet support each other (Johnson, 2011). This theory has been applied quite persuasively in describing the development of behaviours as varied as linguistic processing, social cognition, and face perception (Johnson, 2011). I argue that co-development of online motor control and executive function (EF) is another important case in point.

In typically developing children, I have shown that the expression of rapid online control – supported by dorsal stream and parieto-cerebellar networks – appears to be constrained by concurrent demands on frontal executive systems (i.e. Ruddock et al., 2014). For relatively simple movements to visual perturbation (without an executive load), the capacity to enlist online control improves rapidly between 6 and 9 years of age, followed by steady but more modest growth into older childhood (Wilson & Hyde, 2013). Importantly, online control is based on predictive estimates of limb position. As such, predictive control for simple movements is a landmark achievement of development over early and middle childhood, an ability subserved by posterior visuomotor networks including posterior parietal cortex (Shadmehr et al., 2010)[1]. In contrast, the pattern of development differs when online corrections must be implemented under an executive (inhibitory) load. For anti-reach movements, the performance of mid-age children reduced relative to that of older children aged 10-12 years (Ruddock et al., 2014) and was more similar to the performance of younger children (aged 6-7 years).

The importance of EF to motor control is further supported by evidence that children with atypical motor development (i.e. Developmental Coordination Disorder; DCD) show deficits on tasks that involve the joint action of frontal executive and (dorsal) visuomotor systems. For example, in the case of the online control of reaching, recent research has shown that children with DCD are able to reach to stationary targets as efficiently as age-matched peers, but they take longer to correct arm reaching following unexpected target displacement mid-movement (Hyde & Wilson, 2011a). From a neuro-computational perspective, corrections of this type are predicated by the integrity of predictive control, an argument formalised as the *internal modelling deficit* (IMD) hypothesis of DCD (Adams et al., 2014;

[1] The dorsal visuomotor network comprises the posterior parietal cortex (PPC) and its reciprocal connections to frontal and cerebellar cortices (Shadmehr et al., 2010). PPC is a prime site for processing forward internal models; these neurons are capable of re-mapping their receptive fields in anticipation of the sensory effects of an impending eye movement or goal-directed reach, for example (Shadmehr et al., 2010).

Wilson et al., 2013). Hyde and Wilson (2013) also showed that for older children with DCD, the time taken to implement changes in movement trajectory mid-flight was similar to younger typically developing children (5-7 years old). This pattern suggested that poor predictive control in DCD may reflect a developmental delay of fronto-parietal systems rather than an abnormality.

In a recent cross-sectional study (Ruddock et al., 2015), I compared the ability of children with and without DCD to enlist inhibitory control while implementing online corrections. Using an anti-jump reaching task, children were instructed to reach and touch a target location in the hemispace opposite a cued location. While replicating earlier results for the double-jump reaching task (DJRT), it was also shown that children with DCD were further disadvantaged by the inhibitory load of the anti-jump condition. Importantly, this effect was moderated by age: younger (6-7 years) and mid-age (8-9 years) children with DCD showed substantial difficulties coupling online and inhibitory demands on anti-reach trials, whereas older children with DCD (10-12 years) showed a similar pattern of performance to age-matched TDC. This pattern suggests that immature coupling of cognitive (i.e., inhibitory) and motor control systems is linked to the movement skill problems of younger and mid-age children, while a different mechanism may explain the persistence of clumsiness in older children. However, my ability to make strong causal statements about the interaction of these systems was limited by the cross-sectional design. This was the motivation for the present modelling of the development of cognitive and motor control functions using a sophisticated longitudinal design.

5.1.1 Growth Curve Modelling of Typical and Atypical Motor Development

Examining the motor performance of children longitudinally can be complicated by a range of factors including the amount of time needed to measure a suitable age, the cost of repeated testing, and attrition. However, recent innovations in statistical (multilevel) modelling, particularly the use of growth curve modelling (GCM), has afforded a number of flexible longitudinal research designs in the area of child development. The influence of GCM is most apparent in the field of neural and cognitive development (e.g. Sansavini et al., 2014; Wiebe, Sheffield, & Espy, 2012). This technique is well suited for a range of longitudinal designs and is known for its flexibility in modelling non-linear changes. For example, cohort-sequential (or accelerated) designs provide an extremely efficient means of modelling developmental processes over extended age periods, and are amenable to GCM techniques where growth functions are readily resolved. To my knowledge, GCM has yet to be applied to the development of motor control in children.

The broad aim of my study was to model age-related change in the ability to couple online and executive control using a large sample of children. To capture developmental progression over the ages of 6-12 years, while limiting data collection to a 2-year period, I enlisted a cohort sequential design (CSD), and examined the growth patterns of TDC and DCD groups using model comparison techniques. CSDs enlist a set of adjacent age cohorts that are each tracked longitudinally over a limited time period, but in combination provide an extended age profile that can be analysed to reveal a common developmental trend (or growth function/curve). As such the combination of CSD and GCM is an extremely powerful and efficient means of examining developmental processes at various levels of function (neural, cognitive, and behavioural). Cohort sequential designs maximise the use of incomplete participant data and permit modelling of non-linear data distributions. In light of the suggestion that TDC experience rapid improvement in coupling online motor and executive systems during early and middle childhood, I predicted that a quadratic growth function would best capture developmental change. By comparison, I expected that the typical re-organisation in the coupling mechanism around middle childhood would be disrupted in children with DCD which would manifest as a linear trend on key chronometric and kinematic indices.

5.2 Method

5.2.1 Participants

A group of 196 children was recruited for the study. Children from preparatory to sixth grade (or 6 to 12 years) were randomly selected from primary schools across two metropolitan cities. Figure 5.1 summarises the number of children assessed at each of five occasions of testing.

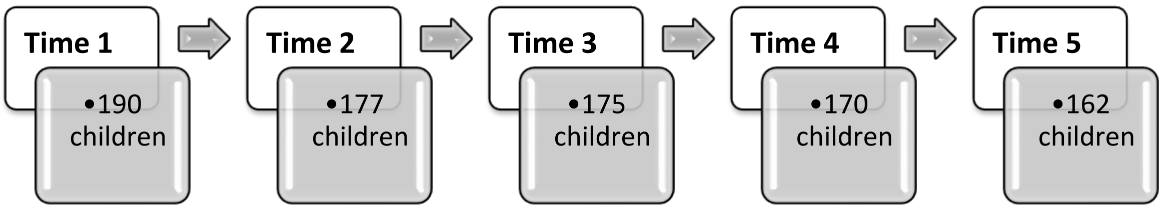


Figure 5.1. Flow chart of participants available for testing at each time point across the study lifespan.

The overall attrition rate between the first and last time of testing (2 years later) was 34 children (17%); among those were 28 children who transitioned into secondary school after graduating from grade six. After screening assessments, the final sample size comprised 109 TDC and 62 with DCD. Demographics for DCD and TDC groups are provided in Table 5.1.

Table 5.1

Descriptive Statistics for Typically Developing Children (TDC) and Developmental Coordination Disorder (DCD) Groups at Time 1

	Gender		Age (years)		Handedness	
	Girls	Boys	*M*	*SD*	Right	Left
TDC						
Age 6	19	9	6.44	0.37	26	2
Age 7	14	7	7.47	0.31	18	3
Age 8	11	10	8.39	0.31	21	0
Age 9	6	12	9.45	0.27	18	0
Age 10	8	7	10.33	0.26	15	0
Age 11	3	2	11.35	0.17	4	1
Age 12	0	1	12.25	0.00	1	0
DCD						
Age 6	4	3	6.43	0.61	6	1
Age 7	4	9	7.53	0.31	13	0
Age 8	2	9	8.56	0.35	10	1
Age 9	4	7	9.50	0.32	11	0
Age 10	9	6	10.55	0.26	13	2
Age 11	4	1	11.28	0.17	4	1

Note. TDC = Typically Developing Children; DCD = Developmental Coordination Disorder.

Motor proficiency was assessed using the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997). Consistent with the recommendations of the Diagnostic and Statistical Manual 5th Edition (American Psychiatric Association, 2013) and meeting research criteria (Blank et al., 2012), children were classified as DCD if their level of movement skill was below expectations for age and they scored less than the 15th percentile on a standardised test of motor proficiency (the MAND) at Time 1 (Noten et al., 2014; Piek et al., 2006; Ruddock et al., 2015) (Criterion A), had motor skill deficits that interfered with daily home and/or school curriculum activities (Criterion B), and an onset of difficulties before school age (Criterion C) as indicated on a parent/teacher pre-screening questionnaire. Children were excluded if the pre-screening questionnaire showed evidence of a previous or current developmental disorder (ADHD, autism), physical disability or health impairment (i.e. asthma, visual impairment, epilepsy, etc…), and/or neurological condition; this met Criterion D, notionally. Typically developing children were identified by a score above the 20th percentile (Hyde & Wilson, 2013). Since children were recruited from mainstream primary schools and were not attending remedial classes for academic skills, it was assumed that IQ scores were within normal range. Informed consent was obtained from all participants, parents and principals involved in the study and relevant ethics clearances were granted from government and tertiary institutions.

5.2.2 Apparatus

A Double-Jump Reaching Task (DJRT) paradigm was used to assess online control. The task was developed using VIRTOOLS Software (3DVIA, 2010) on a PC laptop running Windows XP and projected on a black Samsung 40-inch touch screen with black bezel. The screen was placed on a height-adjustable table and positioned in portrait orientation, raised 10° from the horizontal plane.

Stimuli were presented on a dark background in order to minimise contrast interference. The display consisted of a round green ‘home base’ (2.5cm in diameter), placed 5cm from the near edge of the screen and centred on a sagittal plane. Three yellow cue targets were positioned at -20°, 0°, 20° from a vertical line drawn directly from home base. To accommodate age-related differences in reach, the distance to each possible target location was scaled to 60% of average arm length based on age norms for young children (25cm; 6-7 years), mid-age children (28cm; 8-9 years), and older children (30cm; 10-12 years) (Gerver et al., 1989).

The Zebris CMS10 (Noraxon, 2010) system was used to record arm reach and sampled at 200Hz. The device was clamped to the table and positioned at a height of 1 meter above the middle of the screen. A thin (1mm) cord, 2m in length, extended from the Zebris receiver to a small ultrasonic sensor (7mm in diameter) which was attached via an adhesive strip to the child's dominant index finger; the cord was also tethered to the wrist using an elastic band.

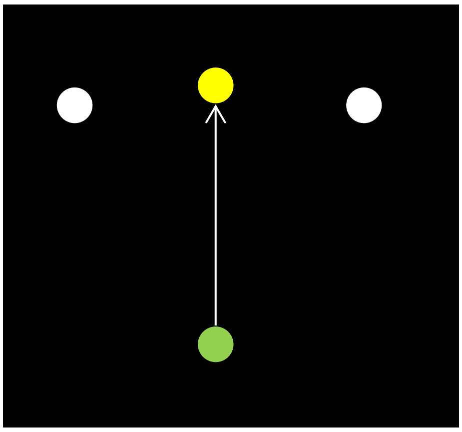
5.2.3 Procedure

The study was conducted over a two year period, with five occasions of testing each separated by six months. Data from Study 1 and 2 (Chapters 3 and 4) were included in the growth curve modelling. At each school, a quiet office was used for assessments, free from environmental distraction. Each room was darkened to minimise use of visual feedback from the moving hand during performance of the DJRT (Farnè et al., 2003). Hand preference was determined using the manual dexterity items of the MAND, and corroborated by both the child and by observation of hand use during writing. Each child was positioned directly in front of the screen as the kinematic sensor was attached to the dominant hand index finger and task instructions were explained.

Administration of the DJRT occurred across two sessions with the order of administration randomised: a standard 'jump' condition and a modified 'anti-jump' condition (see Figure 5.2 for a schematic of the conditions and trial types).

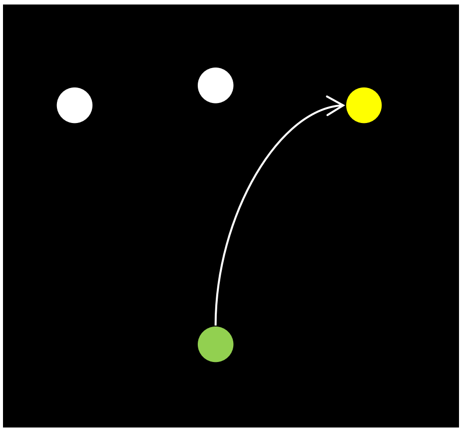
Condition A (standard jump trials)

Non-jump trial



The central target remains lit until touchdown.

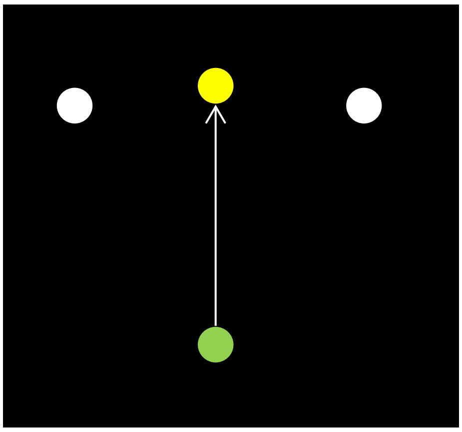
Jump trial



Target *jumps* to either peripheral location at finger lift off

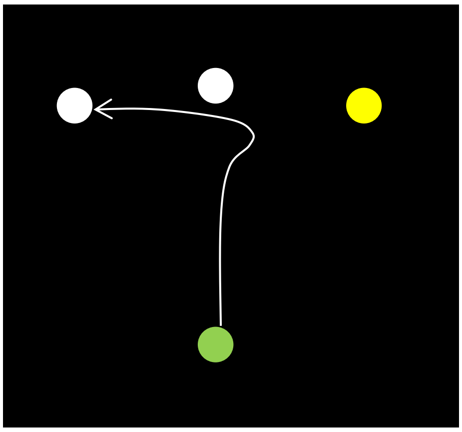
Condition B (with anti-jump trials)

Non-jump trial



The central target remains lit until touchdown.

Anti-jump trial



Reach to the contralateral location is required.

Figure 5.2. Schematic overview of the double jump reaching task showing trial types across two conditions.

On the jump condition, children held their index finger on home base prior to commencing each trial. The imperative stimulus was a doubling in luminance of one of the two peripheral target locations, with simultaneous extinction of the home base. Each trial was programed with a random delay of 500-1500 ms to prevent children from anticipating change in target illumination. Children were also instructed to *follow the target* and touch its centre as *quickly and accurately as possible*. A successful trial occurred when the cued target location was touched within its circular boundary which extinguished the light, accompanied by an auditory tone to indicate trial completion. For the jump condition, on 80% of all trials, the middle target remained lit until touched (*non-jump* trial) while on 20% of all trials the location of the target shifted (or jumped) at movement onset to either the left or right peripheral location (*jump* trial). At the completion of each trial, children returned their finger to the home base, ready for the next trial. The anti-jump condition was administered as a separate task but used the same method described for the jump condition; however, when target displacement occurred to a lateral location, children were instructed to *reach and touch the circle on the opposite side* (*anti-jump* trial).

Prior to each condition, the researcher demonstrated the action required for *non-jump*, *jump*, and *anti-jump* trials. Children were permitted 10 practice trials to familiarise themselves with the task; in rare cases children were given extra trials, if needed. Each condition comprised 80 trials administered in two blocks of 40 trials each (32 *non-jump* and 8 *jump*/*anti-jump*), programmed in a pseudo-random order across left and right target locations. Between conditions, children were provided with a two minute rest. Total administration time of the task was approximately 15-20 minutes per child.

5.2.4 Measures

For all trials, movement time (MT) was recorded on the DJRT and only successfully completed trials were included in the analyses. Across the five test points, an average of 9

(14%) non-jump trials and 3 (18%) jump/anti-jump trials were removed from the DCD group, and 7 (11%) and 2 (13%) respectively from the control group. The effect of inhibitory load on online control was assessed using the difference in MT between anti-jump and jump trials ($AJMT_{diff}$). For anti-jump trials, there are two time points at which trajectory corrections occur. The first, automatic correction (ToC) was defined as the point at which the hand deviates from its dominant trajectory to the central target location and toward the peripheral cue (Hyde & Wilson, 2011b). A second correction (ToC2) then occurs when the hand is directed away from the cued location and toward the contralateral target location (Cameron et al., 2009). ToC2 reflects the integration of inhibitory control as part of the corrected movement plan as the hand is redirected toward the hemispace opposite the original cue. Both $AJMT_{diff}$ and the interval between the first (automatic) corrective movement and the second (inhibitory) correction of hand movement (i.e., ToC*diff*) reflect the ability to enlist inhibitory control in the context of an online motor correction. All data were filtered through a fourth order Butterworth filter with a cut off of 10Hz. Movement trajectories were plotted on a 2D Cartesian plane using MATLAB software (Mathworks, 2010) and ToC and ToC2 values were determined by two independent raters (Ruddock et al., 2014).

5.2.5 Design and Analytic Approach

I combined a cohort-sequential (longitudinal) design (CSD) and growth curve modelling (GCM) to examine developmental trends in the ability to couple inhibitory and online control systems over the course of child development. A CSD – or accelerated design – enlists separate but overlapping age cohorts to test an overarching developmental trend (Duncan et al., 2006). In my study, children were allocated to one of the 13 age cohorts (separated by 6-month increments), which together spanned a 6-year period from 6- to 12-years of age. CSDs maximise the use of incomplete participant data and has been shown to be more powerful and efficient than single-cohort designs in generating developmental data on specific age groups (Grammer et al., 2013). As well, GCM offers a number of major advantages over traditional methods of analysing longitudinal data (such as repeated-measures ANOVA): (i) change in motor and cognitive functions over time is analysed at both a population and individual level which is consistent with theories of developmental psychology; (ii) flexibility is afforded in the treatment of the time variable (i.e., each child does not have to contribute measures over the entire age range of interest); (iii) missing data are accommodated readily under the assumption that they occur randomly; and (iv) modelling can be generalised to non-normal data. Growth curve modelling, in particular, enabled us to examine (predicted) non-linear developmental trajectories and differences between TDC and DCD groups (Bryk & Raudenbush, 1992; Singer & Willett, 2003).

Growth curves were analysed at two main levels: Level 1 examined within-person (or individual) change using 'age' as a predictor variable. This yields individual estimates for intercept and slope on the main outcome measures. All individual estimates are then combined for each age cohort. Cohort-specific trajectories are also plotted and 95% confidence intervals were inspected for overlap at relevant age points. Possible cohort interactions with different change trends were tested using convergence estimates. A common model was then tested under the assumption that members of all 13 age cohorts follow a single underlying developmental trajectory (Duncan et al., 2006). For each dependent variable on the DJRT, linear, quadratic, and cubic growth patterns in the TDC and DCD samples were tested.

While there is some debate on the minimum number of observations per participant that are required to maintain adequate levels of model fit (Curran, Obeidat, & Losardo, 2010), I included all available data in order to ensure the most valid representation of my participant groups (Miers, Blöte, De Rooij, Bokhorst, & Westenberg, 2013). A minimum of three observations per cohort was set so as to prevent over- or under-inflation of mean values at each test point.

Outliers were analysed using a combination of standard regression diagnostics and influence statistics, which is designed to optimise the model fit (Schabenberger, 2004). Because extreme values can influence different parameters within the multi-level model (including estimates of fixed effects, covariance parameters, and fitted and predicted values), removal of data points based on standardised residuals alone can compromise model fit. As such, outliers were removed when two conditions were met: (i) standardised residual value > +/- 3.0 *and* (ii) analysis of individual and multiple data points revealed large values on influence statistics (e.g., *restricted likelihood distance*) (Schabenberger, 2004).

Data analysis was conducted using the PROC MIXED procedure of SAS version 9.3 software (SAS Institute, 2008), running on a Windows 7 platform. This procedure estimates for each child, individual curve functions (i.e., slope and intercept) and, using a random effects approach, models the effect of cohort, age and their interaction, guarding against potentially high correlations from repeated measures of the same individuals over time (Anderson et al., 2009). Fit and comparison between models was assessed using goodness of fit indices, specifically the Bayesian Information Criterion (BIC). This index is useful for comparing different models, with smaller values indicating better fit and a more parsimonious model, regardless of the absolute value. For each group (TDC and DCD), the trajectory of each outcome variable ($AJMT_{diff}$ and ToC*diff*) was tested using polynomial analyses that assessed linear, quadratic and cubic trends in an unstructured covariance matrix. In this analysis, model parameters (i.e. age, cohort, and age*cohort) were tested for their sequential effect to determine the most appropriate growth curve solution (i.e. linear, quadratic, or cubic) using *-2log likelihood* statistic.

5.3 Results

5.3.1 Anti-jump Movement Time Difference

5.3.1.1 Descriptive overview. Plots of cohort values of AJMT$_{diff}$ for control and DCD are presented in Figure 5.3. Mean values for age (collapsed across cohorts) are presented in Table 5.2.

Table 5.2

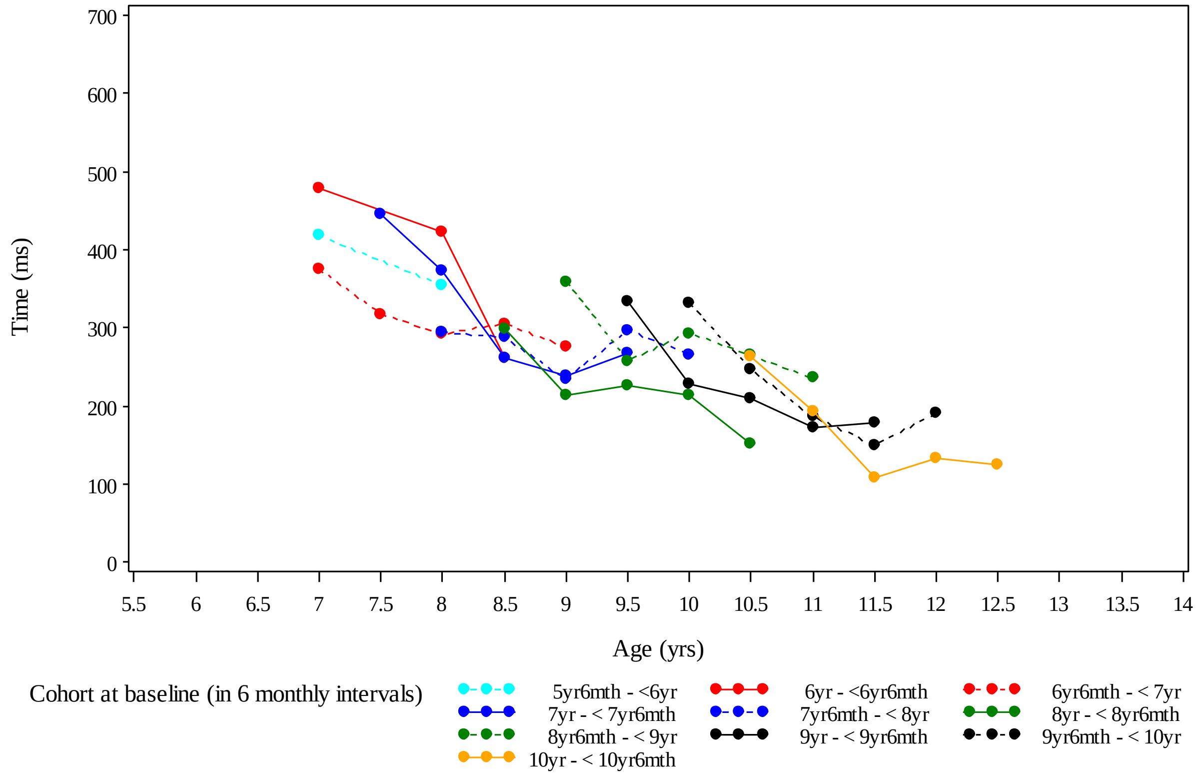
Mean Values for AJMT$_{diff}$ at each Age for TDC, DCD and Total Group

	TDC	DCD	Total Group	TDC vs DCD
Age Group	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*d*
Age 6	407 (200)	444 (175)	412 (194)	.30
Age 7	334 (168)	441 (184)	360 (177)	.63
Age 8	278 (136)	326 (149)	295 (142)	.65
Age 9	273 (131)	293 (151)	281 (139)	.14
Age 10	215 (93)	285 (126)	241 (112)	.66
Age 11	164 (92)	203 (137)	182 (116)	.34
Age 12	117 (72)	119 (71)	117 (69)	.03

Note. All values are in milliseconds. AJMT$_{diff}$ = Anti-jump Movement Time Difference Score; TDC = Typically Developing Children; DCD = Developmental Coordination Disorder.

Three children from the DCD group (one each from cohorts 1, 2, 3) were identified as outliers and removed from subsequent analyses. The plots show that difference scores for both groups decreased monotonically across the age, reflecting quicker response times across childhood on the difference between jump- and anti-jump trials.

(a) TDC



(b) DCD

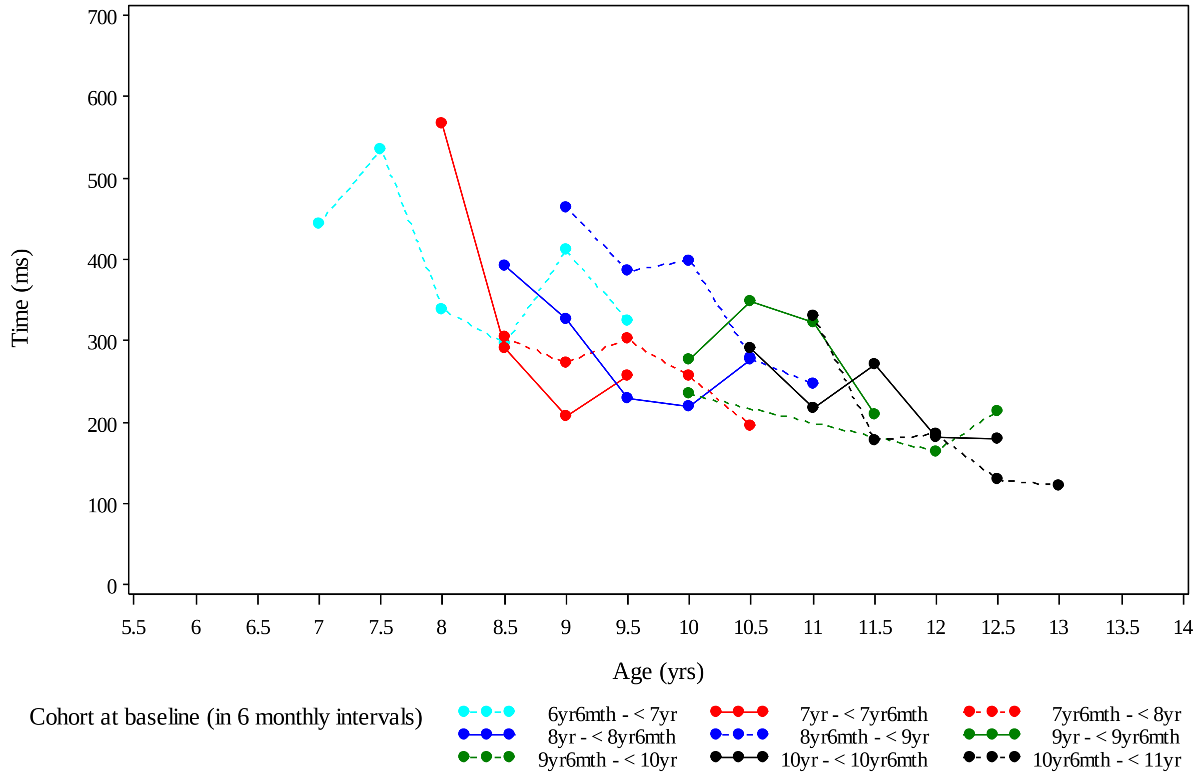


Figure 5.3. Mean AJMTdiff values for each age cohort for (a) TDC and (b) DCD groups on the double-jump reaching task. Individual lines represent age cohorts.

5.3.1.2 Model fitting analysis. For the TDC group, the best fitting growth curve included quadratic growth terms, indicating that TDC showed quick improvement in online corrections under tight inhibitory constraints with development, but growth decelerated over time into later childhood (−2LL = 4808.2, BIC = 4839.8). Adding a cubic term to the model did not result in a better fit (refer to Appendix A for *-2log likelihood* values generated for linear, quadratic and cubic trends of $AJMT_{diff}$ and ToC_{diff} analyses).

In contrast, for the DCD group, the best fitting growth curve was linear, suggesting that there was only generalised improvement across childhood (−2LL = 2921.1, BIC = 2929.9). Adding quadratic and cubic terms to the model showed no improvement to the model fit.

5.3.2 Time of Correction Difference

5.3.2.1 Descriptive overview. Plots of cohort values of ToC_{diff} for control and DCD are presented in Figure 5.4. Mean values for ToC_{diff} at each age are presented in Table 5.3.

Table 5.3

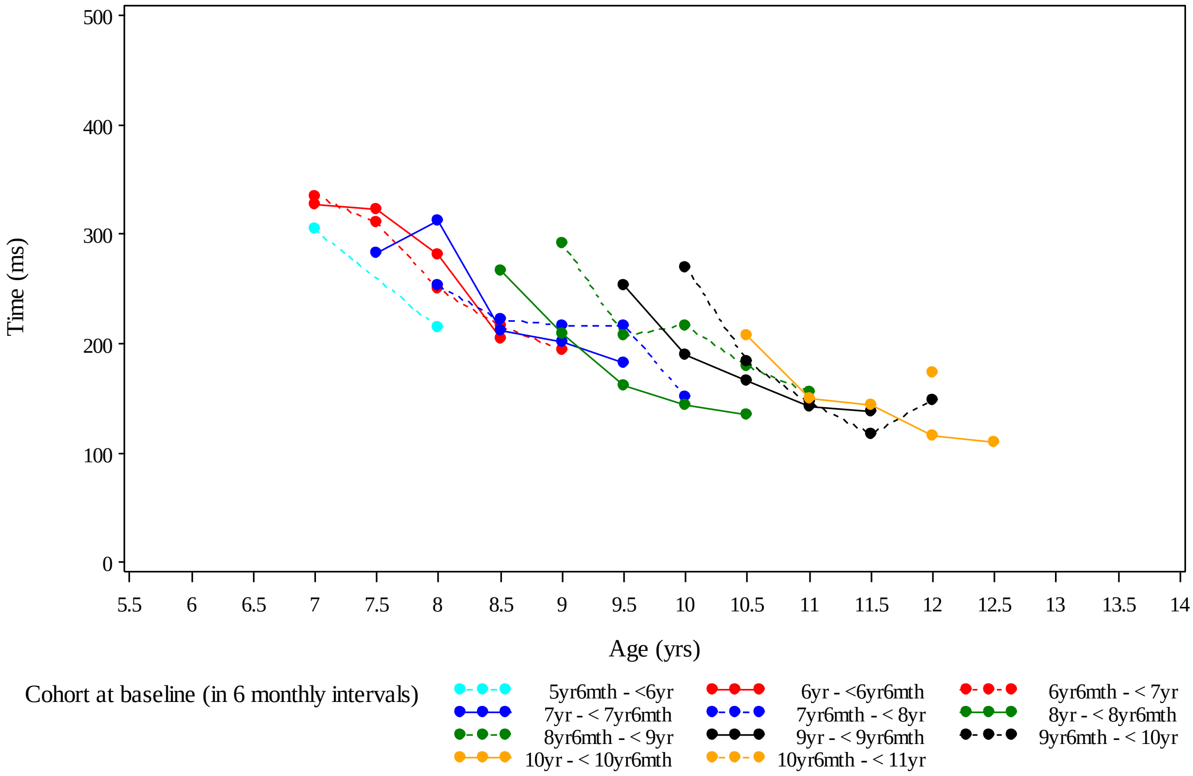
Mean Values (SD) for ToC$_{diff}$ at each Age for TDC, DCD and Total Group

Age Group	TDC *M* (*SD*)	DCD *M* (*SD*)	Total Group *M* (*SD*)	TDC vs DCD *d*
Age 6	326 (78)	354 (16)	329 (73)	.38
Age 7	279 (85)	296 (64)	283 (80)	.21
Age 8	221 (67)	240 (63)	227 (66)	.29
Age 9	202 (66)	215 (62)	207 (65)	.20
Age 10	166 (49)	194 (64)	177 (57)	.49
Age 11	139 (48)	157 (49)	148 (49)	.37
Age 12	106 (26)	129 (31)	121 (31)	.25

Note. All values are in milliseconds. ToC$_{diff}$ = Time of correction difference score; TDC = Typically Developing Children; DCD = Developmental Coordination Disorder.

The plots show that time difference between ToC and ToC2 for both groups decreased across age, resulting in faster response times on anti-jump trials to engage a second (more deliberate) corrective movement.

(a) TDC



(b) DCD

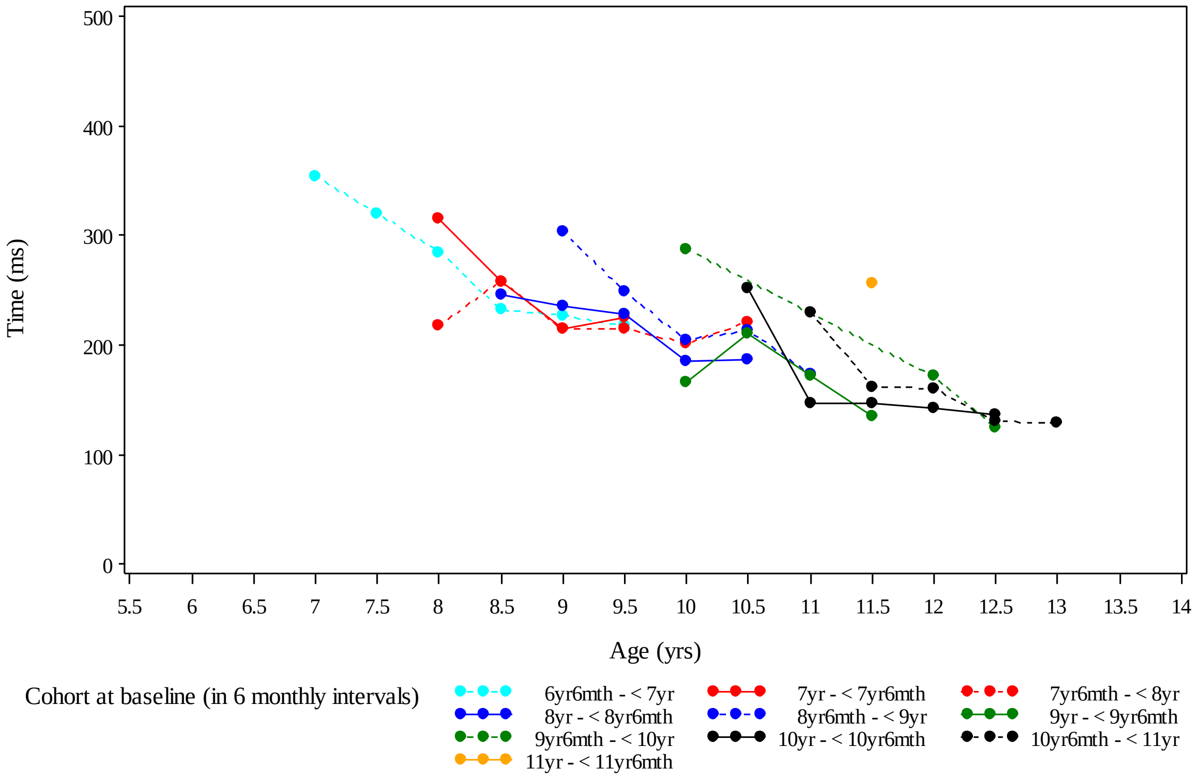
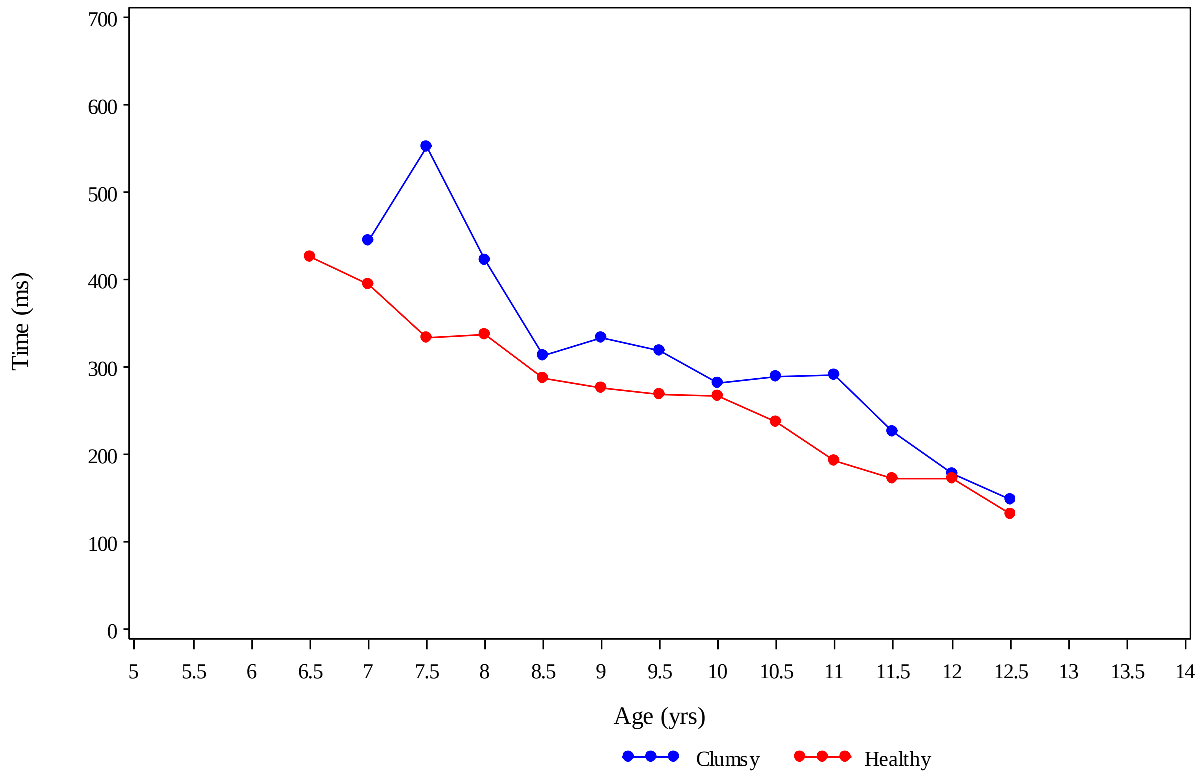


Figure 5.4. Mean ToC$_{diff}$ values for each age cohort for (a) TDC and (b) DCD groups on the double-jump reaching task. Individual lines represent age cohorts.

(a) AJMT$_{diff}$



(b) ToC*diff*

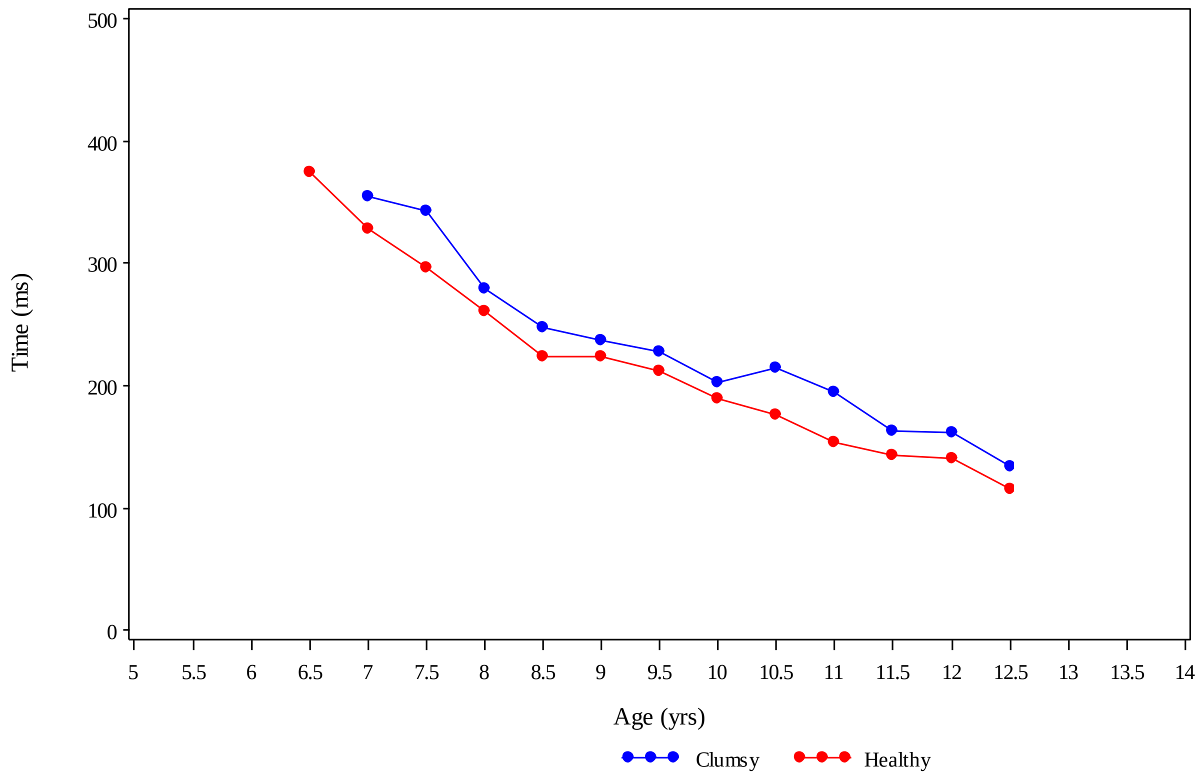


Figure 5.5. Aggregated plots comparing TDC and DCD groups on (a) AJMT$_{diff}$ and (b) ToC$_{diff}$

5.3.2.2 Model fitting analysis. The pattern of results for ToC*diff* was similar to AJMT*diff*. For the TDC group, the best fitting growth curve also included quadratic growth terms, indicating a steady rate of improvement on this measure of coupling up to middle childhood, followed by a shallower rate of improvement into later childhood (−2LL = 4374.6, BIC = 4400.7). The addition of a cubic term to the model did not result in a better fit.

For the DCG group, the best fitting curve solution was linear, indicating a shallow but consistent rate of improvement across childhood (−2LL = 2635.5, BIC = 2934.0). Adding quadratic and cubic terms to the model did not improve model fit.

5.3.3 Summary of Trend Analyses

Overall, both TDC and DCD groups showed an improvement in performance across childhood on key chronometric and kinematic measurements. For TDC, a curve with quadratic terms was found to be the best fit for AJMT*diff* and ToC*diff*, indicating that performance improves rapidly up until middle childhood followed by a more gradual but consistent improvement after this period. For the DCD group, a linear function provided the best fit on both AJMT*diff* and ToC*diff*; however, the rate of improvement was more gradual in comparison to the TDC group. On $AJMT_{diff}$, the level of performance of 12 year old children with DCD was within 2 ms of TDC (p > .10) while on ToC_{diff}, the difference was 23 ms (p > .10).

5.4 Discussion

The aim of this study was to model age-related changes in the coupling of online and executive control. Using a CSD that spanned the 6-12 year-old developmental period, I examined the ability of TDC and DCD groups to perform online corrections under inhibitory constraints (i.e., anti-reach performance) using a double-jump paradigm. Overall, the pattern of performance for both groups showed improvement on key metrics across childhood. However, analysis of growth trajectories using GCM highlighted distinct fit solutions for

TDC and DCD groups. For TDC on both AJMT*diff* and ToC*diff*, a quadratic trend was the most appropriate fit with evidence of rapid improvement in anti-reach performance up until middle childhood (around 8-9 years of age), followed by a more gradual level of improvement into late childhood and early adolescence. Both measures indicate the level of proficiency when enlisting inhibitory control to re-direct (online) a reaching movement away from a compelling visual cue. By comparison, for the DCD group, linear growth curves were found on both AJMT*diff* and ToC*diff* variables. A more moderate slope/linear function in DCD relative to TDC indicates a developmental delay (or more gradual unfolding) of the coupling between inhibitory and rapid online control systems. The implications of these results are taken up for discussion below.

5.4.1 Performance of Typically Developing Children

For TDC, developmental trajectories using GCM were similar on each of the two key performance metrics. Polynomial analysis on AJMT*diff* revealed that a quadratic growth curve was the most optimal fit. Here relative fit statistics (i.e., *-2log likelihood* and BIC) showed that adding a quadratic term to the model produced lower fit metrics and improved the model estimate. This method of model comparison is a valid means for comparing growth profiles (Zhang & Wang, 2009), and provides confidence in the pattern of results. Likewise, for ToC*diff* – also measuring the efficiency of the two-step correctional process for anti-jump trials – a quadratic trend was shown. In response to visual perturbations performed under an executive load, growth curves on these chronometric and kinematic indices show a greater reduction of AJMT*diff* (134 ms) and ToC*diff* (124 ms) in TDC between 6 and around 9 years of age, after which improvement continues, but at a reduced rate, for children 10-12 years of age (98 ms and 60 ms respectively). This pattern is suggestive of an important transition in the coupling of executive (inhibition) and motor systems, particularly during middle childhood; it represents a time when predictive (online) control is being re-organised to better accommodate and support movement complexity and adaptability (Desmurget & Grafton, 2003; Hyde & Wilson, 2011b).

It is no coincidence that the coupling between online and inhibitory control systems emerges on a similar timescale to that of core executive processes per se (i.e., task switching, executive attention, and inhibition). With development, executive control exerts more 'top-down' influence on the goal-directed behaviour of children, enabling the organisation of more flexible and complex responses in novel situations (Diamond, 2013). This progression is highlighted by mainstream research into children's cognitive development showing fast improvement of EF across primary school years, with some variation in the timescales of development between different aspects of EF (Anderson, 2002; Garon et al., 2008). These trajectories of change with age are also mirrored in recent morphological analyses of structural brain networks, also using growth curve modelling (Chen et al., 2013).

The modelling of longitudinal data here for the TDC group are also consistent with and extends on a recent cross-sectional study (Ruddock et al., 2014). In the first developmental study of its type investigating the coupling of inhibitory and online control, I showed that while children aged 8-9 years were able to implement standard online corrections on a DJRT with a level of efficiency comparable to that of older children (10-12 years), their performance on anti-jump trials was compromised and resembled that of younger children (6-7 years). The implication here was that predictive control shows rapid improvement up to middle childhood for simple online corrections but when inhibitory demands are superimposed on the task, performance is compromised, suggesting poor coupling. My modelling work here is remarkably consistent with this pattern in showing a quadratic fit to be optimal in describing change with age. This hypothesis is consistent with other work showing reasonable levels of response inhibition per se by middle childhood, but only for simple tasks (Diamond, 2013; Iani, Stella, & Rubichi, 2014; Luna et al., 2004).

In terms of neuro-maturational development, levels of synaptic proliferation are particularly high during early and middle childhood, while rates of development in WMNs are maximal during later childhood—these changes underpin the emerging capacity for frontal executive control (Johnson, 2013). Similarly, recent advances in brain network mapping, particularly 'growth connectomics' (Ve´rtes & Bullmore, 2014), indicate significant changes in brain architecture over childhood and associated graph metrics. Throughout childhood and adolescence, brain networks mature gradually from local, proximity-based connectivity patterns, to a more spatially distributed and topological integrative organisation supporting higher cognitive functioning. In other words, WMNs are reshaped from early childhood to adolescence with increased global integration and decreased segregation. The connections between major modules of the connectome increase with age as long fibre pathways link the modules together. For example, Chen and colleagues (2013) showed that most changes in WMNs occur during late childhood (10-13 years); that is, specific modular hubs responsible for visual processing, EF, multisensory integration, and a so called default module are established during childhood, but are refined into adolescence. These changes would support greater functional coupling between fronto-parietal systems, for example, consistent with the pattern of changes I observed for older children on the anti-jump task.

In the case of flexible online control, the younger child must learn to couple (emerging) frontal executive systems to the more automatic online control systems of the dorsal stream, e.g., the fast response visuomotor channels of the premotor-parietal axis (Pisella, Binkofski, Lasek, Toni, & Rossetti, 2006). Hence, I expected to see slower performance around this period of development. The growth pattern on the kinematic measure of anti-jump performance (ToC*diff*) also supports the hypothesis that younger and mid-aged children are less efficient at implementing online control when demands on inhibition are imposed. After a period of re-organisation during middle childhood, there was continued and progressive maturation of this coupling into older childhood, providing a critical test of the patterns I observed when age groups were compared cross-sectionally (Ruddock et al., 2015).

5.4.2 Coupling of Online Control and Inhibitory Systems in Children with DCD shows atypical Growth Patterns

In general, the DCD group performed less efficiently than TDC as reflected by their scores on both AJMT*diff* and ToC*diff*. Inspection of the cohort plots indicates slower and more variable performance in younger and mid-age children with DCD compared with TDC up to around 10 years of age, a pattern confirmed by significance tests (Tables 7 and 8). Consistent with a visual inspection of trends on the chronometric (AJMT*diff*) and kinematic (ToC_{diff}) measure of coupling – i.e., steady reduction on difference scores with age – a model comparison of polynomial trends showed that the best fitting growth curve was linear as indicated by *-2log likelihood* and BIC fit metrics. By late childhood, performance metrics for the DCD group were within the range observed for the TDC group. In particular, by 12 years of age, the time between TDC and DCD groups for AJMT*diff* (2 ms) was much closer than those seen in ToC_{diff} values (23 ms difference). These data support, in part, my interpretation that children with DCD require a more extended period of development to effectively couple online motor control and executive systems when completing anti-reach movements.

In terms of neural development, network connections between frontal and parietal systems that are necessary to support predictive and executive control and their coupling appears to require additional time to develop in DCD. This is consistent with some recent fMRI data showing hypoactivation along dorsal stream routes in children with DCD (Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009). Using a visually-guided tracking task that required high levels of predictive control, these authors showed under-activation in PPC and IPL in DCD as compared with controls. Structural MRI studies in ADHD (Sripada et al., 2014) and autism spectrum disorders (Travers et al., 2015) also show growth patterns that suggest developmental lags on cognitive and behavioural functions. For example, individuals with autism display a negative correlation between age and integrity of their white matter connections (for reviews see Dennis & Thompson, 2014; Travers et al., 2012). It is possible that similar lags in neural development may underpin the difficulties that younger and mid-aged children with DCD have in coupling online and executive control systems. By comparison, it appears that the motor difficulties experienced by the older children may not be a function of the ability to couple online motor and inhibitory control but rather something else related to this mechanism.

This raises the issue of what exactly does explain the persistence of clumsiness in older children with DCD. It may be the case that patterns of physical participation learned during earlier childhood are particularly hard to change; without adequate participation (viz learning experiences) there are obvious limits on the acquisition of skill. However, if the underlying control systems for motor prediction and coupling are emergent by older childhood, then one could argue that the motor system would be responsive to various forms of intensive training during this period. In the current study, the fact that older children with DCD showed similar *difference* scores to TDC does not suggest that ubiquitous functional coupling exists within this age group. In cases where older children with DCD do show poor coupling of control systems, a recent systematic review suggests that improving motor performance may be best addressed from task-oriented approaches (Smits-Engelsman et al., 2013).

5.4.3 Interactive Specialization is a Parsimonious Account of Behavioural Development

The pattern of performance on both key metrics for TDC reflects the time course over which different cortical zones unfold during child development. Developmental research shows that cognitive processes emerge over different time intervals, each with their own growth trajectory (Johnson, 2005). However, each emerging process may take some time to be integrated efficiently with existing processes, whether they are perceptual-motor or other. In the case of EF, behavioural changes are associated with an increase in density of the cortical structures tied closely to the prefrontal cortex (PFC). When the raw architecture of neural networks first emerge there tends to be an adjustment (or re-organisation) phase in which new skills are incorporated by the performer (Johnson, 2013). In the case of coupling motor and cognitive processes, efficiency is the result of a combination of neural growth and experience-dependent plasticity along fronto-parietal and other associated networks (Casey et al., 2008; Johnson, 2011). My growth curve modelling suggests that only by late childhood a high degree of efficiency is achieved in TDC, and that a period of re-organisation is needed during middle childhood. Diffusion tensor imaging studies (Collin & Van Den Heuvel, 2013; Tymofiyeva et al., 2013) also highlight the shift neural networks make from supporting proximally based regions to more expanded, distributed networks that are involved with specialised cognitive control. My work here shows that this broad model of neuro-behavioural development (i.e., *interactive specialization*) can be applied to cognitive-motor systems and their coupling, and points to its applications in other areas of behaviour where multiple systems are involved to enact increasingly complex skills. For example, examining patterns of development in kinematic markers necessary for fluid handwriting (Jolly & Gentaz, 2014; Jolly, Huron, & Gentaz, 2014). It is not surprising, then, to see non-linear changes in TDC with regards to performance on step-perturbation tasks; novel skills (i.e. engaging inhibitory control when online corrections are performed) are learned and incorporated into the motor system.

In terms of atypical development, the linear trends from the DCD group lend support to a delay in general growth patterns (Hyde & Wilson, 2013). A naive assumption here would be that children with online motor control deficits *should* eventually show age appropriate skills once the underlying systems emerge. However, simply leaving poor motor coordination untreated, certainly in the case of younger and mid-age children with DCD, should not suggest spontaneous acquisition of motor skills and the absence of intervention; research shows that untreated problems persist into adulthood (Cousins & Smyth, 2003; Kirby et al., 2011; Missiuna et al., 2007). The question here is what type of intervention (e.g., a combination of motor-cognitive approaches) is best suited when multiple systems may not be interacting as expected.

5.4.4 Limitations

No longitudinal study is immune from the threat of attrition. I acknowledge that using any type of value estimation (e.g. multiple imputations) may be advantageous in certain circumstances where missing data occur randomly, and in minimal proportions, to the overall date set (Graham, 2009). However, using such techniques on a large data set, particularly for developmental data where even simple behavioural measures can show large variance (Wilson et al., 2013), would likely provide estimated values that are inaccurate and could seriously undermine the validity of individual scores. In addition, a common threat to the internal validity of any study with recurring measurements is practice effects which have the potential to influence results As tracking maturational changes requires repeated assessment, it is possible participants become familiarised with assessment materials and procedures (i.e., items on the MAND and conditions of DJRT), thus improving their performance over successive measurement points. However, to minimise this threat, I counterbalanced conditions on the DJRT. While this may not completely resolve the issue of assessment familiarisation, future studies could use parallel versions of the test.

Finally, one of the assumptions about EF and its role to ROC is that other EF processes are sufficiently mature enough to support other behaviours. In future, it may be worth modelling other measures of EF (e.g., switching, update), while also testing for IQ levels (as I assumed all children were within normal range based on the school they were recruited from), and try to co-vary online control metrics in an effort to identify risk factors in children who have deficits across cognitive domains and help streamline interventions in goal-directed action and skill.

5.4.5 Conclusion

Modelling of this longitudinal dataset has extended my cross-sectional research and confirmed that the real-time coupling between online control and inhibitory systems follows an atypical pattern in DCD. For children without motor impairment, the pattern of performance on AJMT*diff* and ToC*diff* variables conformed to a quadratic growth curve, with evidence of re-organisation of the coupling around middle childhood. Conversely, children with DCD displayed a more protracted period of development across both measures, as noted from the linear trajectories. Interpreted from the perspective of *interactive specialization*, multiple networks appear to support the fine tuning of anti-jump performance across childhood for TDC while more time is required to integrate the function of control systems in children with DCD.

CHAPTER 6

GENERAL DISCUSSION

6.1 General Discussion

6.1.1 Overview

The aim of this thesis was to clarify how the expression of rapid online motor control (ROC) throughout the primary school period (6-12 years) was constrained by developing executive (inhibitory) systems, in both TDC and children with DCD. A double-jump reaching paradigm was used to examine the development of online motor control and the supporting process of predictive (internal) modelling. This account of motor behaviour is based on the assumption that a functional ROC system uses a predictive estimate of limb positon to correct movements as they unfold in real time. To achieve this aim, I conducted three studies: Study 1 (Chapter 3) used a cross-sectional approach to investigate the degree to which executive systems constrain the online control of reaching in typically developing children aged between 6 and 12 years. A key finding from this study was that middle childhood (around 8-9 years) marks a period of re-organisation in the coupling of control systems to perform more complex reaching movements (i.e., online corrections coupled with an inhibitory load).

In light of previous research which has shown that both online control and executive systems may be compromised in children with atypical motor skills (i.e., DCD), Study 2 (Chapter 4) implemented a cross-sectional comparison between TDC and children with DCD. The results of this study suggested that the ability to couple these two systems follows different developmental trajectories. Specifically, children with DCD were disadvantaged performing online corrections, and showed further problems with performance when an inhibitory load (*viz* anti-jump trials) was imposed. Importantly, this effect appeared to wane into older childhood. A key limitation of Study 1 and 2 was that both were cross-sectional, which placed limits on causal inferences that could made from the data. To address this limitation, a longitudinal investigation was conducted in Study 3 (Chapter 5) to assess how online and inhibitory control systems interact together over the course of child development. Using growth curve modelling techniques, longitudinal data showed a generalised delay in the growth trajectory describing the coupling of online and inhibitory control in children with DCD, unlike that of TDC who showed evidence of improvement during early childhood (6-9 years), followed by more refined performance into older childhood (10-12 years).

In this final chapter, I begin with a review of the three studies that investigated the development in children of coupling between ROC and inhibitory systems. I discuss the results of these studies in relation to recent empirical work in motor development and map the important theoretical contributions of this thesis to our understanding of how online and executive control systems interact in TDC and children with DCD. These findings are interpreted using a neuro-developmental framework and the theory of *interactive specialization* (IS; Johnson, 2011) which discusses the neuro-behavioural underpinnings of online control, EF and their coupling over the course of child development. I then consider the clinical implications of the findings of this thesis for children with impaired motor function (or DCD), who also manifest underlying issues of impaired predictive control, executive dysfunction, and their coupling. I conclude by discussing the limitations of this research and possible avenues for future research.

6.1.2 Summary of Studies

6.1.2.1 Study 1 - Cross-sectional investigation of rapid online control and inhibitory systems across typical child development. The primary school years are a time of marked improvement in a child’s ability to correct their reaching online. Current neuro-behavioural frameworks and the theory of *interactive specialization* (Johnson, 2005, 2011) highlight the role of co-occurring neuro-cognitive systems on behavioural development. The main tenet of this theory is that behaviour can be supported by a number of (initially) separable neural networks whose activity becomes more coordinated with time and experience. From this perspective, I was interested in determining how online control is constrained by the development of executive systems which is also known to undergo considerable maturation throughout childhood. Age-related differences in performance, across the 6-12 year span, were assessed on a DJRT. The main aims of Study 1 (Chapter 3) were to examine how children corrected their arm movement mid-flight during a step-perturbation paradigm (*viz* online control), and how increasing executive load might further constrain their response to a target shift.

Children were split into three age bands: younger (6-7 years), mid-age (8-9 years), or older (10-12 years) to investigate how the changing nature of online control is impacted by developing executive systems. Performance was compared as a function of trial type on the DJRT: non-jump, jump, and anti-jump trials. Experimentally, anti-jump trials represented the ability to inhibit an arm reach to an invalidly-cued yet compelling target while implementing a corrective movement mid-flight. I found that when demands for online control were low (non-jump), all children were able to perform simple aiming movements with good control. That is, similar movement times were found across the three age-groups and suggest that the ability to execute direct aiming movements is well developed by 6 years of age (Chicoine et al., 1992; Fuelscher, Williams, Enticott, & Hyde, 2015; Fuelscher, Williams, & Hyde, 2015). However, when online corrections were required for perturbation (jump) trials, younger children were notably slower to complete the movement and correct their reach compared with mid-age and older children; the latter two groups were not shown to differ. Importantly, when an inhibitory load was superimposed onto corrective actions (as per anti-jump trials), it was found that the performance of mid-aged children was compromised relative to the older group and, indeed, conformed to a pattern similar to that of younger children.

Results for the jump condition replicate previous work showing that the ability to correct movements online is inefficient during early childhood, yet improves substantially by middle childhood (Fuelscher, Williams, & Hyde, 2015; Wilson & Hyde, 2013). The fact that mid-aged children were able to implement online adjustments to jump trials as quickly as older children is evidence of a well-developing predictive control system by the age of 9 years. However, my research extends these earlier findings by showing that when an inhibitory (executive) load was superimposed on the act of completing online corrections (as per anti jump), the efficiency of corrective reaching in middle childhood was comparable to that of younger children. This suggests a non-linear pattern in the coupling of online control and inhibitory systems over childhood. The performance of children at middle childhood was affected to a greater extent than that of older children on anti-jump trials. This anti-jump reaching profile suggests that despite the rapid unfolding of executive systems during middle childhood, coupling between online and inhibitory control is poorly developed, and that the ability to integrate fronto-inhibitory and predictive control during action may require an extended period of development for more fluid and adaptive reaching. This study was one of the first to show age-related change in the relationship between motor control and executive systems in TDC. Study 2 extended this work to the examination of motor-cognitive relations in children with atypically developing motor skills where impaired ROC and inhibitory control have been shown independently in studies of DCD (e.g., Hyde & Wilson, 2011a, 2011b; Hyde & Wilson, 2013). Next, I used a cross-sectional study to assess online control in DCD on the DJRT and the conjoint effect of an added inhibitory load on their performance.

6.1.2.2 Study 2 - Performance of online corrections with inhibitory constraints in atypically developing children. This study (i.e., Chapter 4) used the same paradigm and method as Study 1 (Chapter 3). The focus, however, was to assess how children with DCD performed online corrections when an inhibitory load was superimposed on a double-jump paradigm. Based on previous research that has highlighted a deficit in predictive modelling (e.g., Hyde & Wilson, 2013), and a reduced ability to use inhibitory control across a range of tasks (e.g., Mandich et al., 2002), I expected to see a pronounced slowing of movement time and later corrections to reach trajectories on anti-jump trials, compounding the control issues seen on standard jump trials. The underlying theory supporting these predictions was that a reduced capacity to correct movements online (previously reported as poorer performance on jump trials) would be exacerbated when children with DCD were required to couple an already inefficient motor system with inhibitory control subserved by frontal networks. In other words, the ability to inhibit corrective movements towards a pre-potent stimulus and move to an alternate (uncued) target location (as per anti-jump trials) would be further compromised. Deficits in performance were predicted to manifest as larger MT difference scores between jump and anti-jump trials ($AJMT_{diff}$), and delayed time to correction.

Children were classified according to skill group based on their motor proficiency on the clinical motor test battery (i.e. MAND): either TDC or DCD. Additionally, children were included in the DCD group if their deficit of motor skills interfered with daily activities, were evidence by school age, and reported no previous neurological, developmental or physical condition. As per Study 1 (Chapter 3), children were also divided into three age bands (younger, mid-age, or older) to see how ROC and inhibitory control coupled across age.

Overall, results showed that movement times were similar between skill groups under simple task conditions (non-jump). For perturbation (jump) trials, the DCD group were significantly slower than controls and corrected reach trajectories later in the movement cycle. As expected, on anti-jump trials, the DCD group's performance was even more impaired when required to impose inhibitory control during online corrections. On $AJMT_{diff}$ (a key measure of coupling), the younger and mid-age DCD groups were significantly slower than healthy age-matched control children. Interestingly, however, the performance of the older DCD group was found to be similar to that of older control children.

These results replicate and extend earlier research comparing DCD and TDC on the double-jump paradigm (Hyde & Wilson, 2011a, 2011b). For children with DCD (specifically during younger and middle childhood) internal modelling deficits are suggested; problems exist in generating forward estimates of limb position and then using these estimates to update movement parameters in response to target shifts. Moreover, the requirement that inhibitory control be coupled to predictive online control exacerbates problems in goal-directed reaching. Intriguingly, this deficit appeared to dissipate with age as older children showed age-appropriate coupling performance on anti-jump trials. This result is in line with recent research that suggests that there may be developmental delay in the way children with DCD couple online control and inhibition (Hyde & Wilson, 2013). Like Study 1 (Chapter 3), Study 2 (Chapter 4) was limited by addressing indicative hypotheses; the cross-sectional design only provided general evidence of this relationship in TDC and DCD. Longitudinal data was required to better understand the coupling of these two systems and to provide a strong test of causal hypotheses about maturational trajectories in TDC and children with DCD.

6.1.2.3 Study 3 – Growth trajectories of online control and inhibitory systems.

Study 3 (Chapter 5) used a cohort sequential (longitudinal) design to model the coupling of inhibitory and online motor control over childhood. Based on age trends reported in Study 1 (Chapter 3), the growth pattern of TDC was predicted to show two distinct phases of development: rapid improvement up to 9 years, and following re-organisation around middle childhood, with more modest gains into later childhood. Conversely, for children with DCD, based on evidence that the coupling of online and executive systems is delayed (as per Study 2/Chapter 4), it was predicted that there would be a more protracted period of development as evidenced by a shallow, linear growth function over the 6 to 12 year-old period. Interpreted within the framework of IS, the working assumption for atypical development was that poor anti-jump performance of younger and mid-age children with DCD would reflect a maturational delay in coupling control systems. Using a cohort sequential design, TDC and DCD groups were divided into 13 age cohorts, each separated by six months. The DJRT was assessed at 6-month intervals over two years (five time points in total). The main measures of coupling inhibitory and online control were difference scores on key chronometric (anti-jump movement time difference; $AJMT_{diff}$) and kinematic (difference between ToC and ToC2; ToC_{diff}) variables.

Study 3 (Chapter 5) confirmed the predicted patterns of growth in Study 2: the coupling of online control and inhibitory systems follow different rates of development in TDC and children with DCD. Results showed that performance on the DJRT was slower in children with DCD relative to TDC. For the TDC group, model comparison using growth curve analysis revealed that a quadratic curve was the most appropriate fit. In other words, there was evidence of rapid improvement on anti-reach trials up until middle childhood (around 9-10 years of age), followed by a more gradual rate of development into late childhood and early adolescence. In contrast, for children with DCD, a linear function provided the best fit on the key metrics, with a slower rate of improvement than controls. From the perspective of IS, my data suggests that for TDC, the dorsal motor stream that support rapid online control is functioning well by middle childhood (8-9 years) but that its coupling to frontal inhibitory systems undergoes a period of re-organisation during this period. For children with DCD, the ability to integrate fronto-inhibitory and predictive control during action is less well developed generally, and appears to require a more extended period of growth. These group differences in growth curves are likely to reflect a maturational delay in the development of motor-cognitive networks in children with DCD which has important implications for diagnostics, prognosis and treatment.

6.1.3 Summary of Results from Studies 1, 2, and 3

In review of my three studies, it appears that the ability to couple online motor control with executive (inhibitory) systems on an anti-jump task develops differently for children with DCD compared with TDC. For TDC, this rate of improvement is rapid from early to middle childhood but appears to undergo re-organisation during middle childhood, followed by a continued but more gradual rate of improvement thereafter into older childhood. For children with DCD, there appears to be a developmental delay coupling motor systems with executive control; the re-organisation evident in TDC is not readily observed during middle childhood. However by late childhood, performance metrics (particularly AJMT_{diff} scores) for the DCD group were within the range for the TDC group, suggesting that the timescale over which the coupling occurs may be longer in DCD, and not approach levels of TDC until quite late in childhood. Put another way, deficits in the predictive (internal) modelling of movement are compounded in DCD when inhibitory demands are imposed on task performance; adequate solutions to this control problem are not apparent until late childhood, despite lingering issues in motor skill development per se. From a neuro-computational perspective, the problems that children with DCD showed on the anti-jump condition of the DJRT may be caused by maturational delays in neural networks connecting frontal and posterior parietal regions and parieto-cerebellar circuits. In the forthcoming section, I discuss my findings in relation to existing research on motor control in children with DCD, and the broader implications for goal-directed action and skill.

6.2 Theoretical Implications for Coupling Behaviour of Online Control and Inhibition

My set of studies is part a larger program of work designed to better understand the development of motor control and cognition in children with and without DCD. Results from this thesis offer important insights for understanding the development of ROC and EF across typical development and in DCD. The framework of *interactive specialization* (Johnson, 2005, 2011; Johnson, 2013) provides a parsimonious way to explain the performance patterns observed in normative and atypical motor development, which are discussed in turn in the following section.

6.2.1 Rapid Online Control and Executive Function in Typical Development

The results from my studies have suggested key transitions occur in the coupling of motor control and inhibitory systems across childhood. This conclusion is drawn from several lines of evidence. First, in Study 1 (Chapter 3), younger children were disadvantaged by jump trials, with slower MT and ToC than mid-age and older children, while no difference was found between the two latter groups. This age-related trend is in line with a recent developmental study of ROC (Wilson & Hyde, 2013) The reduced ability of the younger group to move and correct their reach when a visual target was displaced at movement onset (i.e., jump trials) suggests that the predictive modelling system is still emerging at this age. My data is also consistent with previous research suggesting that the efficiency and flexibility of reaching movements improves rapidly after approximately 8 years of age (Bard et al., 1990; Chicoine et al., 1992; Ferrell, Bard, & Fleury, 2001; Hay, 1979; Pellizzer & Hauert, 1996). The reduced ability of the younger group to move and correct their reach when a visual target was displaced at movement onset (i.e., jump trials) suggests that the predictive modelling system is still emerging at this age. A predictive (forward) model uses a copy of the motor command to predict the sensory consequences of an action. Fast internal feedback loops process discrepancies between the intended movement plan and real-time sensory information, generating online corrections (Wilson & Hyde, 2013). The performance of mid-age and older children suggests that predictive modelling is quite well developed, while refinement of the coupling of online and inhibitory control was a more complex proposition for mid-age and younger children.

The ability to couple online motor and inhibitory control on anti-jump trials was operationalised using chronometric (MT, $AJMT_{diff}$) and kinematic (ToC) variables. For kinematic markers, there were two corrective phases: (1) a fast automatic correction that draws the hand (Cameron et al., 2009) toward the visual cue yet incorrect target (ToC) followed by a deliberate re-direction of the hand to a contralateral location. The second correction (ToC2) measures the ability of children to purposefully engage (frontal) inhibitory control to prevent the hand touching the compelling but invalid stimulus—effectively frontal inhibitory systems putting the brakes on the auto-pilot of the fast dorsal stream. In computational terms, ToC represents the point in reaching where feedforward and feedback signals (*viz* internal modelling) are received by the plant to update the motor command in order to correct the reach trajectory (Desmurget & Grafton, 2003; Sarlegna & Mutha, 2014), while ToC2 signals the successful integration and implementation of (top down) inhibitory control, over-riding the auto-pilot.

As per jump trials, younger children were further disadvantaged by the added inhibitory load when completing anti-jump trials; MT, ToC, ToC2, and AMT*diff* (the movement time difference going from non-jump and anti-jump trials) were all found to be significantly larger in younger children compared with the mid-age and older groups. In turn, however, AMT*diff* was significantly longer for mid-age children compared with the older group. Additionally, inspection of MT plots (presented in Chapter 3) confirmed that movement times of the mid-age group were slower than older children and approached those of younger children. In sum, data from Study 1 (Chapter 3) suggests that the change in performance of mid-age children on anti-jump trials represents inefficiencies implementing online control when inhibitory constraints are imposed. That is, while predictive control mechanisms enable a reasonable degree of proficiency on standard jump trials (where demands on EF are minimal), an increase in inhibitory load may reduce the capacity of predictive control. This indicates that coupling of motor and executive control processes undergo a period of re-organisation during middle childhood, ultimately supporting the ability to learn more complex movements.

The third line of evidence supporting non-linear changes in coupling of motor and executive development in TDC is taken from Study 3 (Chapter 5). The longitudinal design provided repeated data points (5 time points over 2 years) to examine the development of online control and its coupling to inhibitory function. Key measures of coupling ($AJMT_{diff}$ and ToC_{diff}) were analysed using advanced growth curve modelling techniques. Results showed that the best fitting curve solution (on both metrics) for TDC was a quadratic trend. A comparison of fit statistics (i.e., BIC and *-2log likelihood*) revealed the lowest estimates for quadratic functions compared with linear and cubic. Inspection of the cohort plots showed greater variability in the anti-jump performance of children in the 6 to 10 year range, followed by tighter clustering after this period. The (quadratic) curve trends from Study 3 shows consistency with the pattern of results from Study 1: anti-reach performance improved rapidly up until approximately 9 years of age followed by more gradual improvement thereafter into later childhood. Taken together, the imposition of an inhibitory load precipitated a decline in the anti-reach performance of mid-aged children relative to older children. For tasks of higher planning complexity, greater integration between control systems is required; to achieve this, children need a longer period of maturation and development than that required for simple goal-directed action.

6.2.1.1 Neural networks of control systems. The neuro-developmental literature suggests that better efficiency of information transfer (e.g., quicker reaction time, reduced errors) occurs between the ages of 6 and 12 years; the same developmental time whereby cognitive control becomes more refined (Diamond, 2013). For instance, Barnea-Goraly and colleagues (2005) used diffusion tensor imaging magnetic resonance imaging (MRI) to measure white matter organisation (indexed by fractional anisotropy; FA) in a sample of 34 children aged 6-19 years. The results showed that FA values of the PFC, ventral visual pathways, and corpus callosum, were positively correlated with age. This study revealed that white matter network (WMN) changes occurred in regions which play an important role in motor and cognitive behaviour. In particular, throughout the course of early and middle childhood, the development of the PFC is unfolding rapidly. And, we know that successful performance on more difficult tasks that also require a degree of self-monitoring is dependent on the integrity of frontal networks and the EF processes they support (Johnson, 2013). That is, proficiency is reached according to level of skill and cognitive maturity. When combined, they enable more complex goal-directed sequences (like anti-jump reaching movements) (Luciana, Conklin, Hooper, & Yarger, 2005; Luciana & Nelson, 1998).

The emerging field of *Growth Connectomics* (GC) provides some important theoretical and empirical insights into the nature of motor and cognitive development, which informs the interpretation of results presented here. Growth connectomics provides a framework for a range of neuro-imaging techniques that investigate relationships between emerging neural networks and associated behaviours: cognitive, motor, affective and other (Ve´rtes & Bullmore, 2014). The theory of GC has only recently been applied to children’s brain development and is akin to that of IS: they both seek to understand brain-function relationships by exploring interconnected neural systems rather than focus on isolated brain regions (Fornito & Bullmore, 2014). Across childhood, neural networks operate within the general confines of their respective local regions, but begin to shift outward from centralised hubs with maturation. With time and experience WMNs graduate from site specific regions to a distributed topology of networks, primed to support more adaptive cognitive control (e.g., inhibition, attention, working memory). During this time, WMNs are subjected to increased production and selective pruning of synaptic connections (Durston et al., 2006), linking the modules of the connectome together as they begin to support other neural regions. Key changes to the structure and organisation of WMNs are seen to take root during late childhood, with more refined shaping of these areas during early adolescence (Chen et al., 2013). More specifically, fronto-parietal WMNs have been linked to improvements in efficiency of EF during later childhood (Chen et al., 2013) and, likely, the coupling of cognitive and motor systems.

In terms of the growth patterns that I observed for TDC in Study 3 (Chapter 5), a likely hypothesis is that coupling between action and cognitive systems is an important developmental achievement during later childhood. We also know that premotor and primary motor cortices reach peak rates of synaptic proliferation and density in early childhood, before later maturation of association cortices (especially parietal and frontal areas) (Casey et al., 2005). Efficient coupling of online control to EF is underpinned by emerging connections between fast (visuomotor) dorsal stream channels and the PFC-parietal network (Pisella et al., 2006). The different timescales of emerging networks (e.g., basic visuomotor channels and EF networks) may explain some of the variability in coupling that was observed on the DJRT in my studies. This argument is explored further in the following section which also posits a unifying theory of neuro-behavioural development in TDC with respect to the control of action.

6.2.1.2 Interactive specialization can account for non-linear behavioural growth.

As argued in Chapters 1, 3, 4, and 5, classical maturational theories of development have suggested a modular account of brain-behaviour relationships. Such theories are being superseded by more interactive models of brain function and behavioural development. An alternative neuro-developmental framework known as *interactive specialization* (Johnson,

2011) can readily account for emerging cognitive systems and their influence on the expression of ROC across childhood. The IS framework is being adopted more widely to explain developmental changes in reading (Dekker, Mareschal, Johnson, & Sereno, 2014), creative thinking (Stevenson, Kleibeuker, de Dreu, & Crone, 2014), and social interaction (Moriguchi, 2014), amongst others. To recap, the main premise of IS suggests that specific neural regions, each with its own maturational timeline, can influence and support the rise of behaviour attributed to other cortical regions. Development of cognitive control and adaptive behaviour more generally is seen as the result of multiple, interactive neural networks that emerge in overlapping timescales (Johnson, 2013). This interaction across the central nervous system serves to support thinking and action, particularly in critical times of child neuro-development (Johnson, 2011)

Data from this thesis, showing non-linear profiles of reaching behaviour on the DJRT (i.e., for jump and anti-jump trials), can be interpreted using the IS framework. Recent developmental research (Wilson & Hyde, 2013) suggests that simple online corrections during reaching can be performed by younger and (6-7 years) and mid-age children (8-9 years), but the more sophisticated and flexible control required of complex task performance under higher cognitive demands require a more mature motor system, as seen in older children. Processes of EF (e.g., working memory, inhibition, executive attention) tend to emerge and develop in a comparable manner to ROC, albeit on slightly adjacent growth timescales. For example, the ability to inhibit the Simon effect is difficult for young children (4-6 years), matures rapidly over childhood, and approaches adult levels of functioning around 12-13 years (Davidson, Amso, Anderson, & Diamond, 2006).

Behavioural changes to EF are mirrored by rapid growth of structures and networks associated with the PFC (Pangelinan et al., 2011). However, maturing control systems may take time before they can support each other in flexible behaviour. The quadratic growth trends found on key coupling metrics (from Chapter 5 data) of the DJRT suggest that a key transition appears to occur around 9-10 years with the integration of two emerging processes, one (ROC) more primitive than the other (EF) but still overlapping in developmental time. The integration of these two systems sees a change in growth curve and it is not until late childhood that we find a higher degree of coupling efficiency is achieved in TDC. Maturational processes supporting this transition can be seen in imaging studies that show neural networks extend beyond their initial proximal based regions to wider, topological systems involved with refined cognitive control (Collin & Van Den Heuvel, 2013; Tymofiyeva et al., 2013). Thus, the broad model of *interactive specialization* can be used to explain the non-linear coupling trends seen in TDC on the DJRT; more complex skills (i.e., anti-jump movements) may require a period of learning and consolidation before they can be performed with a reasonable degree of efficiency.

6.2.1.3 Summary. The unfolding of ROC over childhood and its relationship to executive control is a new line of investigation in children's motor development. Cross-sectional and longitudinal data presented in this thesis have shown age-related differences on the DJRT. For simple target-directed reaches, all children showed a similar degree of proficiency. For reaching performed under visual perturbation, there is rapid improvement in online corrections between 6 and 9 years of age. However, when an inhibitory component is added to the perturbation task, the performance of mid-aged children was reduced relative to the older group and became more like that of younger children.

Online control during double-jump reaching can be enlisted efficiently in children as young as 9 years, and is believed to be subserved by fast visuomotor channels of the dorsal stream comprising motor and parietal cortices (Reichenbach et al., 2014). For mid-age children, reaching performance was compromised on anti-jump trials relative to older children (as per Study 1/Chapter 3 results), while non-linear (i.e., quadratic) growth trends observed in Study 3 (Chapter 5) suggest re-organisation in the coupling over middle childhood. However for children with DCD, results suggest that the expression of online control and its integration with inhibitory control is delayed. This issue is the focus of discussion in the section below.

6.2.2 Online Control, Executive Function and their Coupling are Delayed in Children with Developmental Coordination Disorder

In Chapter 1 I described the diagnosis, presentation and associated problems of children with DCD. Dysfunction in the process of predictive internal modelling (or IMD hypothesis) was shown to be a viable model to account for the motor coordination problems of these children (Hyde & Wilson, 2011b; Wilson et al., 2013). A key argument under this hypothesis is that children with DCD have difficulty generating or using internal models of action as a basis for motor control and learning—e.g., enlisting forward estimates of limb position as a means of online motor control in the face of unexpected or sudden perturbations (Wilson & Butson, 2007). Evidence to support the IMD hypothesis is drawn from a range of experimental paradigms. Covert orienting of visuospatial attention, motor imagery, and anticipatory postural control, and coupling of grip and load force are examples of research that have implicated impaired predictive control as an underlying cause of DCD (either directly or indirectly) (Adams et al., 2014). In addition, the development of co-occurring problems in executive functions (like inhibition) may further constrain the expression of ROC in DCD. I theorised that deficit of EF in DCD would exacerbate the online control difficulties—i.e., coupling these mechanisms to achieve higher levels of action control would be compromised. In the following section, I discuss evidence from my thesis that supports this broad hypothesis.

Results from Study 2 (Chapter 4) are consistent with recent research on ROC from Hyde and Wilson (2011a, 2011b, 2013). This body of works suggests that the ability to use predictive models to update online corrective movements is impaired in DCD. A consistent finding across these studies is that children with DCD take longer to complete perturbation trials and show delayed corrections to reach when a visual target is displaced to a lateral location. Using a neurocomputational approach and the theory of *interactive specialization*, I designed a series of studies that extend this line of enquiry by examining how ROC is constrained by a concurrent load on EF (or frontal executive systems).

To recap, internal modelling theory posits that prior to the initiation of goal-directed reaching, visual and proprioceptive signals are used to estimate the initial state of the limb while visual coordinates estimate the prospective target location (Desmurget & Grafton, 2000). The central nervous system uses this information to generate a motor command to achieve the desired end-state. At movement onset, a corollary burst encodes an (efference) copy of this command which is used by the predictive model to anticipate how the movement will unfold in relation to the target location and its expected sensory consequences (Desmurget & Grafton, 2003). A functional loop between the parietal lobe and cerebellum is suggested to be involved in monitoring and comparing these forward estimates of limb position with the real-time sensory outcomes of movement (Herzfeld & Shadmehr, 2013; Shadmehr et al., 2010). In the case of discrepancy, an error signal is generated and used to update the on-going motor command. Online corrections to movement are implemented by comparing a dynamic error signal onto the ongoing feedforward motor command. This process is vital to maintain the integrity of the unfolding movement since the position of the moving limb can change considerably by the time sensory signals have been encoded and used to correct the ongoing motor command (Adams et al., 2014; Sarlegna & Mutha, 2014).

In the case of performance on a double-jump task, a forward (predictive) model of the limb-target relationship is compared to the sensory consequences throughout the reaching cycle. The unexpected target displacement results in dissonance between the expected and actual outcome of movement. Successful online correction of reaching trajectory towards the newly defined target is dependent on the resultant error signal being integrated effectively with the unfolding feedforward motor command (Hyde & Wilson, 2011a). Disruptions to this process manifest as slower movements and inefficient correction of reaching trajectory towards the updated target. When inhibitory control is added to online corrective movements (as per anti-jump trials), the performer must purposefully interrupt the action (which shows as an automatic correction toward the salient cue on the DJRT) and exert top-down control to redirect movement towards the hemi-space contralateral to that of the cued target. Any pre-existing deficits (as found in DCD research) associated with either the ability to engage predictive control or utilise executive function (or both) would compound the problem of control, expressed as even slower movements and reach trajectories than what would be expected on traditional perturbation trials.

In Study 2 (Chapter 4), when children with DCD were assessed on a standard jump condition on the DJRT, results showed the DCD group to be slower to correct reach trajectory and complete movements. This supports the weight of evidence that shows that children with DCD have difficulties using predictive estimates of limb position to update corrective movements to reaching patterns (Hyde & Wilson, 2011a, 2011b, 2013). Superimposing an inhibitory constraint on the modified reaching task exacerbated the deficits seen in online control among children with DCD; however, this deficit appeared to reduce with age. The cross-sectional data showed that younger and mid-age children with DCD were compromised on anti-jump trials relative to age-matched control counterparts. This was reflected in larger $AJMT_{diff}$ scores which showed significant differences between the younger and mid-age groups. However, the performance of older children with DCD was within the 95% CI of older TDC (with small effect size).

The modelling results of Study 3 (Chapter 5) extended those of Study 2 (Chapter 4). Unlike TDC who showed fast, non-linear growth between 6-9 years on anti-jump trials, growth curve trends confirmed cross-sectional developmental patterns from Study 2: it is likely that a developmental delay is present coupling of motor-cognitive systems in children with DCD. This is consistent with other cross-sectional comparisons in DCD where older children were compared to younger controls and shown not to differ for online motor performance (e.g., Hyde & Wilson, 2013), and in cognate disorders (i.e., ADHD) where morphological evidence shows a 'maturational lag' in connectivity of fronto-parietal and ventral attention networks (Sripada et al., 2014), regions that are implicated with motor and cognitive control respectively (Vossel, Geng, & Fink, 2014). Additionally, fit metrics showed that the growth trajectory on measures of coupling (between online and inhibitory systems) was linear, and that these children performed slower than TDC at every point across the 6-12 year age span, even though the difference between groups by 12 years of age was negligible. The reason for this comparable performance between TDC and DCD groups by older childhood is not fully clear; however, the neural structures and function that have been implicated in atypical motor development offer important insights for theory in DCD, which are explored next.

6.2.2.1 Neural correlates of impaired motor performance in children with DCD.

At present, there are only a limited number of neuroimaging and neurophysiological investigations of neural substrates of DCD. A recent experiment relevant to predictive modelling used task-related fMRI to map brain activation. The team of Kashiwagi and colleagues (2009) tested children with and without DCD on a visuomotor task where children followed a target on a computerised screen using a joystick. To complete the task with a reasonable degree of accuracy (i.e., low number of errors), a level of predictive control was required to estimate the direction of the target which travelled along a repeating path.

Comparison of the activation maps showed that the DCD group displayed less activity in the left PPC and left post central gyrus than control children. Kashiwagi and colleagues (2009) interpreted this pattern in DCD as reflecting poor internal modelling. The PPC is suggested to be a critical site associated with predictive motor control (Desmurget & Sirigu, 2009; Shadmehr & Krakauer, 2008) and is strongly activated during target-directed reaching movements (Reichenbach et al., 2011; Reichenbach et al., 2014).

In another fMRI study, Zwicker, Missiuna, Harris, and Boyd (2011) compared motor learning performance between a small group of DCD and control children using a line tracing task. With reduction in number of errors that occurred over the learning cycle (from the first learning block to retention), reduced activation in cerebellar–parietal and cerebellar–prefrontal axes was observed in the DCD group. However, the task assessed visuo-spatial learning rather than predictive modelling directly; hence, inferences made about neural regions of impaired predictive control are limited.

More recently, the structure of WMNs was investigated by Zwicker, Missiuna, Harris, and Boyd (2012a) using diffusion tensor imaging (DTI). Structural connectivity within motor, sensory and cerebellar networks was compared between a group of seven children with DCD and nine TDC. Results showed that fractional anisotropy values (a measure of connectivity in the brain) in regions such as the corticospinal tract and posterior thalamic radiation were significantly lower in children with DCD. Moreover, axial diffusivity in these regions correlated with motor severity on the MABC. In other words, children who showed greater impairment on a standardised motor test also demonstrated reduced axial diffusivity in the sensorimotor tracts.

While Zwicker and associates did not examine directly the neural underpinnings of predictive control, Zwicker and Holfelder (2013) pose three key assertions that should be considered when conducting further neuro-behavioural studies of children with DCD: (1)

different brain regions are activated during motor task performance in children with DCD; (2) there may be under activation in neural regions linked to motor learning; and (3) children with DCD demonstrate microstructural differences of key motor and sensory pathways. That said, abnormal neural growth in children with DCD alone may not be the most valid nor parsimonious explanation of age-related differences of anti-jump performance, especially when older children with DCD may demonstrate age-appropriate coupling behaviour. As well, it remains unclear whether reduced exposure to motor activities and opportunities for skill learning explains the reported differences in microstructure.

Without use of comparable and valid tasks to assess predictive control, we are left with the question of what mechanism best explains the poor performance of younger and mid-age children with DCD on the anti-jump task. One possibility is that a generalised delay exists in the coupling of frontal and posterior networks. Evidence can be drawn from the field of *growth connectomics* where a growing body of research suggests that the physiology of the brain is organised by large neural networks, and that connections between these regions display specific growth patterns (Ve´rtes & Bullmore, 2014). Reference to related neurodevelopmental conditions offers some insight into the delay hypothesis. For example, resting state scans of children with ADHD reveal a generalised delay in the connections of the large-scale brain networks (e.g., cerebellum) between fronto-parietal systems (Sripada et al., 2014), the same regions that I argue subserve motor and cognitive processes used for the DJRT. In longitudinal research of children with autism spectrum disorders, evidence indicates that WMNs – regions that support cognition and motor behaviour – also show delayed growth development in children 10 years and younger (Travers et al., 2015). Furthermore, it has been found that posterior brain structures such as the cerebellum project to the PFC (Balsters et al., 2013). Again, these neural networks are considered important to cognitive control of motor flexibility (Johnson, 2005) and may subserve the processes required for efficient coupling performance.

6.2.2.2 Summary. Data from Study 3 (Chapter 5) showed that linear trends were the best fitting growth curves of key measures of coupling behaviour in children with DCD. These results are best interpreted in terms of a generalised neurodevelopmental delay, possibly linked to immaturities of WMNs along fronto-parietal and parietal-cerebellar channels (Casey et al., 2008; Chen et al., 2013). This is consistent with the hypothesis proposed from Hyde and Wilson (2013) who inferred growth delay (in predictive control mechanisms) by comparing the performance of children with DCD with that of TDC and healthy adults. Adults were assessed to provide a model or reference point for mature predictive control. However, they made no specific inferences about the interaction of brain systems that support predictive online control. A strength of my thesis has been use of a supporting theoretical framework (i.e., *interactive specialization*) that posits dynamic relationships between brain systems. This is supported by recent morphological evidence from other developmental disorders (e.g. ADHD and autism) that has shown connectivity of WMNs of key motor and cognitive cortices occurs later in childhood. In conjunction with longitudinal data (from Study 3/Chapter 5), which has permitted stronger casual inferences to be made, it seems that that a maturational delay may underlie a vast number of children who have motor control problems. This conclusion has important implications for treatment which is discussed next.

6.3 Clinical Implications for Treating Deficits of Multiple Control Systems

The hypothesis for a maturational delay in coupling of motor and cognitive systems has implications for remediation; these are considered in the forthcoming section. As previously argued, children with DCD have deficits of predictive control and EF. A pertinent issue is how to treat these problems of these systems when they are both enlisted for complex action. In the discussion of intervention research below, I examine the efficacy of a method that may be useful to treat predictive modelling (i.e., motor imagery). I also examine how several cognitive intervention programmes (e.g., Neuromotor Training Tasks and Cognitive Orientation to daily Occupation Performance) may alleviate motor difficulties in children with DCD. These approaches focus on goal orientation and problem solving (or top-down control) where there is a strong need for EF (Smits-Engelsman et al., 2013). The linear trends from the DCD group reflect a delay in growth patterns which suggests that approximately half of children with atypical motor development should eventually show age appropriate skills (although at what point exactly is unclear), while remaining children do not unless treated (Sugden & Wade, 2013; Wilson, 2005). However, this rests on an assumption that children with motor impairments belong to a homogenous group, which is at odds with the general consensus of the DCD research community (Blank et al., 2012; Cairney, 2015; Green, Chambers, & Sugden, 2008; Pieters, Roeyers, Rosseel, Van Waelvelde, & Desoete, 2015; Vaivre-Douret, 2014; Wilson, 2005; Zhu et al., 2014).

Simply leaving children's atypical motor development to unfold (and hopefully 'course correct') without remediation may do little to remedy the motor difficulties that often continue into adolescence and adulthood (Kirby et al., 2011; Missiuna et al., 2007). Indeed, some of the motor control issues observed in children have also been shown to be present in adults with DCD. By way of illustration, Wilmut and Byrne (2014) tested performance on a grip-selection task that measured end-state-comfort: an effect where a starting uncomfortable body position is chosen if the final state is more comfortable (Noten et al., 2014). For the task, participants rotated a disc with pointer attached to it in order to execute a sequence of turns across a number of targets. Not only did children with DCD begin with more comfortable grips, despite leading to awkward end state positions, adults with DCD displayed a similar pattern for more difficult movement sequences.

When considering these results together with other research that suggests children with DCD tend to adopt sedentary lifestyles (Poulsen, Ziviani, Cuskelly, & Smith, 2007; Poulsen, Ziviani, Johnson, & Cuskelly, 2008), it could be that the lack of physical activity and opportunity to engage in new motor behaviour places limits on the acquisition of appropriate motor control mechanisms as well as the attendant movement skills. Consequently, there is a strong case to intervene and treat the immature (or undeveloped) motor system. But how can we streamline remediation when multiple systems may be compromised? To address this, I first review evidence for treating predictive modelling. I pose intervention that treats EF and consider the integration of motor and cognitive approaches together is an appropriate way forward for future intervention strategies.

6.3.1 Intervention for Impaired Predictive Control

Presently, there is limited intervention research aimed at addressing poor predictive modelling systems in children with DCD, but what evidence is available suggests a role for strategies that train motor planning and prediction. Use of motor imagery (MI) training, administered via interactive DVDs, has shown to be as effective as a traditional physical therapy method (Wilson, Thomas, & Maruff, 2002). The goal of the study was to test proposed deficits with forward modelling using MI as a general therapeutic framework. Motor impairment was defined rather loosely by a score under the 50th percentile on a standardised motor test (i.e., MABC), a criterion that is well above the minimum cut-point of 15th percentile that research guidelines recommend (Blank et al., 2012; Geuze et al., 2001; Williams, 2006). Results showed that both intervention groups (i.e., MI and physical therapy) improved their level of coordination. Importantly, it was observed that children with more severe DCD improved the most as a result of the MI training. We also know that motor severity plays an important role in response to cognitive intervention (Green et al., 2008), and may also relevant to MI. For example, Williams and colleagues (2008) found that children who scored below the 5th percentile on the MABC were less responsive to verbal MI instruction. Given that the mode of delivery from Wilson and colleagues (2002) relied more of visuo-motor channels of processing, the reduced response to verbal instruction in Williams and colleague's (2008) study suggests that there may be sub-groups within DCD that respond differently to a certain form of instruction.

This is a reminder of the need to subject interventions to further rigorous scientific validation; individual variability within clinical populations can highlight the need for qualitative differences in the structure of a programme. In the case of MI training, there are other therapeutic issues that should be considered. Adult and patient MI data shows that the effect of improved motor skills performance from intervention is heightened when alternate forms of therapy (e.g., physical activity) are performed along with MI training (Malouin & Richards, 2010; Schack, Essig, Frank, & Koester, 2014). For example, a group study of adults with Parkinson's disease showed that patients who received one hour of combined physical and mental practice performing balance tasks over 12 weeks improved more than a group who received only physical therapy (Tamir, Dickstein, & Huberman, 2007). Thus, for impaired predicate control in children with DCD, MI training should be an adjunct with traditional physical therapies.

The design and implementation of an intervention is important on a number of fronts. As with actual motor rehabilitation, learning should unfold in a staged manner, beginning with simple MI tasks before progressing to more complex ones (Kalicinski, Kempe, & Bock, 2015). This is relevant for children with DCD where more difficult motor behaviour is related to increased MI complexity. As per the younger and mid-age DCD group anti-jump profiles (from Study 2 and 3/Chapters 4 and 5), motor performance also declined with the imposition of higher EF demands. Breaking down learning tasks into its constituent parts is one way to reduce demands on memory, attention, inhibition, etc.

Another possibility is to integrate observational learning with imagery, whether it be use of video models (similar to the DVD intervention mentioned above), performer demonstration or otherwise, and stimulate the mirror system which appears to be a critical network of predictive modelling (Hyde et al., 2013; Wilson et al., 2002). However, as discussed earlier in this chapter and chapter 1, an impairment of predictive modelling is likely to have an impact on a child with DCD, affecting their ability to utilise traditional observational learning techniques. For instance, an individual generates an internal representation of an observed action so that it can be projected to their own motor system (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005). A deficit in the ability to represent movements internally may likely limit the benefits of observational learning. This is certainly relevant to children with DCD as it has been suggested that these children do not learn through observation in the way that a typically developing child would (Cairney, 2015; Larkin & Hoare, 1991). How then, can we remediate the learning experience of children with DCD?

One way would be to modify aspects of observational learning; scaffold tasks so that a movement is shown from different perspectives. For example, demonstration of a throwing action could be shown from certain angles, and from first and/or third person perspectives, similar to the approach used by Wilson and colleagues (2002). In their intervention study, Wilson and colleagues (2002) used videotapes to train balance and ball skills of children with motor difficulties by displaying videos of an internal and external frame of reference of the action. These observational models, when combined with mental rehearsal, were as successful at reinforcing motor learning as traditional perceptuo-motor training. Another alternative might be for health professionals to adopt a kinaesthetic approach to teaching motor skills; children with DCD might need to be guided in their movements, initially by somebody standing close to them. For example, when learning to reach for an object from a table, the clinician might hold the child's hand and guide them through the action. In this way, the therapist can shape the movement for the child, reinforcing the kinaesthetic components of the movement, instead of relying on inaccurate internal representation. In addition to skills acquisition, the interval between sessions should be short enough to prevent participants from forgetting tasks. For children with DCD, repeated performance over small intervals (and more frequent trials) can lead to a greater acquisition of a skilled task (like catching a ball) (Utley & Astill, 2007). Some researchers also recommend between 15-20 minutes per session is optimal time for learning and practice to consolidate and to avoid problems with fatigue (Dickstein & Deutsch, 2007). Conversely, intervals between training sessions should be long enough to allow for skills to consolidate but not too long that excessive task repetition may leave individuals feeling disengaged and/or fatigued. Research has shown that adequate rest periods between sessions can facilitate improved learning (Magill, 2010). For example, recent DCD intervention studies that were conducted on a weekly basis over a 6-8 week period have shown positive outcomes in balance control (De Milander, Du Plessis, & Du Randt, 2014; Jelsma, Geuze, Mombarg, & Smits-Engelsman, 2014). However, variation within motor severity may require researchers to adjust session duration and frequency so that they meet the needs of the child more directly.

Accordingly, preliminary evidence supports the use of MI training as an effective intervention tool for deficits of predictive modeling (and motor skill more broadly) in children with DCD. Certainly, further research is needed to focus on procedural aspects of MI training so that treatment outcomes can be maximised and tailored to sub-types that may respond differently according to the mode of task instructions (like visual or verbal). Differences in motor severity may also be a factor in the way children with DCD respond to intervention. Delivery, length and frequency of content are all issues that should be considered as a 'one size fits all' approach may not accommodate the range of motor deficits seen in DCD. Furthermore, the heterogeneous expression of DCD symptoms suggests that some children may not experience behavioural problems of predictive control. This raises the possibility of pre-screening for deficits in prediction, and tailoring intervention accordingly. Certainly, data from Study 2 and 3 (Chapters 4 and 5) data suggest that there is age-appropriate coupling in older children with DCD. It might be that intervention methods other than MI training are better suited to remediate poor predictive control. Continued research will hopefully shed light on these matters.

6.3.2 Top-down Approaches to Therapy

As discussed in Chapter 1, intervention studies can be categorised into two main areas of research: *process-oriented* and *task-oriented*. Process-oriented (or bottom up) approaches intervene with motor difficulties by targeting the underlying processes required for action. Prior to the mid-90s, traditional process-oriented approaches to motor intervention worked under the assumption that remediating underlying mechanism of motor dysfunction would lead to an improvement in associated skills (Mandich, Polatajko, Macnab, & Miller, 2001). However, success of these interventions like sensory integration training and kinaesthetic training has been limited; evidence from reviews shows little change to functional motor outcomes (Forsyth, Maciver, Howden, Owen, & Shepherd, 2008; Hillier, 2007; Smits-Engelsman et al., 2013). Alternate treatments to motor control (e.g., Thelen, 1995), incorporate task-oriented approaches on the acquisition of skill which also acknowledge task and environmental constraints involved with movement. In recent years, these approaches have been developed so that they are contextually based (in terms of relevance to the child), related to everyday activities, and specific to the needs of the individual engaged in therapy (Missiuna, Polatajko, & Pollock, 2015). These approaches are quite top-down in their orientation, but also based on key motor learning principles (Shumway-Cook & Woollacott, 2011). When task-oriented approaches to intervention is considered in the context of my research, there may be cognitive strategies that will help break down performance (e.g., on anti-jump trials) into simpler components so that better coupling of online and inhibitory control might ensue. Put another way, what might be an effective way to train executive function so that intervention effects translate to better coupling performance on anti-jump trials DJRT?

There is evidence to suggest that children with DCD may benefit from targeted skills training. One body of work that teaches basic principles of motor learning is Neuromotor Training Task (NTT), developed and empirically tested by Smits-Engelsman and associates (Ferguson et al., 2013; Niemeijer, Schoemaker, & Smits-Engelsman, 2006; Niemeijer et al., 2007; Schoemaker, Niemeijer, Reynders, & Smits-Engelsman, 2003). In NTT the emphasis is put on the role that cognitions play in learning (or refining) new movement skills. Complex tasks are broken down into simple skills so that the child can experience success more readily in an environment that is primed for learning and development. Reducing complex movements in this way would benefit the younger and mid-age children with DCD from my studies who showed problems using online control on standard jump trials which were further compounded with the inhibitory demands of anti-jump trials.

In a recent study by Ferguson and colleagues (2013), efficacy of two task-oriented programmes was compared: NTT and a Nintendo Wii Fit Intervention. Outcome measures were motor performance, isometric strength and cardiorespiratory fitness. Children who fell below the 15th percentile of the MABC-2 were allocated to NTT (*n* = 37) or Wii Fit training (*n* = 19) groups. The NTT was administered 2 sessions per week over 9 weeks while Wii Fit training was conducted for 3 sessions per week for 6 weeks. Both intervention groups demonstrated better motor performance over the duration of the programmes but NTT showed greater improvement in measurements of motor performance, functional strength and cardiorespiratory fitness. However, transfer tests (to see if training effects extended into other areas such as home and school) were not administered. These measurements are important because they can inform about the success of an intervention beyond clinical environments. In addition, Ferguson and colleagues (2013) also recognise the importance of the structure of programmes (e.g., intensity, duration and frequency) as recommendations for dosage parameters are yet to be empirically established within the DCD literature, even though a greater number of sessions seems optimal provided the therapy is sufficiently intense, fun and appropriately scaled to the child's needs (Wilson, 2005).

Another cognitive approach with good evidence of efficacy in DCD is Cognitive Orientation to daily Occupational Performance (CO-OP) (Missiuna, Mandich, Polatajko, & Malloy-Miller, 2001; Polatajko, Mandich, Miller, & Macnab, 2001; Polatajko, Mandich, Missiuna, et al., 2001). CO-OP is a child-centred intervention framework that helps children with motor difficulties to reach functional goals by encouraging the child to think about how to perform novel movements. It provides children with meta-cognitive strategies to solve problems, which is based on the assumption that children with DCD possess a limited cognitive capacity to develop motor skills (Jokić & Whitebread, 2011; Jokić & Whitebread, 2014). A CO-OP program is taught over 10 sessions, teaching children to establish a goal, how to formulate and carry out a plan, monitor their performance, and update the plan, if necessary (Missiuna et al., 2001). It is thought that by engaging a child in a CO-OP intervention, the techniques learned will transfer to a wide range of new movement skills (Missiuna et al., 2001). This approach has particular relevance to my thesis where a collaborative approach that involves a substantial cognitive component may be best suited to treat combined motor deficits that involve a higher degree of executive control.

A large number of studies have shown that CO-OP is an effective intervention framework for treating motor problems in school-aged children with DCD (Albers, 2013; Banks et al., 2008; Hyland & Polatajko, 2012; Jokić, Polatajko, & Whitebread, 2013; Martini, Mandich, & Green, 2014; Miller, Polatajko, Missiuna, Mandich, & Macnab, 2001; Missiuna et al., 2012; Rodger & Liu, 2008; Sangster, Beninger, Polatajko, & Mandich, 2005; Sugden, 2007). A study from Miller and colleagues (2001) compared the use of CO-OP with Contemporary Treatment Approach in 27 children with DCD. Contemporary Treatment Approach incorporated neuromuscular, multi-sensory, and biomechanical aspects of motor skill acquisition. Both intervention programmes resulted in improvement of motor performance across sessions; however, greater improvements were found in children of the CO-OP group. The results suggest a CO-OP intervention may be suitable for the children with motor impairment from my studies as they were recruited from mainstream primary schools.

Another study to compare CO-OP with multi-sensory approaches was provided from Zwicker and Hadwin (2009). The researchers showed that CO-OP training for improving handwriting in typically developing school children showed greater treatment gains than a multi-sensory approach. Evidence also indicates that children with DCD do become better at monitoring their own motor behaviour and can apply the skills learnt from CO-OP to novel motor tasks (Hyland & Polatajko, 2012), and this may explain why CO-OP interventions have seen repeated success. This is important to consider in the context of my data; if children with DCD can successfully use strategies that increase their awareness and understanding of motor tasks, particularly those like anti-reach movements where they can be made cognisant of the need to withhold a reach toward a compelling cue, they may be able to learn and perform new motor behaviour with a better degree of flexibility.

However there are a number of caveats to the efficacy of CO-OP programmes. For instance, many studies have used small sample sizes and require further testing with larger group numbers. Additionally, many researchers use the 15th percentile on standardised motor tests to classify children into a DCD group (although ancillary criteria are still used), as was the case with my studies. Recent research has shown that children with more severe coordination problems have greater associated difficulties with activities of daily living, attention, reading and social cognition (Schoemaker, Lingam, Jongmans, van Heuvelen, & Emond, 2013). Greater variability of symptom severity within DCD groups may require more specialised attention to meet the needs of children of individual children (Missiuna et al., 2015). Additionally, CO-OP has generally been conducted in educational environments (e.g., at school). While not a limitation per se, in keeping in line with a goal of intervention, more research is needed to determine if successful motor learning outcomes generalise to other environments.

6.3.3 What Aspects of Interventions can Target Immature Coupling Behaviour?

One of the issues involved with designing intervention programmes for children with DCD is that the heterogeneity seen within the disorder means that some tasks may not be suitable for every child (Martini et al., 2014). Developing remediation for deficits across several systems (as per the reduced performance of younger and mid-age children with DCD on anti-jump trials) presents new challenges to therapists. Anti-jump performance should not be an intervention target in its own right – the movement is too simple to transfer to other, more ecologically valid tasks. Indeed, preliminary evidence of predictive modelling training (such as MI) shows promise (Wilson et al., 2002), as do programmes for cognitive approaches to motor skill learning (Ferguson et al., 2013; Jokić et al., 2013; Martini et al., 2014). One solution might be to reduce the level of challenge associated with anti-jump trials (where coupling of ROC and EF was required) and implement a staged approach. Difficulties coupling inhibitory control to movement could be addressed by other means, such as cuing of attention to external objects or events or engage in video demonstrations of appropriate movement. By breaking down the task into simpler constituents it may reduce the load on EF and assist younger and mid-age children train predictive modelling before it is integrated with inhibitory control. Indeed, Diamond (2013) suggests that EFs are trainable and can be improved with practice; hence, a reductionist approach may an optimal intervention strategy and even benefit older children with DCD who do not show age-appropriate coupling of motor and cognitive systems.

6.4 Limitations and Directions for Future Research

Several caveats exist about the interpretation of results from this thesis. Limitations may be present at an experimental level; for example, there is potential for inadvertent motor learning to occur during the course of performing a repetitive movement (Shadmehr et al., 2010). At a broader level, the severity of motor difficulties may be related to the level of predictive control, while co-morbid symptoms of DCD (shared with other developmental disorders) may provide evidence for alternate explanations of impaired motor ability. Additionally, deficits of other executive processes (such as working memory) may also influence the expression of predictive modelling systems. These limitations, and potential avenues for future research, are discussed below.

6.4.1 Motor Learning may occur over Repeated Trials on the DJRT

From a neurocomputational perspective, internal modelling is a critical concept in models of motor control and learning. As described in Chapter 1, internal modelling involves two separate, but related processes: predictive (forward) modelling and inverse modelling (Desmurget & Grafton, 2003). Forward models provide estimates of limb and body position based on the expected sensory consequences of action learning (Wolpert et al., 2011; Wolpert et al., 2001). Discrepancies between the expected and actual consequences of movement are corrected via error signals, in real time. In the case of motor learning, these error signals also act as a training input for the stored internal model (Shadmehr et al., 2010).

During the course of movement when expected action is incongruent with the incoming sensory action (as per displacement trials on the DJRT), it is conceivable that a representation of the perturbed movement will be stored within the motor system (Shadmehr et al., 2010). By performing repeated corrective actions on double-jump trials (as described in in Chapters 2, 3, 4 and 5), the change to motor behaviour may be sufficient enough to train signals for the nervous system. That is, the motor memory created from frequently displaced trials could provide advanced information for later motor commands (Shadmehr et al., 2010). In order to account for potential learning effects within the double-jump paradigm, I ensured that a small number of displacement trials (20% of the total number of trials) were programmed into each condition. Additionally, the order of these displacement trials was presented randomly; counterbalancing the presentation order of jump and anti-jump conditions also served to reduce learning effects. Furthermore, research using step-perturbation paradigms has shown consistent patterns of performance between blocks of early and late trials (Cameron et al., 2013; Hyde & Wilson, 2011b)

To investigate how learning processes unfold in the context of motor and executive systems, future studies using the double-jump paradigm could vary the presentation of perturbed jumps. Performance would then be compared between early and late trials, both within the jump condition (to assess predictive modelling in isolation from other systems) and anti-jump condition (for the added executive load to predictive control) to examine whether the motor memory is the outcome of predictive control over trials. .

6.4.2 Severity of Motor Impairment

An area of investigation that is important to clarify the nature of predictive modelling deficits in children with DCD relates to the severity of motor ability. The capacity for children with DCD to use predictive control may be expressed differently in a clinical sub-group. For example, Plumb and colleagues (2008) examined online corrections on a step-perturbation paradigm; however, children were allocated to the DCD group with a score below the 1st percentile on the MABC (compared to the 15th percentile used in my research).

On their task, children stood in front of a computer screen to and touched a target with a thin stylus wand. Not surprisingly, the children with DCD from Plumb and colleague's study had problems performing this task which was subsequently modified for them: they performed it seated on a chair and used a thicker wand for better grip. While the study found no evidence for impaired online control, the fact that the task had to be changed to accommodate the children with severe motor difficulties limits comparison of online control performance between studies and suggests that the capacity for predictive modelling may vary across DCD groups.

Evidence from other research has shown that difficulties with imagined movements might be associated with the severity of motor impairment (Williams et al., 2008). Williams and colleagues (2008) found that children with severe DCD (as measured on the MABC-2) showed similar deficits with each other on MI tasks, while children with mild DCD demonstrated less MI deficits. In addition, children with severe DCD also showed a decreased benefit from MI instruction compared to children with mild DCD. As discussed in Chapter 1, the integrity of internal (predictive) modelling systems can be inferred from MI performance. The MI study from Williams and colleagues further suggests that the capacity for predictive modelling may vary across children with DCD and that motor severity may be a moderating factor in symptom expression and intervention success.

With respect to this latter point, treatment outcomes might vary according to clinical presentation; some symptoms of DCD may be more resistant to remedial efforts than others. For example, children with severe motor impairments (i.e., a score below the 5th percentile on the MABC) measured at the commencement of a CO-OP intervention were more likely to experience motor difficulties by the conclusion of the program, despite engaging in remediation (Green et al., 2008). This highlights the need to continue research and create carefully designed interventions.

6.4.3 The Impact of Co-occurring Disorders.

Motor impairment often presents comorbid with other developmental disorders which can make research of “pure” cases of DCD difficult. This is particularly relevant for ADHD where studies have found shared symptoms with DCD (Gillberg et al., 2004; Kaiser et al., 2015; McLeod et al., 2014; Missiuna et al., 2014). Recent evidence suggests that DCD symptoms exacerbate in co-occurring disorders (Jongmans, Smits-Engelsman, & Schoemaker, 2003), and that symptom severity is further affected when several co-occurring disorders are present (Crawford & Dewey, 2008). For example, Jongmans and colleagues (2003) showed that children who were diagnosed with DCD and a learning disability performed significantly worse than a group of children with DCD only on a standardised test (i.e., MABC) of perceptual-motor ability. The co-morbid group also had more difficulty performing balance and manual dexterity tasks, but were as competent with throwing and catching a ball as the DCD group. In more recent research, Jaščenoka, Korsch, Petermann, and Petermann (2015) found that children with DCD and ADHD showed poorer processing speed on the Wechsler Preschool and Primary Scale of Intelligence-III than children with DCD alone. Additionally, negative consequences of comorbid occurrences may extend beyond motor and cognitive problems. For example, research using parent reports showed that children with combined DCD and ADHD suffer from more psychological distress (e.g., symptoms of anxiety and depression) than TDC or children with only DCD (Missiuna et al., 2014).

As research has reported co-morbid occurrences of DCD with other developmental disorders, future research should investigate whether the neuro-cognitive profile of DCD is different to co-occurring developmental disorders (e.g., DCD/ADHD). It may be that co-morbid cases are underlined by different mechanisms. That is, deficits in predictive modelling may be the cause of some motor control problems in DCD; however, inhibitory and attentional control difficulties of ADHD might account for other motor difficulties. For example, Lewis and colleagues (2008) found that a DCD group showed problems generating imagined movements (from which impaired predictive control can be inferred), yet this deficit was not detected in the DCD/ADHD group, possibly due to some other control mechanism. Continued work is needed to clarify neuro-cognitive deficits, particularly where there is evidence that certain behaviours may be controlled by separate systems.

6.4.4 Assessing other Components of EF with ROC

This thesis examined the constraining effect of inhibitory control on online control; however; there are other components of EF that might compromise ROC. In the DCD literature, deficits across other EF processes have been found (e.g., executive attention and working memory) (Wilson et al., 2013) which are also thought to play an important role in motor and cognitive control (Michel, 2012).

As I have shown across Study 2 and 3, there is good evidence to suggest that ROC is constrained (to varying degrees) by the development of EF in children with DCD. However, an underlying assumption about EF and its relationship to ROC is that other executive processes have sufficiently matured to a degree where they can support other cognitive functions. In the case of working memory (WM), for example, a body of research has shown that children with DCD show atypical performance on most measures, particularly on tasks that assess visuospatial WM (Alloway, 2007, 2011; Alloway, 2012; Alloway & Archibald, 2008, 2011; Alloway, Rajendran, & Archibald, 2009; Tsai, Chang, Hung, Tseng, & Chen, 2012).

In terms of performance on the DJRT, the change in complexity from jump to anti-jump trials also places increased demand on visuo-spatial working memory processes (Wilson et al., 2013). Accordingly, impairment in WM could be used to examine its co-development and interaction with online control. The advanced growth curve modelling methodologies used in this thesis would provide a powerful way to monitor the interaction between WM trajectories and online control. Consequently, this may identify whether the coupling deficit seen with inhibitory control in children with DCD is also present in WM which would have implications for interventions that use cognitive strategies to remediate motor coordination difficulties.

6.5 General Conclusion

The studies in this thesis have been one of the first to help clarify the development of rapid online control of reaching across childhood aged 6-12 years, and explore how emerging executive systems constrain it. To measure developmental changes in the online control of reaching, a double-jump paradigm (that included trials with an inhibitory component) was used to assess the integrity of predictive modelling systems in TDC and DCD. This neuro-computational account of motor control is based on the assumption that a healthy ROC system uses a forward (predictive) estimate of limb positon to adjust movements as they occur. Interpreted using a neuro-behavioural framework of *interactive specialization*; results from this thesis suggest that the coupling of ROC and EF undergo different growth patterns in TDC and children with DCD.

For normative development, younger children are disadvantaged by sudden perturbations to movement, an effect that is pronounced when inhibitory control is added to online corrections. By middle childhood, online corrections can be implemented efficiently, yet are reduced (relative to older children) on trials where inhibitory demands are imposed. Middle childhood appears to mark a period of re-organisation in control systems to perform more complex goal-directed reaching. Growth curve analysis of longitudinal data confirms that the coupling of motor and executive systems develops rapidly up to 9-10 years childhood, followed by more steady improvements into older childhood as motor and cognitive systems integrate for fluid action. Conversely, for children with DCD, the coupling of motor and executive systems shows delay in growth. Consistent with previous research, the cross-sectional and longitudinal data of this thesis suggest a delayed developmental trajectory; younger and mid-age children have substantial problems integrating using ROC and inhibitory systems to adjust to visual perturbations while older children show skill levels similar to TDC. From a neuro-computation perspective, delays in growth to fronto-parietal and parietal-cerebellar networks may underlie control problems in children with DCD and suggests a protracted period of development is needed to couple motor and cognitive systems.

Coupling delays of behaviour does not always imply that children with atypical motor skills will eventually ‘catch-up’ to typically developing children research indicates that motor control problems persist into adulthood. Thus, where impairment occurs across systems like ROC and EF that are required for complex movement, drawing strategies from different models of intervention may be an appropriate way to treat a delayed motor system. Accordingly, use of MI to treat impaired predictive control shows potential for improving internal models of actions. Additionally, deficits of EF respond successfully to cognitive-based programmes where children with poor motor skills are taught to think about how to perform novel motor tasks. In this way, children may be better equipped to approach complex motor movements (such as anti-jump trials) by reducing them to simpler skills and lessen the load on executive systems. Certainly, continued research into this area will strengthen interventions for children who do not show age appropriate skills.

In conclusion, the development of online control of reaching across childhood changes according to the constraints of executive (inhibitory) systems. For typically developing children, the processes required for flexible movement develop rapidly during early and mid-age childhood years before a re-organisation of systems that leads to more gradual improvements into older childhood. For children with DCD, this pattern of coupling appears delayed, subserved by immaturities in connections between fronto-parietal systems that are implicated with the cognitive control of action.

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RESEARCH PORTFOLIO

List of Publications

Publication 1

Ruddock, S., Hyde, C., Morris, S., Piek, J., Sugden, D., & Wilson, P. (2014) Executive systems constrain the flexibility of online control in children during goal-directed reaching. *Developmental Neuropsychology*. *39*(1), 51-68. doi: 10.1080/87565641.2013.855215. **5-year Impact Factor: 3.22, SJR: Q1**

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Publication 2

Ruddock, S., Piek, J., Sugden, D., Morris, S., Hyde, C., Caeyenberghs, K., & Wilson, P. (2014). Coupling online control and inhibitory systems in children with Developmental Coordination Disorder: Goal-directed reaching. *Research in Developmental Disabilities, 36*, 244-255. doi: 10.1016/j.ridd.2014.10.013. **5-year Impact Factor: 2.869, SJR: Q1**

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Publication 3

Ruddock, S., Piek, J., Sugden, D., Hyde, C., Caeyenberghs, K., Morris, S., & Wilson, P. (under review). Coupling of online control and inhibitory systems in children with motor clumsiness: A growth curve modelling study. Brain and Cognition. **5-year Impact Factor: 3.790, SJR: Q1**

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Title: Coupling online control and inhibitory systems in children with Developmental Coordination Disorder: Goal-directed reaching

Publication: Research in Developmental Disabilities

Licensee: Scott Ruddock

License Date: 29 January 2015

License Number: 3558480577734

Statement of Contribution of Others

Publication: Executive systems constrain the flexibility of online control in children during goal-directed reaching

I acknowledge that my contribution to the above publication is 10 percent.
Author: Prof Jan Piek
Signature:
Date: 01/03/2015

I acknowledge that my contribution to the above publication is 10 percent.
Author: Prof David Sugden
Signature:
Date: 26/02/2015

I acknowledge that my contribution to the above publication is 10 percent.
Author: Dr Christian Hyde
Signature:
Date: 02/03/2015

I acknowledge that my contribution to the above publication is 10 percent.
Author: Dr Sue Morris
Signature:
Date: 02/03/2015

I acknowledge that my contribution to the above publication is 10 percent.
Author: Prof Peter Wilson
Signature:
Date: 02/03/2015

Publication: Coupling online control and inhibitory systems in children with developmental coordination disorder: Goal-directed reaching

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Prof Jan Piek

Signature:
Date: 01/03/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Prof David Sugden

Signature: David A. Sugden
Date: 26/02/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Dr Christian Hyde

Signature:
Date: 02/03/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Dr Sue Morris

Signature: S Morris
Date: 02/03/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Prof Karen Caeyenberghs

Signature: KCaeyenberghs
Date: 02/03/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Prof Peter Wilson

Signature:
Date: 02/03/2015

Publication: Coupling of online control and inhibitory systems in children with and without motor clumsiness: A growth curve modelling study

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Prof Jan Piek
Signature:
Date: 01/03/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Prof David Sugden
Signature:
Date: 26/02/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Dr Christian Hyde
Signature:
Date: 02/03/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Dr Sue Morris
Signature:
Date: 02/03/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Prof Karen Caeyenberghs
Signature:
Date: 02/03/2015

I acknowledge that my contribution to the above publication is 8.33 percent.
Author: Prof Peter Wilson
Signature:
Date: 02/03/2015

Additional Publications

The following journal and conference publications have been completed in addition to the main studies presented in this thesis.

Journal Publications

Noten, M., Wilson, P., Ruddock, S., & Steenbergen, B. (2014). Mild impairments of motor imagery skills in children with DCD. *Research in Developmental Disabilities*. *35*(5), 1152-1159. doi: 10.1016/j.ridd.2014.01.026

Wilson, P. H., Ruddock, S., Smits-Engelsman, B., Polatajko, H., & Blank, R. (2013). Understanding performance deficits in developmental coordination disorder: A meta-analysis of recent research. *Developmental Medicine and Child Neurology, 55*(3), 217-228. doi: 10.1111/j.1469-8749.2012.04436.x

Peer Reviewed Conference Presentations

Ruddock, S., Hyde, C., Piek, J., Sugden, D., Morris, S., & Wilson, P. (2014, July). A 2-year longitudinal study of motor control and executive function in children with Developmental Coordination Disorder: Modelling patterns of change with age. Paper presentation at the European Academy of Childhood Disability, Vienna, Austria, 03-05 July2014.

Ruddock, S., Hyde, C., Piek, J., Sugden, D., Morris, S., & Wilson, P. (2013, November) Executive systems modulate the way primary school children enlist online corrections: Assessing the consistency of performance on a double-step task. Paper presentation at the 11th Motor Control and Human Skill, Melbourne, Australia, 27 November – 29 November 2013.

Ruddock, S., Hyde, C., Piek, J., Sugden, D., Morris, S., & Wilson, P. (2013, June). Inhibitory constraints on the goal-directed reaching of children with developmental coordination disorder. Paper presented at the 10th International Conference on Developmental Coordination Disorder (DCD-X), Ouro Preto, Brazil, June 28 – July 1 2013.

Noten, M., Wilson, P., Ruddock, S., & Steenbergen, B. (2013, June). Mild impairments of motor imagery skills in children with DCD: Is motor imagery related to anticipatory action planning? Paper presented at the 10th International Conference on Developmental Coordination Disorder (DCD-X), Ouro Preto, Brazil, June 28 – July 1 2013.

Ruddock, S., Wilson, P., Hyde, C., Piek, J., Sugden, D., Rigoli, D., & Morris, S. (2011, November). The development of online motor control in children: Variations with age as a function of inhibitory demands. Paper presentation at the 10th Motor Control and Human Skill, Mandurah, Western Australia.

Wilson, P., Ruddock, S., Hyde, C., Piek, J., Sugden, D., Rigoli, D., Morris, S. (2011, November). Inhibitory demands impede online control in children with developmental coordination disorder (DCD). Paper presentation at the 10th Motor Control and Human Skill, Mandurah, Western Australia.

Wilson, P., Ruddock, S., Hyde, C., Piek, J., Sugden, D., Rigoli, D., & Morris, S. (2009, June).The relationship between the development of movement skill, online control and executive control in children: a longitudinal investigation. Paper presentation at the 9th International Conference on Children with Developmental Coordination Disorder, Lausanne, Switzerland, June 27-29 2011

APPENDICIES

Appendix A Polynomial Fit Analyses for AJMT*diff* and ToC*diff*

	Model	Sequential effect in model	TDC -2log likelihood	TDC *p* for sequential test	DCD -2log likelihood	DCD *p* for sequential test
AJMT*diff*	Linear	cohort	4821.00	<.001	2921.10	<.001
		age		<.001		<.001
		age*cohort		.48		.31
	Quadratic	cohort	4808.20	<.001	2930.00	<.001
		age		<.001		<.001
		age*cohort		.69		.31
		agesquare		.03*		.23
	Cubic	cohort	4810.60	<.001	2928.60	<.001
		age		<.001		<.001
		age*cohort		.70		.30
		agesquare		.07		.22
		agecube		.17		.28
ToC*diff*	Linear	cohort	4381.90	<.001	2635.50	<.001
		age		<.001		<.001
		age*cohort		.10		.11
	Quadratic	cohort	4374.60	<.001		
		age		<.001		
		age*cohort		0.11		
		agesquare		.016*		
	Cubic	cohort	4376.60	<.001	2648.30	<.001
		age		<.001		<.001
		age*cohort		.10		.07
		agesquare		.02		.21
		agecube		.14		.87

Note. **p* < .05. AJMT*diff* = Anti-jump Movement Time Difference Score; ToC_{diff} = Time of correction difference score; TDC = Typically Developing Children; DCD = Developmental Coordination Disorder.

Appendix B Ethics Approval: Australian Catholic University

From: Gabrielle Ryan [mailto:Gabrielle.Ryan@acu.edu.au]
Sent: Thursday, 29 March 2012 10:28 AM
To: PeterH Wilson;
Cc: Gabrielle Ryan
Subject: Ethics Application approved 2012 73V

Dear Peter,

Ethics Register Number: 2012 73V
Project Title: The development of rapid on-line motor control in children End Date: 30/06/2013

This email is to advise that your application has been reviewed by the University Human Research Ethics Committee and your approval has been transferred from RMIT HREC to the ACU HREC. ACU HREC is now the primary HREC on this project. Please ensure that you have completed the relevant processes to close off this project at RMIT, if there are no ongoing links with researchers still at RMIT.

Whilst the data collection of your project has received ethical clearance, the decision to commence and authority to commence may be dependent on factors beyond the remit of the ethics review process. For example, your research may need ethics clearance from other organisations or permissions from other organisations to access staff. Therefore the proposed data collection should not commence until you have satisfied these requirements.

If you require a formal approval certificate, please respond via reply email and one will be issued.

Decisions related to low risk ethical review are subject to ratification at the next available Committee meeting. You will only be contacted again in relation to this matter if the Committee raises any additional questions or concerns.

This project has been awarded ethical clearance until 30/06/2013 and a progress report must be submitted at least once every twelve months.

Researchers who fail to submit an appropriate progress report may have their ethical clearance revoked and/or the ethical clearances of other projects suspended. When your project has been completed please complete and submit a progress/final report form and advise us by email at your earliest convenience. The information researchers provide on the security of records, compliance with approval consent procedures and documentation and responses to special conditions is reported to the NHMRC on an annual basis. In accordance with NHMRC the ACU HREC may undertake annual audits of any projects considered to be of more than low risk.

For progress and/or final reports, please complete and submit a Progress / Final Report form:
http://www.acu.edu.au/about_acu/research/staff/research_ethics/

For modifications to your project, please complete and submit a Modification form:

http://www.acu.edu.au/about_acu/research/staff/research_ethics/

Researchers must immediately report to HREC any matter that might affect the ethical acceptability of the protocol e.g.: changes to protocols or unforeseen circumstances or adverse effects on participants.

Please do not hesitate to contact the office if you have any queries.

Kind regards,
Gabrielle Ryan

Ethics Officer | Research Services
Office of the Deputy Vice Chancellor (Research) Australian Catholic University Locked Bag 4115, Fitzroy, VIC, 3065
T: 03 9953 3150 F: 03 9953 3315

Appendix C Ethics Approval: Department of Education

Department of Education and
Early Childhood Development

Office for Policy, Research and Innovation

2 Treasury Place
East Melbourne, Victoria 3002
Telephone: +61 3 9637 2000
DX 210083
GPO Box 4367
Melbourne, Victoria 3001

2010_000645

Associate Professor Peter Wilson
Psychology, School of Health Sciences
Royal Melbourne Institute of Technology
GPO Box 2476V
MELBOURNE 3001

Dear Associate Professor Wilson

Thank you for your application of 3 June 2010 in which you request permission to conduct a research study in government schools titled: *The development of rapid on-line motor control in children.*

I am pleased to advise that on the basis of the information you have provided your research proposal is approved in principle subject to the conditions detailed below.

1. Should your institution's ethics committee require changes or you decide to make changes, these changes must be submitted to the Department of Education and Early Childhood Development for its consideration before you proceed.

2. You obtain approval for the research to be conducted in each school directly from the principal. Details of your research, copies of this letter of approval and the letter of approval from the relevant ethics committee are to be provided to the principal. The final decision as to whether or not your research can proceed in a school rests with the principal.

3. No student is to participate in this research study unless they are willing to do so and parental permission is received. Sufficient information must be provided to enable parents to make an informed decision and their consent must be obtained in writing.

4. As a matter of courtesy, you should advise the relevant Regional Director of the schools you intend to approach. An outline of your research and a copy of this letter should be provided to the Regional Director.

5. Any extensions or variations to the research proposal, additional research involving use of the data collected, or publication of the data beyond that normally associated with academic studies will require a further research approval submission.

6. At the conclusion of your study, a copy or summary of the research findings should be forwarded to Education Policy and Research Division, Department of Education and Early Childhood Development, Level 3, 33 St Andrews Place, GPO Box 4367, Melbourne, 3001.

Every child, every opportunity

Victoria
The Place To Be

I wish you well with your research study. Should you have further enquiries on this matter, please contact Jonathan Howcroft, Policy and Research Officer, Education Policy and Research, by telephone on (03) 9947 1892 or by email at <howcroft.jonathan.j@edumail.vic.gov.au>.

Yours sincerely

Dr Elizabeth Hartnell-Young
Group Manager
Education Policy and Research

08/07/2010

enc

Appendix D Ethics Approval: Catholic Education Office

Catholic Education Office

In reply please quote:

GE10/0009
1610

20 May 2010

Prof P Wilson
RMIT University
GPO Box 2476V
MELBOURNE VIC 3001

Dear Prof Wilson

I am writing with regard to your research application received on 19 May 2010 concerning your forthcoming project titled *The development of rapid on line motor control in children.* You have asked approval to approach Catholic primary schools in the Archdiocese of Melbourne, as you wish to have students and parents participate in your research.

I am pleased to advise that your research proposal is approved in principle subject to the nine standard conditions outlined below. Additionally, I ask that you forward to this Office a copy of the notification of approval from the University's Ethics Committee when it becomes available.

1. The decision as to whether or not research can proceed in a school rests with the school's principal, so you will need to obtain approval directly from the principal of each school that you wish to involve.

2. You should provide each principal with an outline of your research proposal and indicate what will be asked of the school. A copy of this letter of approval, and a copy of notification of approval from the university's Ethics Committee, should also be provided.

3. A *Working with Children* (WWC) check – or registration with the Victorian Institute of Teaching (VIT) – is necessary for all researchers visiting schools. Appropriate documentation must be shown to the principal before starting the research in each school.

4. No student is to participate in the research study unless s/he is willing to do so and informed consent is given in writing by a parent/guardian.

5. You should provide the names of schools which agree to participate in the research project to the Knowledge Management Unit at this Office.

6. Any substantial modifications to the research proposal, or additional research involving use of the data collected, will require a further research approval submission to this Office.

1 of 2

James Goold House [illegible]

Prof P Wilson - 2 - 20 May 2010

7. Data relating to individuals or schools are to remain confidential.

8. Since participating schools have an interest in research findings, you should consider ways in which the results of the study could be made available for the benefit of the school communities.

9. At the conclusion of the study, a copy or summary of the research findings should be forwarded to this Office. It would be appreciated if you could submit your report in an ***electronic format*** using the email address provided below.

I wish you well with your research study. If you have any queries concerning this matter please contact Mr Martin Smith of this Office.

The email address is <skm@ceomelb.catholic.edu.au>.

Yours sincerely

Nancy Bicchieri
DEPUTY DIRECTOR

2 of 2

Appendix E Plain Language Statement for School Principals, Study 1, 2, 3

INVITATION TO PARTICIPATE IN A RESEARCH PROJECT
PROJECT INFORMATION STATEMENT

Project Title:
Development of rapid, online motor control in children

Investigators:
- Associate Prof. Peter Wilson (Principle Investigator: Psychology, RMIT University, peter.h.wilson@rmit.edu.au, (03) 9925 2906.)
- Prof. Jan Piek (Principle Investigator, School of Psychology and Speech Pathology, Curtin University, J.Piek@curtin.edu.au)
- Prof David Sugden (Principle Investigator, School of Education, Leeds University, d.a.sugden@education.leeds.ac.uk)
- Mr Scott Ruddock (BSocSc (Psych), Honours Student, RMIT)
- Miss Rhianna Mann (BSocSc (Psych), Honours Student, RMIT)
- Mr Henry Bell (BSocSc (Psych), Honours Student, RMIT)
- Mr Christian Hyde (BSc, Grad. Dip. Psych, PhD Candidate)
- Ms Daniela Rigoli (BA Psychology – Honours, Curtin University)

Dear <Insert Name of Principal of School>,

Your school has been invited to participate in a research project being conducted by RMIT University. This information sheet describes the project in straightforward language, or ‘plain English’. Please read this sheet carefully and be confident that you understand its contents before deciding whether or not you wish for children from your school to be approached to participate. If you have any questions about the project, please ask one of the investigators.

Who is involved in this research project? Why is it being conducted?
Our names are Scott Ruddock, Rhianna Mann, Henry Ball, Daniela Rigoli, and Christian Hyde and we are conducting a research project with Associate Professor Peter Wilson in the School of Psychology which has been funded by the Australian Research Council (ARC). This means that we will be preparing a research report from the results of this study. We would like to invite children from your school to participate in this research subject to their parent’s written consent. This project has been approved by the RMIT University Human Research Ethics Committee and <insert relevant educational body>.

What is the project about? What are the questions being addressed?
Our project examines how children learn motor skills and the strategies they use to assist them. This knowledge will also help us understand why some children have more difficulty performing movements than others. To do this we will assess children at different points over time, and examine how their performance changes with age.

If I agree for my school to participate, what will those children who are involved be required to do?
Children’s motor skills will first be assessed using a small set of movement tasks. These include manual skills like bead threading and larger skills like standing broad jump. Children will also complete a set of computer-based tasks assessing thinking skills and speed. Using a small tablet PC, children will be asked to press keys in response to a set of playing cards displayed on the screen. For example, they will be asked to hit a YES key whenever they see a red card, or decide if a displayed card is the same as one displayed previously. Finally, they will be asked to point and touch targets displayed on a larger touch screen as they appear. We will assess their speed and accuracy on these tasks. Finally, parents will also be asked to complete a short questionnaire about their child’s participation in physical activities and factors that may impact on this.

Since we are interested in changes in the strategies that people use to perform movements over time, children will be assessed *once every 6 months for a period of 2 years* (5 times in total). Each session will take roughly 30 to 45 minutes to complete and be conducted at school.

What are the risks or disadvantages associated with participation?
Very occasionally, people find being assessed uncomfortable or upsetting. If at any stage during the study your child feels uncomfortable or upset about the tasks, they are encouraged to let the researcher know and the assessment will cease.

What are the benefits associated with participation?
Children will find the tasks both enjoyable and challenging. They will be aware that their participation will help us add to knowledge about the way children and adults learn new skills, and why some children find it difficult. There will be no financial benefit or reward for participating in this study.

What will happen to the information provided by the research?
All aspects of the study, including results, will be strictly confidential and only the researchers will have access to information on participants. To maintain confidentiality children's names will not appear on any of the data. A code number will be assigned each child's data. The consent forms will not be kept in the same place as each child's results so there will be no way to identify which results have been obtained of each child.

Storage of the data collected will adhere to the University regulations and be kept in secure storage for 5 years. A report of the study may be submitted for publication, but individual participants will not be identifiable in such a report, as only aggregated group data will be reported.

In order to assist with research examining movement development, each child's anonymous data may be used for other projects in this area. All data will be completely anonymous and each child's identity will not be disclosed.

What are the rights of my students as participants?
As this study is completely voluntary, children and their parents are under no obligation to consent to participation and children may withdraw at any stage for any reason. Further, children have the right to ask questions regarding the project at any time.

Whom should I contact if I have any questions?
If you, your students or their parents have any queries or would like to be informed of the aggregate research findings, please contact A. Prof Peter Wilson on (03) 9925 2906 or peter.h.wilson@rmit.edu.au. Should you, your students or their parents have any concerns about the conduct of this research project, please contact A. Prof Peter Wilson on the contact details above.

Yours sincerely,

A/Prof Peter Wilson BAppSc (PE), BBSc (Hons), PhD	A/Prof Jan Piek BSc (Hons), PhD	A/Prof David Sugden PhD
Scott Ruddock B/SocSc (Psychology)	Rhianna Mann BSocSc (Psych)	Henry Bell BSocSc (Psych)
Daniela Rigoli BA Psychology (Honours)	Christian Hyde Bachelor of Science, Grad. Dip. Psych.	

Any complaints about children from your school's participation in this project may be directed to the Executive Officer, RMIT Human Research Ethics Committee, Research & Innovation, RMIT, GPO Box 2476V, Melbourne, 3001.
Details of the complaints procedure are available at: http://www.rmit.edu.au/rd/hrec_complaints

Appendix F Plain Language Statement and Consent Form for Parents, Study 1, 2, 3

INVITATION TO PARTICIPATE IN A RESEARCH PROJECT
PROJECT INFORMATION STATEMENT

Project Title:
The development of rapid online motor control in children

Investigators:
- Associate Prof. Peter Wilson (Principle Investigator: Associate Professor, Psychology, RMIT University, peter.h.wilson@rmit.edu.au, (03) 9925 2906.
- Prof. Jan Piek (Principle Investigator, School of Psychology and Speech Pathology, Curtin University, J.Piek@curtin.edu.au)
- Prof David Sugden (Principle Investigator, School of Education, Leeds University, d.a.sugden@education.leeds.ac.uk)
- Mr Scott Ruddock (BSocSc (Psych), Honours Student, RMIT)
- Miss Rhianna Mann (BSocSc (Psych), Honours Student, RMIT)
- Mr Henry Bell (BSocSc (Psych), Honours Student, RMIT)
- Mr Christian Hyde (BSc, Grad. Dip. Psych, PhD Candidate)
- Ms Daniela Rigoli (BA Psychology – Honours, Curtin University)

Dear Parent,

Your child has been invited to participate in a research project being conducted by RMIT University in partnership with Curtin University (WA) and Leeds University (UK). This information sheet describes the project in straightforward language, or 'plain English'. Please read this sheet carefully and be confident that you understand its contents before deciding whether or not you wish for your child to participate. If you have any questions about the project, please ask one of the investigators.

Who is involved in this research project? Why is it being conducted?
Associate Prof. Peter Wilson from the Discipline of Psychology at RMIT University leads a team of investigators (listed above) on this project, which is funded by the Australian Research Council (ARC). The project is designed to add to our understanding of how children acquire motor skills and some of the potential barriers. We will be preparing a number of interesting research reports from the results of this study. I would like to invite your child to participate in this research. This project has been approved by the RMIT University Human Research Ethics Committee (HREC).

Why has my child been approached?
The Principal of your child's school has agreed to allow us to approach students to invite them to participate in our project.

What is the project about? What are the questions being addressed?
Our project examines how children learn motor skills and the strategies they use to assist them. This knowledge will also help us understand why some children have more difficulty performing movements than others. To do this we will assess children at different points over time, and examine how their performance changes with age.

If I agree for my child to participate, what will they be required to do?
Your child's motor skills will first be assessed using a small set of movement tasks. These include manual skills like bead threading and larger skills like standing broad jump. Your child will also complete a set of computer-based tasks assessing thinking skills and speed. Using a small tablet PC, children will be asked to press keys in response to a set of playing cards displayed on the screen. For example, they will be asked to hit a YES key whenever the see a red card, or decide if a displayed card is the same as one displayed previously. Finally, they will be asked to point and touch targets displayed on a larger touch screen as they appear. We will assess their speed and accuracy on these tasks. Finally, you will also be asked to complete a short questionnaire about your child's participation in physical activities and factors that may impact on this.

Since we are interested in changes in the strategies that people use to perform movements over time, your children will be assessed *once every 6 months for a period of 2 years* (5 times in total). Each session will take roughly 30 to 45 minutes to complete and be conducted at school.

What are the risks or disadvantages associated with participation?
Very occasionally, people find being assessed uncomfortable or upsetting. If at any stage during the study your child feels uncomfortable or upset about the tasks, they are encouraged to let the researcher know and the assessment will cease.

What are the benefits associated with my child's participation?
Your child will find the tasks both enjoyable and challenging. Your child will be aware that their participation will help us add to knowledge about the way children and adults learn new skills, and why some children find it difficult. There will be no financial benefit or reward for participating in this study.

What will happen to the information that my child provides?
All aspects of the study, including results, will be strictly confidential and only the researchers will have access to information on participants. To maintain confidentiality your child's name will not appear on any of the data. A code number will be assigned to your child's data. The consent forms which you will sign will not be kept in the same place as your child's results so there will be no way to identify which results have been obtained from your child.

Storage of the data collected will adhere to the University regulations and be kept in secure storage for 5 years. A report of the study may be submitted for publication, but individual participants will not be identifiable in such a report, as only aggregated group data will be reported.

In order to assist with research examining movement development, your child's anonymous data may be used for other projects in this area. All data will be completely anonymous and your child's identity will not be disclosed.

What are my child's rights as a participant?
As this study is completely voluntary you and your child are under no obligation to consent to participation and your child may withdraw at any stage for any reason. Your child has the right to ask questions regarding the project at any time.

Whom should I contact if I have any questions?
If you have any queries or would like to be informed of the aggregate research findings, please contact A/Prof. Peter Wilson on (03) 9925 2906 or peter.h.wilson@rmit.edu.au. Should you or your child have any concerns about the conduct of this research project, please contact A/Prof. Peter Wilson on the contact details above.

Yours sincerely,

A/Prof Peter Wilson BAppSc (PE), BBSc (Hons), PhD	A/Prof Jan Piek BSc (Hons), PhD	A/Prof David Sugden PhD
Scott Ruddock B/SocSc (Psychology)	Rhianna Mann BSocSc (Psych)	Henry Bell BSocSc (Psych)
Daniela Rigoli BA Psychology (Honours)	Christian Hyde Bachelor of Science, Grad. Dip. Psych.	

Portfolio **Science, Engineering and Health**
School of **Health Sciences**

Name of participant:			
Project Title:	The development of rapid online motor control in children		
Name(s) of investigators (1)	**A/Prof Peter Wilson**	Phone:	c/o (03) 9925 2906
(2)	**Prof Jan Piek**	Phone:	c/o (03) 9925 2906
(3)	**Prof David Sugden**	Phone:	c/o (03) 9925 2906
(4)	**Scott Ruddock**	Phone:	c/o (03) 9925 2906
(5)	**Christian Hyde**	Phone:	c/o (03) 9925 2906
(6)	**Rhianna Mann**	Phone:	c/o (03) 9925 2906
(7)	**Christian Hyde**	Phone:	c/o (03) 9925 2906
(8)	**Daniela Rigoli**	Phone:	c/o (03) 9925 2906

1. I have received a statement explaining the tests/procedures involved in this project.

2. I consent to my child's participation in the above project, the particulars of which - including details of tests or procedures - have been explained to me.

3. I authorise the investigator or his or her assistant to use with my child the tests or procedures referred to in 1 above.

4. I acknowledge that:

   (a) The possible effects of the tests or procedures have been explained to me to my satisfaction.
   (b) I have been informed that my child is free to withdraw from the project at any time and to withdraw any unprocessed data previously supplied (unless follow-up is needed for safety).
   (c) The project is for the purpose of research and/or teaching. It may not be of direct benefit to my child.
   (d) The privacy of the personal information my child provides will be safeguarded and only disclosed where I have consented to the disclosure or as required by law.
   (e) The security of the research data is assured during and after completion of the study. The data collected during the study may be published, and a report of the project outcomes will be provided to Dr Peter Wilson. Any information which will identify my child will not be used.

I consent to the participation of ___________________________________ in the above project

Signature: (1) (2) ______________________________ Date: ____________________

(Signatures of parents or guardians)

Witness: ______________________________ Date: ____________________

(Witness to signature)

<u>PLEASE RETURN YOUR SIGNED CONSENT FORM BACK TO YOUR CHILD'S CLASS TEACHER</u>

Any complaints about your child's participation in this project may be directed to the Executive Officer, RMIT Human Research Ethics Committee, Research & Innovation, RMIT, GPO Box 2476V, Melbourne, 3001. The telephone number is (03) 9925 2251.
Details of the complaints procedure are available from the above address.

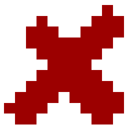
Appendix G Consent Form for Older Children, Study 1, 2, 3

INVITATION TO PARTICIPATE IN A RESEARCH PROJECT
PROJECT INFORMATION SHEET- CHILD VERSION

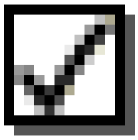
Hello, our names are Dr Jan Piek, Dr David Sugden, Scott Ruddock, Rhianna Mann, Henry Ball, Daniela Rigoli and Christian Hyde and we would like to invite you to participate in a project that we are conducting with Dr Peter Wilson from RMIT University. The aim of this project is to learn about how children move.

What will I be doing?
You will be asked to do some activities that most children really enjoy like threading beads, balancing on one leg, and jumping as far as you can. We will also ask you to play some games on a computer. On one game you will touch playing cards as quickly as you can as they appear on a computer screen. On another you will try to find a hidden path through a maze, and remember objects that appear on the screen. Last, you will touch targets as they jump from one place to another.

What if I do NOT want to take part in the project?
You do not have to take part in this project if you do not want to. Also, if you do decide to join in the project but change your mind at any time, you are free to stop whenever you want. There will be no penalty if you decide to stop at any time during the project.



What if I do want to take part in the project?
Please sign the sign the form below.



Thank you. ☺

I agree to take part in the project which has been described above.

Participant's name ....

Signature ....
Date............... /.................. /..................

Appendix H Consent Form for Younger Children, Study 1, 2, 3

INVITATION TO PARTICIPATE IN A RESEARCH PROJECT
PROJECT INFORMATION SHEET- CHILD VERSION

What is this project about?

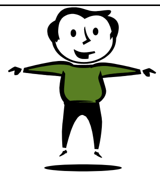
- Learning about how children move

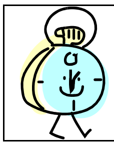
Who is running this project?

- Dr Peter Wilson from RMIT University peter.h.wilson@rmit.edu.au, tel. 9925-2906, Dr Jan Piek, Dr David Sugden, Scott Ruddock, Rhianna Mann, Henry Bell, Daniela Rigoli and Christian Hyde.

What will I do?

You have been chosen to be part of a project about how school children learn new skills like catching, throwing, and jumping.

	You will be asked to do some activities that most children really enjoy like threading beads, balancing on one leg, and jumping as far as you can. We will also ask you to play some games on a computer. On one game you will touch playing cards as quickly as you can as they appear on a computer screen. On another you will try to find a hidden path through a maze, and remember objects that appear on the screen. Last, you will touch targets as they jump from one place to another.	

	We will measure how you go. This will help us learn more about how children do things and how they grow.	

Would you like to be part of the project?

YES 

OR

NO! 

Yes, I would like to do the activities. – Please sign the form ✓

No – That's ok!

Name: ______________________________ **Date:** ______________

THANK YOU ☺

Appendix I Child Development Parent Questionnaire, Study 1, 2, 3

Child Development Questionnaire for Parents/Guardians

The following questionnaire is designed for parent/s who have agreed for their child to participate in the RMIT University study, *'The development of rapid on-line control in children'*. Parents will be asked to answer some questions about their child's development, level of physical activity, and other things associated with physical activity. Your answers will be confidential so please answer them as accurately as possible. If for any reason you do not wish to complete one or more question/s, just go to the next question.

Identifying Information

Your Name: ______________________________

Please provide the following details about your child:

Name: ______________________________

Date of Birth: / /

Gender: Male ☐ Female ☐

Background Information and Participation

Question 1

Has your child had any difficulties learning movement skills? Yes ☐ No ☐

If YES, have these movement difficulties affected any of the following:

Their ability to complete school work	Yes ☐ No ☐
Their ability to perform everyday activities at home (e.g., dress themselves, clean their teeth or cut their food)	Yes ☐ No ☐
Their ability to participate in recreational activities involving movement (i.e., sport, free play, music lessons, etc.)	Yes ☐ No ☐

Question 2

Has your child ever been diagnosed with a major medical condition (e.g., asthma, epilepsy, etc.)? Yes ☐ No ☐

If YES, please specify the condition(s):

____

____

____

____

Question 3
Has your child ever been diagnosed by a health professional with one/or more of the following:

	Tick if Yes
• Motor Coordination Problems	☐
• ADHD	☐
• Conduct Disorder	☐
• Autism Spectrum Disorder (i.e. Asperger's Syndrome or Autism)	☐
• Dyslexia	☐
• Specific Language Impairment	☐
• Other Learning Disorder	☐
• Intellectual Disability	☐

Is your child receiving support for a learning disability? Yes ☐ No ☐
If YES, please specify the disability and type of support:

____

____

Is your child receiving ongoing support for any other disability? Yes ☐ No ☐
If YES, please specify the disability and type of support:

____

____

Question 4
This question asks you to think about all your child's physical activities in the past month.
(i) List the **organised physical activities** that your child has participated in during this time (like netball, football, dancing, lessons, etc.):

____

____

How many hours a week? ________ hours.

(ii) List the types of **free play involving physical activity** that your child has participated in during this time (like hide and seek, chasing games, climbing, etc.):

____

____

How many hours a week? ________ hours.

Question 5

Does your child participate in any seasonal physical activities that they may not have done in the past month? (e.g., football, skiing, swimming) Yes ☐ No ☐

Types of seasonal activity (not listed in Q.4): ____________________________________

____

____

Hours per week: __________

Question 6

Please rate your child's **interest in participating** in organised physical activities (like netball, football, dancing lessons, etc.) or free play involving movement?

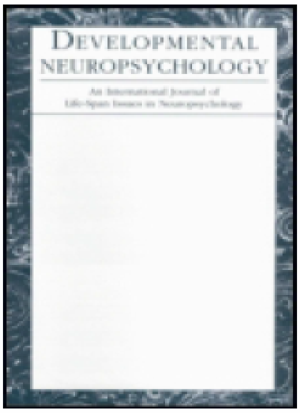
☐	☐	☐	☐	☐
Very Disinterested	Somewhat disinterested	Neutral	Somewhat interested	Very interested

Question 7

Please rate your child's **skill level** when performing physical activities (like those referred to in Question 4 and 5)?

☐	☐	☐	☐	☐
Well below average	Somewhat below Average	Average	Somewhat above average	Well above average

Appendix J Published Article – Study 1



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Executive Systems Constrain the Flexibility of Online Control in Children During Goal-Directed Reaching

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We examined the influence of inhibitory load on online motor control in children. A sample of 129 school children was tested: younger, mid-age, and older children. Online control was assessed using a double-step perturbation paradigm across three trail types: non-jump, jump, and anti-jump. Results show that mid-aged children were able to implement online adjustments to jump trials as quickly as older children, but their performance on anti-jump trials regressed toward younger children. This suggests that rapid unfolding of executive systems during middle childhood may constrain the flexibility with which online control can be implemented, particularly when inhibitory demands are imposed.

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ONLINE CONTROL IS PART OF A BROADER COGNITIVE SYSTEM THAT UNDERLIES ACTION SYSTEMS AND IS SUBJECT TO CHANGING CONSTRAINTS WITH CHILDHOOD DEVELOPMENT

The ability to rapidly and seamlessly adjust arm movements in response to sudden or unexpected changes in the environment (i.e., *online control*) is crucial to flexible and efficient action. Current neuro-computational modeling holds that this form of control is dependent on an individual's ability to generate a predictive model of an intended movement and integrate it "on the fly" with sensory feedback throughout the movement cycle (Desmurget & Grafton, 2000; Izawa & Shadmehr, 2011; Wolpert, Diedrichsen, & Flanagan, 2011). In essence, this mechanism allows the nervous system to circumvent delays associated with basic sensory feedback processing. That is, if incongruence between the estimated (according to the predictive model) and actual consequences of movement is detected, rapid corrective mechanisms can be implemented within 100 msec (Castiello, Bennett, & Chambers, 1998; Paulignan, MacKenzie, Marteniuk, & Jeannerod, 1991), far too quickly to be accommodated by sensory processing alone. Thus, a system of predictive control, also referred to as an *internal feedback loop*, is critical for movement stability under dynamic conditions. From a neural perspective, these systems appear to be supported by finely tuned reciprocal connections between parieto-cerebellar cortices and upstream motor areas (Shadmehr & Krakauer, 2008). Surprisingly, little is known of its development.

Efficient online correction of reaching is a key indicator of a functional and mature motor system. Developmentally, the motor system matures rapidly over childhood; however, the trajectory does not appear to be linear (for a review see Elliott, Chua, & Helsen, 2001). Our earlier work using a double-step perturbation suggests a somewhat different trajectory with rapid development of online control after early childhood (6–7 years), and then similar levels of proficiency when mid-aged (8–9 years) and older (10–12 years) children are compared (Wilson & Hyde, 2013) Results showed that 5–7 year olds were significantly slower to adjust their reaching to visual perturbation than either mid-aged or older children while the latter two groups did not differ. Interestingly, online corrections occurred somewhat earlier in adults, manifest by a more efficient trajectory on jump trials, a pattern not seen in children of any age. Hence, the fast internal feedback loops that support very early and rapid changes in trajectory may not fully mature until adolescence or early adulthood (Farnè et al., 2003).

To date, there is little direct neurophysiological data on rapid online control (and predictive modeling) in children. However, adult data suggests a pivotal role for the parietal cortex, especially the PPC, in the ongoing representation of body schema, the dynamic mapping of limb-to-target relations, and the real-time integration of feedforward commands with sensory feedback. For visually guided reaching, the PPC is thought to play a crucial role in state estimation, continuously integrating dynamic visual inflow with predictive estimates of limb position (Wolpert, Ghahramani, & Flanagan, 2001) and is also involved in processing the resultant error signal; for example, a spike in PPC activity occurs immediately after unexpected target displacement and is tuned to its direction (Reichenbach, Bresciani, Peer, Bulthoff, & Thielscher, 2011). This signal would be transferred to frontal motor centers, modulating the motor command as it unfolds and modifies the flight path of the hand, so to speak, with minimal lag.

Importantly, recent morphological evidence indicates that the cortical structures involved in goal-directed action and predictive control (principally the fronto-parietal axis), follow a protracted period of development (Johnson, 2005). Motor and perceptual centers do mature earlier than higher-cortical areas associated with cognitive control, and the pattern of activation tends to shift from diffuse to more focal with age across childhood (Casey, Tottenham, Liston, & Durston, 2005). Importantly, the rapid improvement in online control we see after early childhood occurs after a period of rapid growth in white matter volume in parietal and frontal cortices. This is followed by a period of neural sculpting during middle and later childhood; a combination of factors, both progressive (i.e., myelination) and regressive (e.g., synaptic pruning and/or grey matter loss) contribute to this, mediated by experience (Casey et al., 2005). A switch from diffuse to localized neural firing throughout this period play an important role in neuro-cognitive development broadly. This process is underpinned by continued white matter maturation but also experience driven synaptic pruning through childhood (and into adolescence), contributing to improvements in cognitive and motor skills (e.g., Barnea-Goraly et al., 2005)). These changes to pre-frontal cortices and their connectivity to other neo- and sub-cortical structures (e.g., visual pathways and cortico-thalamic and cortico-spinal tracts) support greater cognitive flexibility in children, and top-down modulation of what were previously more automatic processes in infants and young children. The ability to enlist inhibitory control in the face of compelling environmental cues is a case in point (Casey et al., 2005). We argue that prefrontal motor control processes that are supported by parieto-cerebellar pathways (e.g., rapid online control and motor adaptation) enable more behavioral flexibility under changing external conditions (Posner, Rothbart, & Sheese, 2007).

INTERACTIVE SPECIALIZATION: IMPLICATIONS FOR THE INTERPLAY BETWEEN ONLINE CONTROL AND EXECUTIVE FUNCTION

The notion of interactive specialization posits that some regions of the cortex, while unfolding at a relatively slow rate, can still modulate the activity of other areas, influencing the tenor of cognitive processing (Johnson, 2005). In other words, the emergence of a new behavior is the result of weighted activity from several brain regions whose modular architecture and rate of maturation may differ in complexity and timescale. Neuronal regions are initially ill-defined and are enlisted in response to a broad range of stimuli. With time and experience, cortical regions become more specialized, and shift from diffuse to more focal activation for a given class of stimuli (Durston et al., 2006). Importantly, functional activity of a given cortical region is determined by how it is coupled to other regions and their modulating effect. New cognitive processes and behaviors thus arise as a result of changes to multiple regions rather than site-specific effects.

In the context of action, frontal systems, in particular, play an increasingly important role in the control of movement throughout development as environmental constraints become more complex or variable and demands on top-down control increase (Brocki & Bohlin, 2004). For example, increases in task complexity that occur when an individual is required to unexpectedly and rapidly adjust their reaching place demands on limited capacity working memory systems, subserved by a functional loop between the dorso-lateral prefrontal cortex and parietal cortex (Suchy, 2009). Moreover the degree of coupling between anterior and posterior regions increases over childhood (Casey, Getz, & Galvan, 2008). Taken together, it is possible that that ability to enlist online control of movement under more complex task constraints (e.g., when executive control demands are higher) may be limited in younger children to the extent that the modulating effect of frontal executive functions is less well coupled to posterior visual-motor centers.

Perhaps the most significant transition in the development of executive function occurs between 4 and 8 years where cognitive flexibility expands concomitant to continued myelination and synaptic pruning of the prefrontal cortex (PFC) and its reciprocal connections downstream (Casey et al., 2008; Johnson, 2005). What is particularly interesting is the fact that at a time when specialized frontal functions are unfolding during middle childhood (but not necessarily consolidated) we also see evidence of different solutions to online control; for example, greater reliance on feedback control under some circumstances (e.g., Chicoine, Lassonde, & Proteau, 1992). That said, we have little direct evidence to test the hypothesis that children of middle childhood perform goal-directed reaching much like older children under simple task constraints, but may struggle when these constraints are heightened, enlisting greater frontal modulation.

Nonetheless, correlational data suggest a link between executive control and the development of movement skill, more generally. We know from behavioral studies that levels of inhibitory control (e.g., Stroop performance and initiation of anti-saccades) are correlated with movement skill in both younger (Livesey, Keen, Rouse, & White, 2006) and older (Piek, Dyck, Francis, & Conwell, 2007) children. Similarly, we see that problems of inhibition are common in children with poor motor skills (Mandich, Buckolz, & Polatajko, 2002; Wilmut, Brown, & Wann, 2007).

We suggest that the development of online control is likely to be constrained by the unfolding of fronto-executive systems. Hence, the aim of this study was to understand how executive control is enlisted in the context of movement that requires rapid online adjustments. Using a double-jump reaching task, we predicted that because mid-aged children are still developing a workable coupling between frontal and posterior (motor control) systems, they would show performance decrements under conditions of inhibitory load; this would result in slower online corrections, and a pattern of behavior more akin to that observed in younger children.

METHOD

Participants

The sample was taken from a larger study in a longitudinal project. The sub-sample consisted of 129 children (56 boys and 73 girls) between the ages of 6 and 12 years. Children were divided into three age bands: young (6–7 years); mid-age (8–9 years); and older (10–12 years). Table 1 displays the descriptive data for age, gender, and handedness of each group. Table 2

TABLE 1
Descriptive Statistics of Age Groups in the Double Jump Reaching Task

	Age		*Gender*		*Handedness*	
	M	*SD*	*Male*	*Female*	*Right*	*Left*
6–7 years ($n = 38$)	7.1	0.6	14	24	33	5
8–9 years ($n = 50$)	8.9	0.6	26	24	48	2
10–12 years ($n = 41$)	10.6	0.5	16	25	38	3

Note. $N = 129$.

TABLE 2
Descriptive Statistics for the Double Jump Reaching Task on Chronometric and Kinematic Variables

		RT (msec)		*MT (msec)*		*ToC (msec)*		*ToC 2 (msec)*		*PCT (msec)*		*AE*		*TDE*		*CTE*		*AJE*	
Age Group	*Trial Type*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
6–7 Years	Non-jump	554	75	469	74	–	–	–	–	–	–	2.85	2.07	5.21	3.36	–	–	–	–
	Jump	580	95	837	158	309	46	–	–	468	62	0.81	0.85	6.10	2.74	1.90	2.08	–	–
	Anti-jump	590	114	1236	238	319	39	619	99	549	112	0.54	0.71	5.14	2.96	0.60	1.58	1.36	2.01
8–9 Years	Non-jump	488	71	476	82	–	–	–	–	–	–	2.00	2.14	4.53	2.95	–	–	–	–
	Jump	511	87	727	92	292	45	–	–	433	63	0.44	0.60	3.89	2.53	0.81	1.17	–	–
	Anti-jump	480	85	1080	160	303	41	571	83	516	96	0.38	0.78	3.66	2.25	0.25	1.00	0.63	1.20
10–12 Years	Non-jump	455	60	434	79	–	–	–	–	–	–	2.26	2.36	4.11	2.93	–	–	–	–
	Jump	458	80	681	80	269	26	–	–	408	65	0.57	0.95	4.11	2.47	1.00	1.37	–	–
	Anti-jump	472	70	984	152	273	26	499	82	477	91	0.63	0.94	3.92	2.76	0.18	0.53	0.82	1.38

Note. RT = Reaction Time; MT = Movement Time; ToC = Time of Correction; ToC2 = Second Time of Correction; PCT = Post Correction Time; AE = Anticipatory Error; TDE = Touch Down Error; CTE = Centre Touch Error; AJE = Anti-Jump Error; msec = Milliseconds.

displays the descriptive statistics of all variables recorded on the double jump reaching task. Parents completed a questionnaire to indicate if their child suffers from a previously diagnosed intellectual/developmental/ learning disorder or serious medical condition (e.g., asthma, visual impairment, epilepsy), which was then corroborated by the child's classroom teacher. Five children were excluded from the study based on a previously diagnosed developmental disorder: one child reported motor control difficulties; one reported Autism Spectrum Disorder; one reported Dyslexia; and two reported Specific Language Impairment. No child reported intellectual disability; accordingly, since all children were recruited from mainstream primary schools, it was assumed that children included in the study were within normal IQ range (Hyde & Wilson, 2011a).

Materials

The Double-Jump Reaching Task (DJRT) paradigm was used to assess online motor control. The VIRTOOLS Software Package (3DVIA, 2010) was used to develop the computer interactive display on a black Samsung 40" touch screen television (refer to Figure 1 for experimental set-up). The television was placed on top of a table with its screen facing up and was raised at a 10^0 angle from horizontal and positioned in portrait view when a child performed the task. The background of the monitor screen was black to match the frame of the TV and reduce contrast while the participant performed the task. The display consisted of a green "home base" circle 2.5 cm in diameter and positioned 5 cm from the edge of the display. Three yellow targets were situated above the home base in the middle of the screen. Target locations were positioned –20^0, 0^0, 20^0 from the direction of the home base target. To account for age-related differences in arm reaching, the distance to the yellow targets were scaled according to arm length (taken

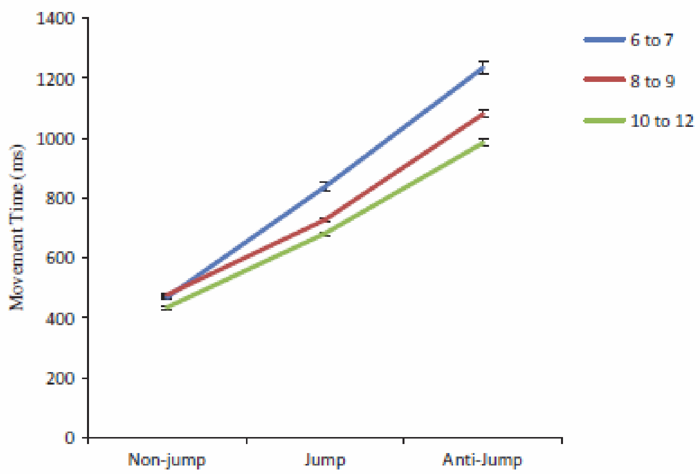

FIGURE 1 Mean movement time (MT +/− SE) values for age groups on the double-jump reaching task. (color figure available online)

from Gerver, Drayer, & Schaafsma, 1989) across the three groups: young children, 25 cm; mid-age children, 28 cm; and older children, 3 cm. Arm movement was captured using the Zebris CMS10 (Noraxon, 2010) system for 3D-motion analysis, which sampled at 200 Hz. It was placed one meter directly above the center-point of the television. A small ultrasonic marker (7 mm in diameter) was used to track arm movement. The marker was connected by cord from the Zebris to the child's dominant index finger and held in place by an adhesive pad that was stuck to the tip of the index finger nail.

Procedure

Principals from six randomly selected primary schools were contacted and invited to participate in the study. Information about the study was sent home via letter with children at each school, outlining the nature of the research to parents. The study was approved by relevant ethics committees. Informed consent was provided by each school principal and children were eligible to participate if their parent/guardian completed and returned an informed consent statement to the head researcher.

Hand preference was assessed using a two-step procedure: (i) children were asked which hand they liked to write with and (ii) children were handed a pen to write their name and observed which hand they used. All trials were performed using the dominant hand. To ensure the cord attached to the kinematic sensor on the child's index finger did not obscure hand movement and interfere with movement trajectory, the researcher secured cord slack away from the child. Before the commencement of the experiment, children were explained the nature of the task. The DJRT was performed in a quiet school classroom with low light to prevent visual feedback from the moving limb (Farnè et al., 2003). Children stood in front of the monitor and used their index finger to reach and touch the targets.

Two versions of the DJRT were administered during the testing session: a typical DJRT and an anti-jump DJRT. For the typical DJRT, the green "home base" was first illuminated at the start of each trial. Children held their index finger stationary on this target until the "home base" light was extinguished and a yellow target was simultaneously illuminated: a random delay of 500–1,500 msec minimized anticipatory effects. To direct visual attention to the same place on each trial, children were instructed to reach and touch in the middle of the target as *quickly and accurately as possible* until the light was extinguished. A successful trial was indicated with an auditory tone when the center of the correct newly acquired target was pressed. For the majority of trials (80%), the initially illuminated target remained stationary until it was pressed (*non-jump* trial). However, for a small percentage of trials (i.e., remaining 20% of trials) the target jumped to either of the peripheral target location after finger lift-off (*jump* trial) from the home base. During these "jump" trials, children were instructed to also *follow and press the middle of the target as quickly and accurately as possible.* Upon completion of each trial, children were instructed to return their finger to home base ready to repeat the next trial.

During the anti-jump DJRT, children performed a modified version of the first DJRT: similarly to the earlier version, for most trials (80%) the target remained stationary for the duration of movement, yet for a small percentage of trials (20%) the target "jumped" laterally at movement onset. During the latter condition, children were instructed to reach to the target on the opposite side of the illuminated target (see Figure 1).

The order in which the two conditions were presented to children was randomized to account for potential learning effects. Within each condition, children were administered two blocks with each block contained 40 trials: 32 *non-jump* trials and 8 *jump/anti-jump* trials (four trials to the left and four to the right peripheral location). The sequence of trials was programmed into the task so that non-jump, jump, and anti-jump trials occurred pseudo-randomly. At the end of each testing block, children were permitted a 2-minute interval to rest.

Before the task commenced, a researcher demonstrated the action required for the 3 trials; *non-jump*, *jump*, and *anti-jump*. Children were then given 10 practice trials (8 *non-jump* trials and 2 *jump/anti-jump* trials) to become familiar with the task. Where necessary, the researcher provided additional practice trials until he was satisfied that children understood the task.

Data Analysis

Chronometric measures taken were reaction time (RT), measured as the time between illumination of the central target and finger lift-off from "home base," and movement time (MT), defined as the time taken between finger lift of from "home base" to the moment the index finger successfully touched inside the yellow target. Only valid *non-jump, jump*, and *anti-jump* trials (i.e., where a child successfully touched the center of a yellow target) were included. Outliers were removed, defined as those values $> +/- 2.5$ *SD*s from the mean. An average of 19 (24%) non-jump trials and 2 (25%) jump/anti-jump trials were removed from the younger group, 18 (23%) and 2 (25%), respectively, from the mid-age group, and 18 (23%) non-jump and 2 (25%) jump/anti-jump trials respectively from the older group. *Jump*- and *anti-jump* trials were collapsed over left and right target locations. Trials that incurred an error were removed from the data set. A criterion of 8 successful *jump/anti-jump* trials per block was set as a minimum requirement to include the data in the analysis. Mean RT and MT were then calculated for each child. Mean RTs were compared between age groups using 1-way ANOVA. The pattern of mean MT was compared between groups using 2-way repeated measures ANOVA (3[Group] $\times$ 2 [Trial Type: Jump & Anti-Jump]). Movement time difference scores were also calculated between the average MT for *non-jump* and *jump* trials (MT_{diff}) and then between *non-jump* and *anti-jump* trials (AMT_{diff}). Each difference score was compared between age groups using 1-way ANOVA.

In addition, three kinematic variables were recorded. Kinematic data (i.e., ToC, ToC2, and PCT) were filtered post-task using a fourth order Butterworth filter with a cutoff of 10 Hz. For *jump*- and *anti-jump* trials, time of correction (ToC) represented the first detectable point at which the finger deviated from its straight movement path toward the center yellow target when it changed direction toward a peripheral target (Hyde & Wilson, 2011b; Pisella et al., 2000; Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007). Similarly to healthy adults who perform tasks that require inhibition of a prepotent response toward a cued stimulus, participants showed a tendency for the hand's "automatic pilot" to initially reach toward the illuminated target on displacement trials of the "anti-jump" DJRT, prior to re-directing their reach trajectory toward the opposite target location (Cameron, Cressman, Franks, & Chua, 2009). Hence, for anti-jump trials two ToC values (ToC and ToC2) were measured: the first trajectory correction away from the initial target to the illuminated target, and a second re-direction of the reach trajectory toward the opposite target location. Movement trajectories were plotted on a 2D Cartesian plane using MATLAB (Mathworks, 2010) computer software where ToC and ToC2 values were independently determined by two researchers to ensure reliability. ToC was analysed using a 2-way repeated measures ANOVA (3[Group: younger × mid-age × older children] × 2 [Trial Type: Jump & Anti-Jump]) to assess for an interaction effect between groups on trials where an inhibitory load is present or not while ToC2 was analyzed using 1-way ANOVA. In addition, post-correction time (PCT) was recorded from the initial point of movement correction on both jump and anti-jump trials to successful finger touchdown on the touchscreen. This was analyzed using 2-way repeated measures ANOVA. Kinematic data (i.e., ToC/ ToC2 and PCT) were filtered post-task using a fourth order Butterworth filter with a cutoff of 10 Hz. For each dependent variable outliers were removed if they were deemed –2.5 < or > 2.5+ *SD* from the mean score.

Four types of response errors were recorded for the DJRT: touch down error (TDE) occurred when children touched outside the boundaries of a yellow target; anticipatory error (AE) was recorded when lift-off from "home base" occurred before the yellow central target was illuminated and/or when RT was less than 150 msec (Wilson, Maruff, & McKenzie, 1997); center touch error (CTE) was defined as a touch to the central target instead of a peripheral target during a jump trial; and anti-jump error (AJE) occurred when children pressed the incorrect (or cued target) during an anti-jump trial. One-way ANOVA was also used to assess the mean difference between groups on each error variable (TDE, AE, CTE, & AJE). Preliminary analyses showed that site location and gender were not systematically related to performance on any measure. Measures of effect size (partial η^2) were used to interpret the magnitude of the effect.

RESULTS

Reaction Time

Overall, there was a significant age effect, $F(2,92) = 24.29$, $p < .001$, partial $\eta^2 = .35$: RTs for older children (462 msec) were faster than 8–9-year-olds (508 msec) who, in turn, were faster than 6–7-year-olds (575 msec).

Movement Time

The mean MT (+/– SE) for each group is displayed in Figure 2. The 2-way ANOVA on mean MT showed a significant main effect for trial type, Wilks' $\Lambda = .08$, $F(2,99) = 609.76$, $p < .001$, partial $\eta^2 = .93$, and age group, $F(2,100) = 18.52$, $p < .001$, partial $\eta^2 = .27$. The interaction between age group and trial type was also significant, Wilks' $\Lambda = .77$, $F(4,198) = 6.91$, $p < .001$, partial $\eta^2 = .12$.

Tests of simple effects showed no differences between the three age groups on non-jump trials. For jump trials, 6–7 year olds (837 msec) were significantly slower than both 8–9 year-olds (727 msec), $p < .001$, partial $\eta^2 = .15$, and 10–12 year-olds (681 msec), $p < .001$, partial $\eta^2 = .28$, while the two older groups were not shown to differ, $p = .23$, partial $\eta^2 = .07$. On anti-jump trials, younger children (1,235 msec) were significantly slower than 8–9 (1,080 msec), $p = .003$, partial $\eta^2 = .13$ and 10–12 year olds (984 msec), $p < .001$, partial $\eta^2 = .28$. The difference between the two older groups was not significant, $p = .079$, partial $\eta^2 = .10$.

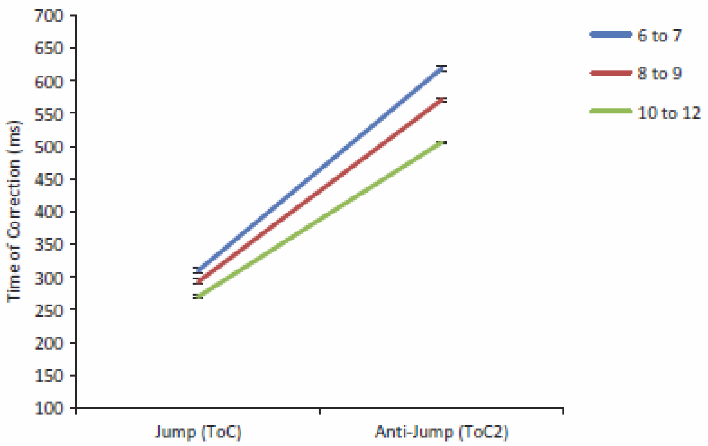

FIGURE 2 Mean time of correction on jump trial and second time of correction on anti-jump trial (ToC and ToC2 +/− SE) values for age groups on the double-jump reaching task. (color figure available online)

Movement Time Difference

The average MT_{diff} score between non-jump trials and jump trials was calculated and compared between the groups. 1-way ANOVA revealed a significant effect for age group, $F(2,116) = 10.54$, $p < .001$, partial $\eta^2 = .15$. Post-hoc tests revealed that the MT_{diff} score for the youngest children (393 msec) was significantly longer than that for 8–9-year-olds (286 msec), $p = .002$, and 10–12-year-olds (253 msec), $p < .001$. The comparison between the two older groups was not significant, $p = .49$.

For the AMT_{diff} score between non-jump and anti-jump trials, 1-way ANOVA revealed a significant age group effect, $F(2,110) = 19.30$, $p < .001$, partial $\eta^2 = .26$. Follow-up tests revealed that the AMT_{diff} score of the youngest children (750 msec) was significantly greater than the 8–9-year-olds (611 msec), whose score, in turn, was greater than the 10–12-year-olds (524 msec), with each $p < .05$.

Time of Correction (ToC and ToC2)

The average ToC (+/− SE) for each group is displayed in Figure 3. The 2-way ANOVA on the mean ToC found no significant interaction between group and trial type, Wilks' $\Lambda = .99$, $F(2,98) = 0.34$, $p = .71$, partial $\eta^2 = .007$. Overall, children were faster to correct initial trajectory on standard jump trials (290 msec) than anti-jump trials (298 msec), Wilks' $\Lambda = .95$, $F(1,98) = 5.47$, $p = .021$, partial $\eta^2 = .05$. The main effect for age group was also significant, $F(2,98) = 12.75$, $p < .001$, partial $\eta^2 = .21$. Averaged over jump and anti-jump trials, older children (272 ms) were significantly faster to correct than 8–9-year-olds (298 msec) who, in turn, were faster than 6–7-year-olds (314 msec).

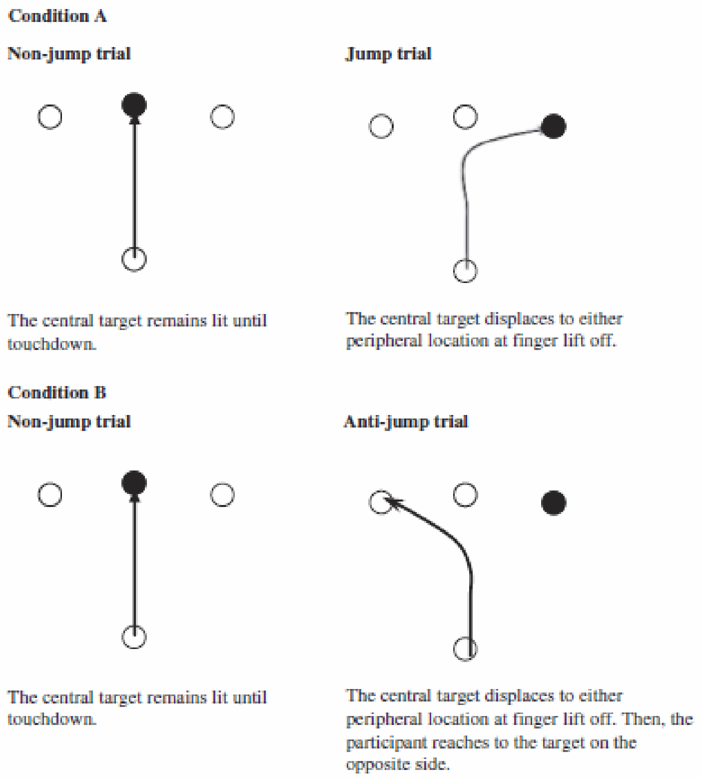

FIGURE 3 Experimental set-up of double jump reaching task for non-jump, jump, and anti-jump trials.

1-way ANOVA on the mean ToC2 showed an overall age effect, $F(2, 113) = 14.33$, $p < .001$, partial $\eta^2 = .20$. Post-hoc tests using Tukey's HSD indicated that older children (506 msec) were significantly faster than mid-aged (571 msec; $p = 005$, $\eta^2 = .12$) and younger children (618 msec; $p < .001$ $\eta^2 = .26$); the latter two groups were not shown to differ ($p = .06$, $\eta^2 = .06$).

Post Correction Time

A 2-way ANOVA showed no significant interaction between group and jump/anti-jump trials on PCT, Wilks' $\Lambda = 1.00$, $F(2,94) = 0.22$, $p = .80$, partial $\eta^2 = .005$. PCTs were faster on jump trials (431 ms) than anti-jump (509 ms), Wilks' $\Lambda = .60$, $F(1,94) = 62.78$, $p < .001$, partial $\eta^2 = .40$. The main effect for age group was significant, $F(2,94) = 6.73$, $p = .002$, partial $\eta^2 = .13$. Averaged over jump and anti-jump trials, 10–12-year-olds (443 msec) and 8–9-year-olds (475 msec) did not differ significantly, while the former were faster than 6–7-year-olds (509 msec).

Errors

Overall, there was no difference between age groups on the mean number of AEs, $p = .19$: 6–7-year-olds (1.4), 8–9-year-olds (0.9), and 10–12-year-olds (1.2). For TDEs, there was a significant age effect: younger children committed more errors (5.5) than 8–9-year-olds (4.0) and 10–12-year-olds (4.0), $F(2,101) = 4.94$, $p = .009$, partial $\eta^2 = .09$. There was no difference between age groups on the number of CTEs, $p = .25$, partial $\eta^2 = .07$: 6–7-year-olds (1.3), 8–9-year-olds (0.5), and older children (0.6). Finally, a 1-way ANOVA on AJEs revealed no difference between age groups, $p = .45$, partial $\eta^2 = .04$: 6–7-year-olds (1.4), 8–9-year-olds (0.6), and older children (0.8).

DISCUSSION

This study investigated how online control develops across childhood and the extent to which it is constrained by demands on (inhibitory) executive control in three different age-groups: 6–7-year olds (younger), 8–9-year olds (mid-age), and 10–12-year-olds (older). Consistent with our predictions, we found that the pattern of performance on non-jump trials was similar between age groups. However, when a target perturbation was applied at movement onset, children in the younger group showed disproportionately slower movement time compared to both mid-aged and older children, as well as slower reaching trajectory corrections. Furthermore, when we imposed the inhibitory demand (instructing children to move their arm to the side opposite the target perturbation, i.e., anti-jump trials), we found that younger children continued to show delayed changes in trajectory and slower movement times compared with older children; indeed, the group difference on MT increased from around 150 msec for jump trials to around 250 msec for anti-jump trials. Interestingly, the performance of mid-aged children was compromised relative to the older group on anti-jump trials, but regressed away from older children on anti-jump trials this was evident on both movement time and a delay in the reaching trajectory away from the illuminated target towards the correct target. This pattern is broadly consistent with the hypothesis that the ability to enlist online control is not linear in development, but depends on the nature of the task constraints and associated load on executive control systems. We argue that the ability to utilize predictive control as a means of reducing the latency of online corrections is well developed by 8–9 years of age. However, in cases where rapid online control must be implemented under conditions of real-time inhibitory load (viz., anti-jump conditions), then the performance of mid-aged children is somewhat constrained. By 10–12 years, children are better able to integrate the demands of both online and executive systems in the service of a goal-directed action. These findings are discussed in further detail below.

Non-Jump Trials

As predicted, an age-effect on RT was observed. Specifically, older children tended to initiate movement more quickly than mid-age children and younger children. This finding accords with earlier developmental research where performance of typically developing primary-school-aged children was compared on the double-step reaching task (Hyde & Wilson, 2013). Since the time taken to initiate reaching toward a prepotent visual target likely reflects information/neural processing efficiency (Wilson & McKenzie, 1998), this pattern of results supports developmental literature suggesting increased processing efficiency between the ages of 5 and 12 years, linked to white matter maturation among other factors (Barnea-Goraly et al., 2005; Luna, Garver, Urban, Lazar, & Sweeney, 2004).

The mean MT of each group was similar on non-jump. Simple, stimulus-driven movements of this type place minimal demands on online control (and hence predictive modeling). Computationally, since the target remains stationary throughout the movement; discrepancy between the expected (according to the predictive model) and actual consequences of action is minimal, assuming that the initial motor command is accurate (Desmurget & Grafton, 2000). Accordingly, in light of current accounts of motor control (i.e., Shadmehr, Smith, & Krakauer, 2010), our results suggest that the ability to complete rudimentary movements within peripersonal space is well developed by 5 years of age (e.g., Chicoine et al., 1992). Importantly, the similar movement times observed across age-groups here on non-jumps highlights that the developmental differences we observed for jump and anti-jump reaching cannot be explained by general maturation of the motor system but rather by the unfolding of specific control systems (i.e., predictive modeling and executive functioning). This argument is taken up below.

Jump Trials

Like earlier studies (e.g., Castiello et al., 1998; Farnè et al., 2003; Hyde & Wilson, 2011a; Paulignan et al., 1991), MT increased from non-jump to jump trials. This is explained by the added processing demands in detecting target perturbation and then implementing a corrective shift in movement trajectory (which itself was longer in distance). The additional time taken to implement the anti-jump movement can be attributed to the demands imposed on inhibitory processing and the associated requirement that children withhold the prepotent response to the cued location and then implement a movement to the opposite side.

Younger children were disadvantaged by target shifts relative to mid-aged and older children, as shown by the significant interaction between age and trial type on MT. Whereas there was significant difference between groups when the target remained stationary, younger children were slower to adjust on jump trials: MT*diff* scores were significantly longer for younger children (393 msec) compared with both mid-aged (286 msec) and older children (253 msec). This pattern replicates an earlier study by our group (Hyde & Wilson, 2013). Across both studies, the slower adjustments to target perturbation shown by younger children suggests that the process of motor prediction that supports rapid online control is less efficient in younger children but develops rapidly after the age of 6–7 years. Indeed, the performance of 8–9-year-olds was not significantly different to that of older children on standard jump trials, suggesting a more gradual trend in development from middle childhood. Analysis of kinematic variables further support this view: correction of the reaching trajectory occurred later for younger children (309 msec) compared with both mid-aged (292 msec) and older children (269 msec), with the latter two groups not shown to differ significantly. Importantly, ToC reflects the stage in reaching where *internal* feedback signals are integrated with the motor command to initiate correction away from the initial direction of movement. Higher ToC suggest that this aspect of predictive control is not fully integrated into the motor system of younger children. Taken together, our results for jump performance supports a growing body of evidence suggesting that online control (i.e., predictive modeling) mechanisms undergo rapid developmental change between the ages of 6 and 8 years, with less marked change during the later stages of childhood (Casey et al., 2005, 2008; Johnson, 2005, 2011). Other data suggest that further changes occur after the age of 12 years and into early adulthood, although the exact trajectory is unknown (Hyde & Wilson, 2013).

Anti-Jump Trials

Crucially, we observed significant group differences between mid-aged and older children on MT when an inhibitory load was imposed on the movement following target perturbation. This was shown by progressively smaller AMT*diff* scores with age: the difference in MT between non-jump and anti-jump trials was greater in 6–7-year-olds (750 msec) than 8–9 year-olds (610 msec), whose score, in turn, was greater than the older children aged 10–12 years (524 msec). In contrast, no such difference between mid-aged and older children was observed on MT*diff* scores.

On the kinematic data, there was a tendency for children to perform a two-step correctional process: first an initial correction toward the illuminated target prior to re-directing their reach in a second stage toward the opposite target location. This pattern of performance is a stable characteristic of healthy adults when performing similar tasks (e.g., Cameron et al., 2009) The lack of condition effect when comparing this initial ToC measure on anti-jump trials to ToC values measured during jump trials suggests that the hand's "automatic pilot" is initially drawn to the illuminated target (Cameron et al., 2009; McIntosh, Mulroue, & Brockmole, 2010; Striemer, Yukovsky, & Goodale, 2010). Importantly, the second corrective movement (i.e., ToC2) indicates conscious and purposive inhibition of the nervous system's tendency to reach toward a prepotent (yet incorrect) target before re-directing the hand to the opposite (correct) target. Our data confirms this pattern and showed that younger and mid-age children not only took longer to make the first automatic correction, but also took significantly longer (618 msec and 571 msec, respectively) to inhibit their response from the cued location than older children (506 msec). In contrast on standard jump trials, children were merely required to correct their reaching toward the new stimulus location, the shifting target serving to bias trajectory in, at least, a spatially meaningful way. The pattern of performance for anti-jump trials supports the hypothesis that mid-aged children are less efficient at implementing online control when demands on inhibition are imposed, performing more like younger children than older.

This suggests a crucial transition in both executive control and motor systems during middle childhood, an age where motor control is thought to transition to a well-integrated system of feedback and feedforward mechanisms (Pellizzer & Hauert, 1996). During this same maturational period, frontal executive systems undergo a period of rapid growth and brain connectivity which sees executive systems exert more (top-down) control over behavior (Durston et al., 2006). However, some theorists point to a lag period during which the child learns (implicitly) to harness or couple these emerging frontal networks to other systems (Johnson, 2011). In the case of adaptive online control, the child must learn to couple frontal executive systems to the more automatic online control systems of the dorsal stream. As such, we might expect to see a performance decrement in middle childhood when a task places demands on both systems; experience-dependent learning to that point in development is perhaps not sufficient to build an integrated network of top-down modulation.

Taken from the perspective of interactive specialization, maturation of different cortical zones can change how previously acquired cognitive functions are represented in the brain (Johnson, 2011). That is to say that the same behavior could potentially be supported by different neural substrates at different ages during development. Developmental studies of children reveal that cognitive processes emerge at different points in time, each showing its own maturational trajectory (Anderson, 2002; Garon, Bryson, & Smith, 2008). In general, executive function develops rapidly during the primary school years and then continues at a slower pace during adolescence (Anderson, 2002). During this time, the emergence of complex processes such as set shifting, working memory and inhibition may take some time to be integrated efficiently with existing processes, perceptual-motor and other. The question here is to assess is how inhibitory control becomes integrated into functional systems of motor control.

At a neural level, behavioral improvements in inhibition appear to be paralleled by refinements in the underlying brain activity in the PFC and in networks that include the PFC (Durston et al., 2006). We know that frontal systems reach a peak in synaptogenesis during early childhood, and that structural MRI shows a progressive increase in myelination along anterior-to-posterior pathways over childhood and adolescence, including reciprocal connections to the PPC (Bunge & Wright, 2007; Durston et al., 2006). Indeed, diffusion tensor imaging research also suggests that white matter development underlies an important role with mechanisms that shape cognition (Barnea-Goraly et al., 2005), and subcortical structures may play a role in rapid adjustments to target perturbations (Day & Brown, 2001). While these structural changes occur rapidly over early development, the degree of functional coupling that occurs along these networks appears to be more protracted. The online control system that supports (simple) goal-directed reaching is quite functional by early childhood, but undergoes significant change between 5 and 8 years. However, the difficulty that mid-aged children had with online adjustments under an inhibitory load supports the hypothesis that coupling between anterior and posterior systems takes some time to fully emerge. Our data show that the coupling unfolds rapidly between middle and later childhood, while experience-driven learning continues to influence the development of motor and executive systems.

In terms of attentional shifts to abrupt-onset cues, the consensus of opinion is that the process of engagement and disengagement is largely a motor preparatory process (Rizzolatti, Riggio, & Sheliga, 1994). More specifically, the putative disengagement process has been conceptualized as an aspect of inhibitory motor control (Mandich, Buckolz, & Polatajko, 2003). As such, it could be argued that the effects we observed for the jump trials could involve aspects of motor inhibition. For anti-jump, the inhibitory demand is such that more controlled, frontal processing is required to counter the compelling effect of the cued target location on motor planning and, hence, hand trajectory. Further research is needed to disentangle these components of attention and motor control as a function of task complexity.

Limitations

For repeated movements during which we experience error between the intended action and incoming sensory information (i.e., a target shift), it is possible that a memory representation builds up for the adjusted movements (Shadmehr et al., 2010). In other words, the repeated corrections to limb position could act as a training signal for the brain. This has been observed for actions involving mechanical perturbation of the moving limb: the motor memory associated with the effects of the perturbation may provide advance information for subsequent motor commands. However, when this logic is applied to the paradigm used in our study, it is unlikely that memory effects would accrue over repeated arm movements because there were only a limited number of jump/anti-jump trials within a given block, and those that did were interspersed randomly. Furthermore, we counterbalanced the order of jump and anti-jump conditions to ensure learning effects were minimized. In the future, we could vary the probability of jumps and also compare early and late trials on our task to resolve memory-related effects from predictive control per se.

CONCLUSION

For some time now, the maturational viewpoint has been a widely adopted explanation of motor development in children. Maturational theories seek to interpret emerging sensory, motor, and cognitive functions in terms of the development of particular regions of the brain, usually specific areas of cerebral cortex. Alternatively, under the assumption of interactive specialization, a new cognitive function or skill is acquired through the re-organization of interactions of different brain structures and regions. Our results are broadly consistent with this view as they show that age-related variation in the ability to implement rapid online is contingent on (frontal) inhibitory constraints. By middle childhood, online adjustments can be implemented as quickly as those seen in later childhood. However, when demands are imposed on executive systems (as per anti-jump trials) online corrections are slowed in mid-aged children relative to older. Rapid maturation of executive systems during this period may constrain the flexibility with which online control can be implemented. More precisely, the ability to modulate online control via the inhibitory system requires a more protracted period of development over childhood.

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Appendix K Published Article – Study 2

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ELSEVIER

Coupling online control and inhibitory systems in children with Developmental Coordination Disorder: Goal-directed reaching

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ABSTRACT

For children with Developmental Coordination Disorder (DCD), the real-time coupling between frontal executive function and online motor control has not been explored despite reported deficits in each domain. The aim of the present study was to investigate how children with DCD enlist online control under task constraints that compel the need for inhibitory control. A total of 129 school children were sampled from mainstream primary schools. Forty-two children who met research criteria for DCD were compared with 87 typically developing controls on a modified double-jump reaching task. Children within each skill group were divided into three age bands: younger (6–7 years), mid-aged (8–9), and older (10–12). Online control was compared between groups as a function of trial type (non-jump, jump, anti-jump). Overall, results showed that while movement times were similar between skill groups under simple task constraints (non-jump), on perturbation (or jump) trials the DCD group were significantly slower than controls and corrected trajectories later. Critically, the DCD group was further disadvantaged by anti-jump trials where inhibitory control was required; however, this effect reduced with age. While coupling online control and executive systems is not well developed in younger and mid-aged children, there is evidence of age-appropriate coupling in older children. Longitudinal data are needed to clarify this intriguing finding. The theoretical and applied implications of these results are discussed.

1. Introduction

Deficits in motor prediction have been implicated as one possible cause of motor clumsiness in children with Developmental Coordination Disorder (Hyde & Wilson, 2013). A recent meta-analysis has shown deficits in studies as varied as target-directed reaching, grip force control, dynamic balance, and eye-movement control (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). Also seen as part of the constellation of processing problems in DCD is poor executive control, evident across tasks of selection attention, working memory, and response inhibition. Of some importance in

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developmental terms is how predictive (online) control and executive function (EF) are coupled in the service of goal-directed action. This issue has also emerged as a focus in recent developmental research (Gonzalez et al., 2014) with data showing that motor control and EF emerge along similar timelines and share overlapping neural networks (Pangelinan et al., 2011). To address this issue in relation to the neurocognitive underpinnings of DCD, we enlisted a double-jump paradigm performed with and without inhibitory constraints.

The ability to correct one's movement in response to unexpected target or environmental changes (viz. online control) is a critical part of efficient, goal-directed action. Recent neuro-cognitive models of human reaching propose that online control occurs by the action of *internal feedback loops* that generate forward estimates of the dynamics of limb position and egocentric location – a process referred to variously as (forward) internal modelling or predictive control (Ruddock et al., 2014). This system of rapid control is critical for movement stability because of processing delays associated with sensory feedback loops and general impedance of the motor plant (Wolpert & Flanagan, 2001). For visually guided movements, adult studies have shown recruitment of reciprocal loops between premotor cortex, posterior parietal cortices (PPC), and cerebellum, with strong PPC-cerebellar activation under target perturbation (Gréa et al., 2002; Reichenbach, Bresciani, Peer, Bulthoff, & Thielscher, 2011; Reichenbach, Thielscher, Peer, Bülthoff, & Bresciani, 2014). Only recently has the nature of online control in children with and without motor difficulties been studied with renewed focus.

Available data suggest that mechanisms linked to fast corrective processes undergo considerable change between 6 and 12 years of age (Bard, Hay, & Fleury, 1990; Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007; Wilson & Hyde, 2013). Younger children (5–7 years of age) are able to generate fast, ballistic movements but are slower to integrate online feedback when correcting their reaching mid-flight, resulting in reduced endpoint accuracy and/or inefficient timing. During middle childhood (around 8–9 years) there is earlier and greater use of sensory feedback (e.g. Chicoine, Lassonde, & Proteau, 1992) as both feedforward and feedback (predictive) control become better integrated, resulting in better online error correction. By 9–12 years, the system of predictive control is well developed, approaching adult levels (e.g. see Wilson & Hyde, 2013).

It is no coincidence that the developmental timescale over which online control unfolds coincides with periods of increased myelination and structural connectivity along fronto-parieto pathways (Casey, Tottenham, Liston, & Durston, 2005; Lebel, Walker, Leemans, Phillips, & Beaulieu, 2008). Predictive control in particular is underpinned by maturation of reciprocal connections between frontal, parietal and cerebellar cortices, pathways that are sculpted by experience (Gaveau et al., 2014) In short, an interplay between external (i.e., experiential) and internal (e.g. neural myelination and synaptic pruning) factors support the fidelity of predictive control with development (Casey, Getz, & Galvan, 2008).

A unifying hypothesis in cognitive neuroscience that can shed light on the development of function in DCD is the notion of *interactive specialization* (Johnson, 2011). Here it is posited that behavioural competencies unfold through the interaction of several brain regions whose individual growth trajectories may differ in developmental time. For example, (automatic) online control is supported by fast dorsal motor systems (Pisella et al., 2000) that forge reciprocal connections with frontal executive systems over the course of childhood, bestowing a degree of flexibility in action (i.e. Ruddock et al., 2014). However, this coupling between motor and executive systems is not well refined until later childhood. Using a target perturbation paradigm, we found that under an inhibitory load (or anti-reach condition), the ability to adjust movement trajectory was reduced in mid-aged children (8–9 years) relative to older children (10–12 years), despite the fact that online control per se was well developed by 9 years of age (Wilson & Hyde, 2013). We observed that the time taken to correct reach trajectories (in this case to the hemi-space opposite the target jump) increased in mid-aged children to an extent similar to that seen in younger children (6–7 years). We argued that while frontal systems are unfolding rapidly during the middle childhood period, there is lag in the coupling of these systems to more posterior perceptual–motor systems. Only by later childhood do we see evidence of more seamless integration of fronto-parietal systems, manifest as smooth and efficient reach trajectories and greater endpoint accuracy under not only double jump constraints but also anti-reach conditions (Wilson & Hyde, 2013).

1.1. The link between executive function and online control in children with Developmental Coordination Disorder

Importantly, deficits in both executive and motor control systems are widely reported in children (Livesey, Keen, Rouse, & White, 2006; Michel, Roethlisberger, Neuenschwander, & Roebers, 2011; Piek, Dyck, Francis, & Conwell, 2007) and adolescents (Rigoli, Piek, Kane, & Oosterlaan, 2012) with atypical motor development (or DCD), suggesting that the process of coupling between systems may be particularly problematic with development. Recent studies of goal-directed reaching have shown that children with DCD aged 8–12 years are disadvantaged by target perturbation, taking longer to correct movements on jump trials (Hyde & Wilson, 2011a). This pattern of performance is thought to reflect an underlying difficulty using predictive models of action. Additionally, Hyde and Wilson (2013) showed that the performance of children with DCD aged 8–12 years was not qualitatively different to younger typically developing children suggesting a neurodevelopmental delay in structures that underpin predictive control, particularly fronto-parietal and parieto-cerebellar loops. Other work using fMRI suggests possible disruption of top-down (or anterior) modulation of posterior networks for tasks requiring inhibition (Querne et al., 2008). Converging evidence of reduced executive function in DCD (Piek et al., 2007; Wilson et al., 2013) suggest a more generalised level of delay in these children.

Problems of inhibitory control are particularly common in DCD (Livesey et al., 2006; Michel et al., 2011). On the Simon Task, for example, children with DCD show difficulty inhibiting a manual response to a visual stimulus relative to controls

(Mandich, Buckolz, & Polatajko, 2002). On tasks of *voluntary* visuospatial attention, poor inhibitory control has also been identified (Mandich, Buckolz, & Polatajko, 2003; Tsai, Yu, Chen, & Wu, 2009; Wilson & Maruff, 1999; Wilson, Maruff, & McKenzie, 1997.), inferred from a reduced ability to disengage visual attention from invalidly cued locations (Mandich et al., 2003). This raises the possibility that children with DCD may be particularly disadvantaged when called to enlist inhibitory control in the context of a motor task requiring motor prediction.

Our main hypothesis here is that impaired coupling between frontal executive and more posterior visuo-motor regions associated with predictive control (and spatial updating) may be an important factor in DCD. Hence, the broad aim of our study was to examine whether poor online control in DCD is exacerbated when tasks demand higher levels of executive control, specifically response inhibition. Addressing this issue will also clarify the often cited observation that motor skill deficits in DCD are more pronounced under conditions of high cognitive load (Wilson et al., 2013). Specifically, we assessed children's ability to implement rapid online corrections on a double-jump perturbation paradigm under three task conditions: non-jump, jump, and anti-jump. In line with earlier studies of online control (Hyde & Wilson, 2011a, 2011b, 2013) we predicted that, overall, children with DCD would be slower to correct their reach trajectory mid-flight following an unexpected target shift than typically developing children. Moreover, we also predicted that their performance would be further compromised by the addition of an inhibitory load (viz. anti-reach condition), manifest as slower movement time and delayed time to correction, but that the deficit would be less pronounced in older children in lieu of the developmental delay suggested by earlier work (Hyde & Wilson, 2013).

2. Method

2.1. Participants

The sample was drawn from a large longitudinal project and consisted of 129 children: 42 in the DCD group and 87 in the control group (refer to Table 1 for descriptive data). Group selection involved a two-step process: (a) parents completed a medical and developmental history questionnaire and (b) children's motor proficiency was tested using the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997). On the MAND, children who scored less than 15th percentile (Noten, Wilson, Ruddock, & Steenbergen, 2014; Piek, Baynam, & Barrett, 2006) (Criterion A), whose difficulty learning motor skills was deemed to interfere with daily activities (Criterion B), and whose movement difficulties were evident by school age (Criterion C), were included in the DCD group. Children scoring above 20th percentile were placed into the control group (Hyde & Wilson, 2011a). Additionally, selection for the DCD group adhered to research criteria specified from the Diagnostic and Statistical Manual 5 (American Psychiatric Association, 2013). Children were excluded from the study if they reported a developmental, neurological and/or physical condition (Criterion D), which was confirmed by the child's school health officer. As children were recruited from mainstream primary schools and attending standard classes, intelligence was assumed to within the normal range (Gueze, Jongmans, Schoemaker, & Smits-Engelsman, 2001).

All children and parents gave their informed consent to participate in the study which was approved by institutional and government research ethics committees.

2.2. Instrumentation

A modified version of the Double-Jump Reaching Task (DJRT) was used to assess online motor control using VIRTOOLS Software Package (3DVIA, 2010) and presented on a black Samsung 40-in. touchscreen. The touchscreen was in portrait orientation on a table and elevated at 10° from horizontal. The background of the display was black to match the bezel of the TV, reducing contrast interference. The computerised display consisted of a circular 'home base', 2.5 cm in diameter, positioned centrally 5 cm from the near edge of the bezel. Three yellow targets were positioned above the home base, located at −20°, 0°, 20° from a vertical line extending upward from the home base. All target distances were scaled according to three age groups: young children, 25 cm; mid-age children, 28 cm; and older children, 30 cm (Gerver, Drayer, & Schaafsma, 1989). Arm movement was recorded using the Zebris CMS10 (Noraxon, 2010) system for 3D-motion analysis with 200 Hz sample rate. The motion tracking system was secured to the table and positioned at a height of 1 m above the centre of the screen. A 7 mm ultrasonic sensor/marker was attached by adhesive pad to the child's dominant index finger tip and tethered with adhesive tape along the arm and then to the Zebris receiver.

Table 1
Sample characteristics for the DCD and control groups.

	Control					DCD				
	n	Sex		Age (years)		*n*	Sex		Age (years)	
		Girls	Boys	*M*	*SD*		Girls	Boys	*M*	*SD*
6–7	26	17	9	7.20	0.46	10	5	5	7.27	0.69
8–9	38	23	15	8.92	0.63	16	5	11	8.87	0.63
10–12	23	13	10	10.74	0.49	16	10	6	11.07	0.38

Note. $N = 129$

2.3. Procedure

Hand preference was assessed by asking each child which hand children he/she wrote with, and then observing them as they wrote their name. The DJRT was performed in a quiet classroom under low lighting conditions to prevent visual feedback from the hand (Farnè et al., 2003) and the imposition of environmental distractors. At the beginning of the DJRT, the nature of the task was explained and the child was then directed to stand in front of the screen while the kinematic sensor was attached to the index finger of their dominant hand.

Testing was conducted in two blocks, with the order of conditions randomised: a typical 'jump' DJRT and modified 'anti-jump' DJRT. For the jump condition, children were instructed to place their index finger on the green home base at the beginning of each trial. The three possible target locations were indicated at the start of each trial, while individual targets per se were triggered on a trial-by-trial basis by a doubling in luminance. The finger was held stationary until the home base was extinguished and the middle yellow target doubled in luminance at the same time and a random delay of 500–1500 ms was programmed across trials to ensure participants did not anticipate the change in target illumination. Children were instructed to *follow the target* and touch its centre as *quickly and accurately as possible*. A successful trial resulted in the newly acquired target light being extinguished while an auditory tone was emitted to reinforce to children that the trial was complete. On 80% of trials the middle target remained lit until touched (*non-jump* trial) while on 20% of trials the location of the target jumped at movement onset either to the left or right position (*jump* trial). At the end of each trial, children repositioned their finger back on home base in readiness for the next trail. The anti-jump condition was administered using the same procedure described for the jump condition. However, children were instructed to reach and touch the opposite side (*anti-jump* trial) when the target shifted to a peripheral location (refer to Fig. 1).

At the commencement of the first condition, the researcher modelled the action necessary for *non-jump, jump*, and *anti-jump* trials. Children were then given 10 practice trials to familiarise themselves with the nature of the task and permitted additional practice trials if task requirements were not met. Children performed two blocks within each condition; each block was of 40 trials (32 *non-jump* and 8 *jump/anti-jump*) which were interspersed pseudo-randomly across left and right target locations. At the end of the first condition, children were permitted a 2 min rest before commencing the second condition. Total administration time of the task was 15 min.

2.4. Data analysis

For each child, reaction time (RT) and movement time (MT) of the DJRT was recorded. Only successfully completed trials were included and outliers for all chromomeric and kinematic variables were excluded from analysis; outliers were defined as values $>\pm 2.5$ *SDs* from the mean (Ruddock et al., 2014). An average of 20 (14%) non-jump trials and 4 (25%) jump/anti-jump trials were removed from the DCD group, and 18 (13%) and 3 (19%) respectively from the control group. *Jump*- and *anti-reach* trials were aggregated over left and right target locations and eight successful *jump/anti-jump* trials per block was a minimum requirement for valid data inclusion (Ruddock et al., 2014). MT was compared between groups using 3-way repeated measures ANOVA (3 [Age] $\times$ 2 [Skill Group] $\times$ 3 [Trial: non-jump, jump & anti-jump]). RT was compared between groups using 2-way repeated measures ANOVA (3 [Age] $\times$ 2 [Skill Group]). We measured the impact of the inhibitory load on online control by calculating the difference in MT between anti-jump and jump trials ($AJMT_{diff}$). Specifically, using a 2-way ANOVA, we tested whether the effect of inhibitory load (as measured by $AJMT_{diff}$) varied as a function of the interaction between group and age.

Kinematic variables were time of correction (ToC) and time of correction 2 (ToC2; for anti-reach trials only which was the interval between first corrective movement onset and the point at which spatial trajectory changed towards the location opposite that of the target), and were filtered post-task using a fourth order Butterworth filter with a cut off of 10 Hz. For jump trials, time of correction (ToC) was defined as the point at which the hand initiated a change in direction away from the centre target towards the left or right peripheral target (Hyde & Wilson, 2011b). On anti-jump trials, the critical deviation in trajectory occurs after an initial deviation towards the cued location (Cameron, Cressman, Franks, & Chua, 2009); this second correction (ToC2) reflects the implementation of inhibitory control as part of the corrected movement plan towards the location opposite the cued side. All participants demonstrated a tendency for the hand to be drawn first towards the illuminated target before (purposefully) redirecting movement to the opposite target location (Cameron et al., 2009). Finally, post correction time for anti-jump trials (PCT-AJ) was defined as the time taken after TOC2 to touch the location contralateral to the cue.

Movement trajectories were plotted on a 2D Cartesian plane using MATLAB (Mathworks, 2010) computer software and ToC and ToC2 values were determined by two independent raters (Ruddock et al., 2014). Time of correction was analysed using 2-way repeated measures ANOVA (2 [Age] $\times$ 2 [Skill Group]).

Error responses were also recorded on the DJRT. A touch down error (TDE) occurred when a participant touched outside of the yellow target boundary. Anticipation error (AE) was recorded when finger lift-off from 'home base' occurred before the yellow central target illuminated. Logically, this cannot vary as a function of cue type as there is no probability information available to predict this with any certainty. Centre touch error (CTE) was defined as a touch to the centre target instead of a peripheral target during a *jump/anti-jump* trial. Finally, an *anti-jump* error (AJE) occurred when the incorrect (i.e., cued target) was touched on anti-jump trials.

Initial analyses showed that both gender and site locations were not systematically related to performance on any measure. Partial η^2 was used to interpret the magnitude of the effect size.

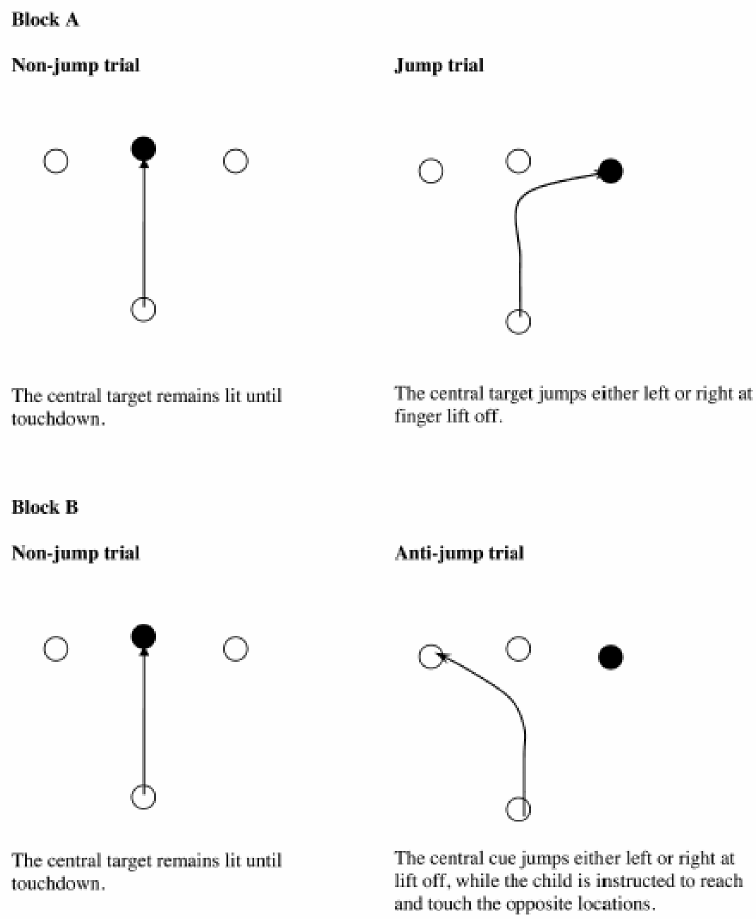

Fig. 1. Experimental set-up for the double jump reaching task showing trial types over two blocks of trials.

3. Results

Table 2 displays the values for each variable across skill group and age.

3.1. Reaction time

As there were no significant effects involving trial type, mean RT was averaged over this factor. Two-way ANOVA showed a significant main effect for age, $F(2,127) = 33.58$, $p < .001$, partial $\eta^2 = .35$, with younger children (607 ms) slower than mid-aged (499 ms) who were in turn slower than older (442 ms), $p < .05$. The main effect of group was also significant with controls (498 ms) faster than DCD (540 ms), $F(1,127) = 10.39$, $p = 002$, partial $\eta^2 = .08$. The interaction between age and group was not significant, $F(2,127) = 2.40$, $p = .10$, partial $\eta^2 = .04$.

3.2. Movement time

Mean MT (±SE) for age groups within DCD and control group are displayed in Fig. 2. 3-way ANOVA on MT showed significant main effects for age, $F(2,123) = 54.63$, $p < .001$, partial $\eta^2 = .47$, skill group, $F(1,123) = 14.42$, $p < .001$, partial $\eta^2 = .11$, and trial, Wilks' $\Lambda = .08$, $F(2,122) = 754.88$, $p < .001$, partial $\eta^2 = .93$. The higher order 3-way interaction between these factors was also

Table 2
Descriptive statistics for the performance of DCD and Control groups on the Double Jump Reaching Task.

Skill	Age	Trial	MT (ms)		$AJMT_{diff}$ (ms)		ToC (ms)		ToC2 (ms)		PCT-AJ (ms)		TDE		AE		CTE		AJE	
			M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Control	6–7	N-J	504	88									7.96	7.28	3.58	2.73				
		J	855	157			307	51					5.32	3.19	1.08	1.26	2.73	2.97		
		A-J	1220	215	352	170	304	41	625	115	594	115	3.31	2.15	1.00	1.20	0.38	1.02	0.96	1.40
	8–9	N-J	497	93									5.00	5.16	1.66	1.73				
		J	733	95			286	36					3.26	2.67	0.76	1.60	1.55	2.29		
		A-J	989	140	248	102	272	40	497	81	488	75	3.08	2.16	0.53	0.65	0.53	0.95	0.79	1.23
	10–12	N-J	445	68									3.43	3.38	1.35	1.53				
		J	630	67			252	36					1.78	2.07	0.48	0.66	0.29	0.55		
		A-J	840	116	210	91	242	27	421	70	417	53	2.43	1.56	0.52	0.79	0.17	0.48	0.50	1.17
DCD	6–7	N-J	620	140									11.00	8.31	4.30	3.74				
		J	894	114			375	70					4.60	3.10	1.60	1.51	1.10	1.73		
		A-J	1393	139	499	166	361	38	691	94	707	117	3.80	2.10	1.70	1.16	0.50	0.85	1.00	1.49
	8–9	N-J	482	80									7.06	5.97	5.00	5.37				
		J	792	141			320	51					4.50	2.83	0.81	0.66	2.06	3.70		
		A-J	1135	175	359	128	309	53	566	87	564	108	3.25	1.65	0.88	1.03	0.24	0.44	1.29	1.40
	10–12	N-J	468	91									3.31	2.91	2.00	2.00				
		J	685	114			272	39					1.94	1.95	0.56	0.89	0.25	0.68		
		A-J	892	134	207	99	269	40	442	70	450	74	2.13	1.86	0.69	1.20	0.31	0.48	0.38	0.89

Note. MT = movement time, $AJMT_{diff}$ = movement time difference between anti-jump and jump trials, ToC = time of correction (jump trials), ToC2 = time of correction for anti-jump trials, PCT-AJ = post correction time anti-jump trials, TDE = touch down error, AE = anticipation error, CTE = centre touch error, AJE = anti-jump error, N-J = non jump, J = jump, A-J = anti-jump.

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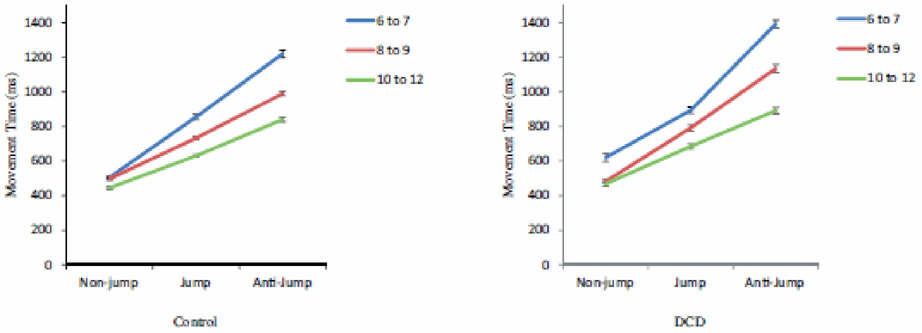

Fig. 2. Mean movement time (MT ± SE) values of young (6–7), mid-age (8–9) and older (10–12) children for DCD and control groups on the double-jump reaching task.

significant, Wilks' Λ = .91, $F(4,244)$ = 2.92, p = .022, partial η^2 = .05. Simple interaction effects were therefore explored within each skill group.

For the control group, there was a significant simple interaction between age group and trial, $F(4,166)$ = 12.80, p < .001, partial η^2 = .24. Follow-up tests of the simple effect of age revealed the following: for non-jump trials, there was no significant difference between mid-aged and younger children, whereas both these groups were slower than the older children. For jump trials, younger children were slower than mid-aged who, in turn, were slower than older children (by around 105 ms). For anti-jump trials, younger children were slower than mid-aged (by ~230 ms) who, in turn, were slower than older children (by around 150 ms).

For the DCD group, the simple interaction between age and trial type was also significant, $F(4,76)$ = 8.67, p < .001, partial η^2 = .31. For non-jump trials, mid-aged and older children with DCD were not shown to differ, unlike controls; both these groups were, in turn, faster than younger children. For jump and anti-jump trials, the pattern of differences between age groups was similar to that shown for controls; however, the mean difference between mid-aged and older children on anti-jump trials was very large at around 245 ms.

Importantly, for older children on anti-jump trials there was no significant difference between skill groups whereas the same comparisons for mid-aged and younger children showed faster performance in controls.

We also examined the magnitude of group differences within each trial condition. For non-jump trials, the effect of group varied with age: there was no difference between mid-aged DCD and control children (partial η^2 = .00), and between older DCD and controls (.05). However, younger children with DCD (630 ms) were significantly slower than younger controls (501 ms), partial η^2 = .27. For jump trials, the significant difference between DCD and controls (partial η^2 = .05) did not vary as a function of age: the simple interaction of group by age was not significant, $F(2,132)$ < 1. Finally, for anti-jump trials, the difference between DCD and control groups varied as a function of age: for younger children, partial η^2 = .20, for mid-age (.17), and for older children (.04).

3.3. Anti-jump movement time difference

The mean AJMT$_{diff}$ for DCD and control group is displayed in Fig. 3. Three outliers (2 older controls and one mid-aged DCD) were removed from the 2-way ANOVA as values were greater than 2.5 *SDs* from the mean. Results showed a significant main effect for age group, $F(2,120)$ = 24.47, p < .001, partial η^2 = .29, with values for younger children (395 ms) higher than that for both the mid-aged (280 ms) and older children (209 ms). The difference between mid-aged and older children was also significant. Overall, the DCD group (334 ms) were significantly higher than controls (269 ms), however the main effects were moderated by a significant interaction between age and group, $F(2,120)$ = 3.40, p = .037, partial η^2 = .05. The simple effect for skill group was significant for younger children, $F(1,35)$ = 6.89, p = .013, partial η^2 = .17, mid-aged children, $F(1,54)$ = 11.69, p = .001, partial η^2 = .18, but not older, $F(1,41)$ < 1, partial η^2 = .00.

3.4. Time of correction

3.4.1. TOC for jump trials

The average ToC (±SE) for DCD and control group is displayed in Fig. 4. 2-way ANOVA on mean ToC showed no significant interaction between skill group and age, $F(2,127)$ = 1.21, partial η^2 = .02. The was a main effect for age group, $F(2,127)$ = 32.27, p < .001, partial η^2 = .34 and skill group, $F(1,127)$ = 28.85, p < .001, partial η^2 = .19. Younger children (321 ms) were slower to correct trajectory than mid-aged (283 ms), who in turn were slower than older (253 ms). Overall, children with DCD (307 ms) were slower than controls (274 ms).

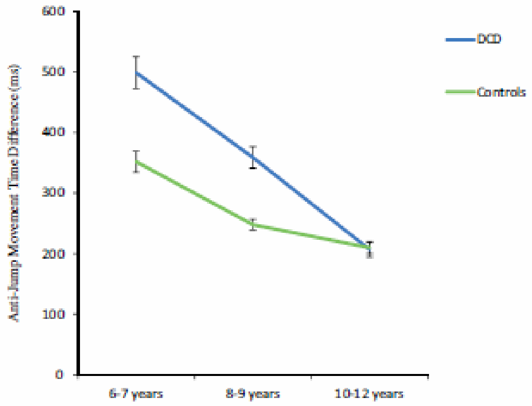

Fig. 3. Mean anti-jump movement time difference ($AJMT_{diff} \pm SE$) values of young (6–7), mid-age (8–9) and older (10–12) children for DCD and control groups on the double-jump reaching task.

3.4.2. TOC2 for anti-jump trials

For ToC2 on anti-jump trials, 2-way ANOVA showed no significant interaction between age and skill group, $F(2,124) < 1$, partial $\eta^2 = .01$. There was a main effect for age group, $F(2,124) = 53.51$, $p < .001$, partial $\eta^2 = .46$, and skill group, $F(1,124) = 9.31$, $p = .003$, partial $\eta^2 = .07$. Younger children (644 ms) were slower to make the second correction on anti-jump trials than mid-aged (519 ms), who in turn were slower than older (431 ms). Overall, children with DCD (550 ms) were slower than controls (516 ms).

3.5. Post correction time for anti-jump trials

2-way ANOVA revealed a significant effect for group, $F(1,129) = 19.64$, $p < .001$, partial $\eta^2 = .13$, and age, $F(2,129) = 50.42$, $p < .001$, partial $\eta^2 = .44$, while the interaction was not significant, $p = .18$. Older children (432 ms) had faster PCTs than mid-aged (514), who were in turn faster than younger (628). Children with DCD (555 ms) were slower to finish the post-correction phase than controls (502 ms).

3.6. Response errors

Initial analyses on TDEs and AEs showed no effects involving trial type; hence, error variables were examined as a function of age and group.

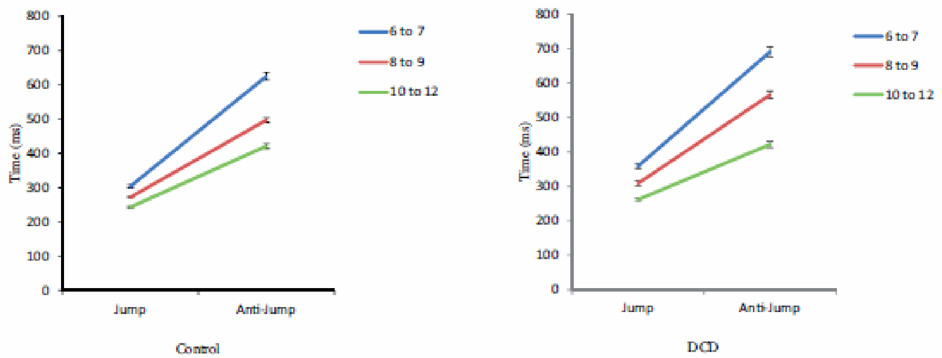

Fig. 4. Mean time of correction (±SE) showing initial correction (ToC) and second correction (ToC2) on anti-jump trials for DCD and control group on the double-jump reaching task.

3.6.1. Touch down errors

2-way ANOVA showed no significant interaction between age and skill group, $F(2,124) < 1$, partial $\eta^2 = .006$. A main effect for age was significant, $F(2,124) = 3.92$, $p = .022$, partial $\eta^2 = .06$; younger children (3.44) made significantly more TDE than older children (2.31) but not mid-age (3.15). There was no difference between mid-age and older children. There was no effect for group as DCD and control groups made 2.98 errors respectively, $F(1,124) < 1$, partial $\eta^2 = .001$.

3.6.2. Anticipation errors

2-way ANOVA revealed no interaction between age and group, $F(2,124) < 1$, partial $\eta^2 = .01$. There was a main effect for age, $F(2,124) = 5.23$, $p = .005$, partial $\eta^2 = .08$, and skill group, $F(1,124) = 5.33$, $p = .023$, partial $\eta^2 = .04$. On average, younger children (1.19) made significantly more AE than mid-age (0.65) and older children (0.59). There was no difference between mid-age and older children. The DCD group (1.02) made significantly more errors than controls (0.67).

3.6.3. Centre touch errors

For CTE, there was no 2-way interaction between age and group, $F(2,125) < 1$, partial $\eta^2 = .02$. There was no main effect for age, $F(2,125) < 1$, partial $\eta^2 = .01$: younger (0.42), mid-age (0.44) and older (0.23) children; and no effect for group: DCD (0.33) and controls (0.29), $F(2,125) < 1$, partial $\eta^2 = .001$.

3.6.4. Anti-jump errors

On AJE, there was no interaction between age and skill groups, $F(2,125) < 1$, partial $\eta^2 = .01$. There was a main effect for age, $F(2,125) = 3.04$, $p = .05$, partial $\eta^2 = .05$; younger children (mean of 0.97 out of 8 anti-jump trials) had significantly more AJE than older children (0.45) but not mid-age (0.95). The difference between mid-age and older children was also significant. There was no significant difference between DCD (0.88) and controls (0.76), $F(2,125) < 1$, partial $\eta^2 = .003$.

4. Discussion

The aim of the study presented here was to examine the ability of children with DCD to implement online control when inhibitory constraints are superimposed on a reaching task. Using a double-jump paradigm, we confirmed that these children were significantly slower than non-DCD to adjust their arm reaching movement on jump trials, evident by longer movement time and delayed time to initiate a corrective movement. Importantly, on anti-jump trials, children with DCD were further disadvantaged relative to controls, evident by larger $AJMT_{diff}$ scores and longer duration to implement a second corrective movement (i.e. ToC2) after their hand was first drawn to the cued location. However, this effect was moderated by age such that the anti-reach performance of older children with DCD approached that of their age-matched peers. These results support the hypothesis that children with DCD have particular difficulty coupling executive control (i.e., response inhibition) to online control during goal-directed action, particularly during younger and middle childhood. This deficit might explain the particular difficulty these children have with more complex tasks, both cognitively and from a motor control perspective. The implications of these findings are discussed below.

4.1. Chronometric performance measures

For reaction time, the non-significant effect for trial type (non-jump vs jump vs anti-jump) and its interactions were expected since the stimulus display up to the point of finger lift-off was identical for each condition. The DCD group was slower to initiate reaching than controls which is in line with recent studies of online control (Hyde & Wilson, 2011a, 2013) and accords with a recent meta-analysis (Wilson et al., 2013) that shows longer latencies when responding to externally cued stimuli. Reduced neural transmission times when responding to external events may underlie this issue.

For non-jump trials, only the younger children with DCD differed from their age-matched controls. This accords with earlier research showing that mid-aged and older children with DCD can complete simple goal-directed reaching within a comparable timeframe as typically developing children of the same age, at least where the need for online adjustments is minimal (Wilmut, Wann, & Brown, 2006; Wilson & Hyde, 2013). What our data suggests is that younger children with DCD may be slower to implement even simple movements within peripersonal space.

For both DCD and control groups, movement time increased significantly from non-jump to jump trials. This accords with previous work (Castiello, Bennett, & Chambers, 1998; Hyde & Wilson, 2011a) and reflects the added computation and implementation time involved when modulating movements in-flight to perceptible changes in target location. In a recent review of online control, Gaveau et al. (2014) have commented that increased MT is generally observed when target jumps are of sufficient extent to enlist more voluntary aspects of online control. By comparison, under conditions of saccadic suppression, fast online corrections to relatively small target jumps are performed automatically, without conscious awareness, and with no significant increase in MT relative to non-jump trials. In line with previous studies (Querne et al., 2008; Rigoli et al., 2012) performance deficits were manifest by longer response times while group differences were not found on touch down, centre touch or anti-jump errors. The added (temporal) costs associated with using feedback-based control are likely to explain this effect, perhaps a function of reduced efficiency in processing visual information through fast dorsal stream channels (Wilson et al., 2013).

Overall, children with DCD were slower to correct movements in response to jump trials (TOC). Indeed, this effect was not moderated by age suggesting some residual deficit in online control per se over childhood. What is intriguing, however, is the differential effect between groups of the added inhibitory load, measured both chronometrically and kinematically. This finding is described in detail below and is the central focus for the remainder of the discussion.

4.2. Deficits in the online control of reaching are exacerbated with increased inhibitory demands

Movement times increased between jump- and anti-jump trials for both groups. For anti-jump trials, we saw two corrective movements in response to the (perceptible) shift in target location which account for the increase in MT over what is a longer trajectory length. The first correction occurs towards the compelling lateral cue and the second inhibiting movement away from the cued location and towards the contralateral target, equidistance from the midline. This bi-phasic correction has also been noted in studies of healthy adults (Pisella et al., 2000) and in our recent developmental work assessing children aged 7–12 years (Ruddock et al., 2014). The first correction is considered automatic in that the initial deviation is very difficult to withhold under task instructions that emphasise both speed and accuracy (Gaveau et al., 2014). The second correction is voluntary for what is an unfamiliar task.

Results for $AJMT_{diff}$ suggest a specific impairment in younger children with DCD that may subside with age. Overall, the $AJMT_{diff}$ score (i.e., between jump and anti-jump trials) was larger for the DCD group compared with controls, but importantly its magnitude varied as a function of age. Only for younger and mid-aged children was the comparison between skill groups significant. This suggests a reduced capacity in DCD over this age period to integrate inhibitory and online control during the brief time course of goal-directed reaching. However, by older childhood this capacity in DCD may approach levels of typically developing children. Interestingly, while TOC and TOC2 were delayed in DCD as a whole, there was no moderation of this effect with age. Measures of MT appear to be more sensitive than kinematic measures to change with age and as a function of motor skill.

Finally, children with DCD as a whole were also slower to complete the post-correction phase on anti-jump trials. However, this effect did not decline as a function of age. This suggests two possibilities: first, it could be taken as evidence that the early stages of online control (up to TOC) are not fully developed in younger and mid-aged children with DCD, or second, it may suggest that the process of implementing trajectory changes remains problematic in DCD over childhood. In lieu of the compelling results for $AJMT_{diff}$, we suggest that the former hypothesis is more likely.

Taken together, our results suggest that the online motor control difficulties of children with DCD are exacerbated when an inhibitory load is superimposed on a dynamic reaching task. Importantly, however, our cross-sectional data shows that by older childhood the level of efficiency in controlling anti-reach movements approaches that seen in typically developing children. We argue that in younger and mid-aged children with DCD, their slower anti-reach performance reflects an immature coupling between frontal and posterior control systems (likely PPC), delaying the voluntary adjustment of movement trajectories in real time. Evidence for improved coupling in older children can be attributed to a combination of neural maturation and experience-dependent plasticity in these same networks (Casey et al., 2008; Johnson, 2005). For example, Balsters, Whelan, Robertson, and Ramnani (2013) found that cerebellum Crus I and II are strongly connected with the prefrontal cortex (PFC) which may support the cognitive control of action systems. What remains to be seen is how particular forms of practice or intervention can alter these couplings over short and long timescales.

From a neural perspective, changes to EF appear to be mirrored by an increase in (sub)cortical structures tied closely to the PFC (Durston et al., 2006). When emerging networks come 'online' there is often a period of adjustment as new skills are adopted and refined (Johnson, 2011). With regards to performance on step-perturbation tasks, non-linear changes (i.e. more variability in performance) become apparent as the child learns to hone their motor skills in the pursuit of goal-directed action. The problems the older DCD group showed, in particular, when making online adjustments under an inhibitory load might be either the result of executive systems further containing an already impaired ability to redirect movement, or problems coupling multiple systems to more demanding action. Certainly, neuroimaging studies could help clarify the specific structures and regions at play here and shed light on how the two proposed systems interact.

4.3. Implications and limitations

Comparison of the results from the current study to previous online control research may be limited due to several reasons. First, it may be difficult to directly assess data from mid-age children as the age groups defined here (i.e., 6–7, 8–9, and 10–12) are different from the criteria used in the study from Hyde and Wilson (2013) where younger children were grouped between 5 and 7 years. In addition, we used the 15th percentile as a cut point to define the DCD group compared with the 10th percentile used by Hyde and Wilson. The online deficit on jump trials was somewhat more pronounced in the earlier study, underlining the issue of severity in causal accounts of DCD. Finally, to provide a stronger test of the hypothesis that children with DCD have difficulty coupling online control and executive systems we suggest use of a longitudinal design (c.f. the cross-sectional data presented here). This would provide a clearer window into the developmental trajectory of these control systems, and their pattern of interaction over childhood.

5. Conclusion

Overall, results extend earlier work by showing that children with DCD have difficulty performing online adjustments and that this is compounded when inhibitory constraints are imposed on a reaching task. Importantly, however, the latter effect was reduced as a function of age. Whereas younger and mid-aged children with DCD were disadvantaged by anti-jump trials – as shown by MT and $AJMT_{diff}$ scores – older children were not relative to age-matched controls. This intriguing finding suggests that whatever is driving the poor motor skill performance of older children with DCD, it is not the ability to couple inhibitory function with online control. Before this age, however, immature coupling may compound the performance issues in DCD, particularly when motor tasks make demands on executive function. Put another way, the coupling between these systems may require a more protracted period of development in DCD before being functionally integrated. Longitudinal data is needed to unravel the changing pattern of interaction between these systems with age and their relationship to other aspects of executive function.

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Appendix J Published Article – Study 3

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Abstract: Introduction: Previous research indicates that children with Developmental Coordination Disorder (DCD) show deficits performing online corrections, an issue exacerbated by adding inhibitory constraints; however, cross-sectional data suggests that these deficits may reduce with age. Using a longitudinal design, the aim of the study presented here was to model the coupling that occurs between inhibitory systems and (predictive) online control in typically developing children (TDC) and in those with developmental coordination disorder (DCD) over an extended period of time, using a framework of interactive specialisation. We predicted that TDC would show a non-linear growth pattern, consistent with re-organisation in the coupling during the middle childhood period, while DCD would display a developmental lag.
Method: A group of 196 children (111 girls and 85 boys) aged between 6 and 12 years participated in the study. Children were classified as DCD according to research criteria. Using a cohort sequential design, both TDC and DCD groups were divided into age cohorts. Predictive (online) control was defined operationally by performance on a Double-Jump Reaching Task (DJRT), which was assessed at 6-month intervals over two years (5 time points in total). Inhibitory control was examined using an anti-jump condition of the DJRT paradigm whereby children were instructed to touch a target location in the hemispace opposite a cued location.
Results: For the TDC group, model comparison using growth curve analysis revealed that a quadratic trend was the most appropriate fit with evidence of rapid improvement in anti-reach performance up until middle childhood (around 8-9 years of age), followed by a more gradual rate of improvement into late childhood and early adolescence. This pattern was evident on both chronometric and kinematic measures. In contrast, for children with DCD, a linear function provided the best to fit on the key metrics, with a slower rate of improvement than controls.

Conclusion: We conclude that children with DCD require a more extended period of development to effectively couple online motor control and executive systems when completing anti-reach movements, whereas TDC show rapid improvement in early and middle childhood. These group differences in growth curves are likely to reflect a maturational lag in the development of motor-cognitive networks in children with DCD.

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Title

Coupling of online control and inhibitory systems in children with atypical motor development: A growth curve modelling study

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function provided the best to fit on the key metrics, with a slower rate of improvement than controls.

Conclusion: We conclude that children with DCD require a more extended period of development to effectively couple online motor control and executive systems when completing anti-reach movements, whereas TDC show rapid improvement in early and middle childhood. These group differences in growth curves are likely to reflect a maturational lag in the development of motor-cognitive networks in children with DCD.

1. Introduction

Everyday tasks such as selecting a book from a shelf, dressing, or simply walking through a busy room are acquired easily by most children but certainly not all. Typically developing children (TDC) acquire motor skills quite seamlessly over the course of development, mainly by a process of visual modelling but also through verbal instruction and hands-on manipulation by a skilled adult or caregiver (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). Changes in performance are shown by greater synergy between joints and muscle activations, and enhanced perceptual-motor coupling, measured on kinematic and kinetic markers. In general, there is a gradual transition from initial freezing of degrees of freedom to a more unconstrained exploration of movement space (Asmussen, Przysucha, & Dounskaia, 2014). With this transition, there is an enhanced ability to adapt movements to variability or complexity in the environment. For example, a basic running or catching action in a closed environment is translated to open conditions where the action space is shared with other children or obstacles.

One of the hallmarks of a healthy motor system in children is the ability to quickly update movement plans in the face of sudden changes (or perturbations) in the environment, like a moving object in the field of view or a physical force as when one's arm is knocked in the act of reaching (Shadmehr, Smith, & Krakauer, 2010). Neuro-computational models of human reaching posit that online motor control is critical for fluent and efficient movement. Underpinning online control are fast *internal feedback loops* which utilise predictive (or forward) estimates of limb position based on the expected sensory consequences of self-motion (Desmurget & Grafton, 2003). Once (actual) visual and proprioceptive signals become available to the nervous system at movement onset, these signals are compared with those predicted by a 'forward' model in real-time. Where discrepancies arise, error signals are generated and relayed back to the controller to be integrated with the unfolding motor command, allowing for rapid adjustments to limb dynamics should they be necessary (Desmurget & Grafton, 2000). Impressively, these corrections can occur within 100ms (Castiello, Paulignan, & Jeannerod, 1991) and support the stability of the motor system with minimal processing delay.

While the nature of rapid online control during reaching and its neurocognitive bases have been well studied in adult populations (e.g. Gaveau et al., 2014; Pisella et al., 2000), only recently has it been addressed in children. While this work is in its formative stage, it is becoming clear that mechanisms linked to fast corrective processes undergo considerable changes between the ages of 6 and 12 years (Bard, Hay, & Fleury, 1990; Van Braeckel, Butcher, Geuze, Stremmelaar, & Bouma, 2007; Wilson & Hyde, 2013). By 7 years of age, children are able to generate fast and accurate ballistic movements but are slower to integrate online feedback than older children, resulting in some inefficiency for more complex movements. At around 8-9 years of age, children are able to make earlier and greater use of sensory feedback (e.g. Chicoine, Lassonde, & Proteau, 1992) as both feedforward and feedback (predictive) control become better integrated, resulting in a steep improvement in their capacity to implement corrective actions. By 9-12 years, the nervous system is able to integrate predictive and sensory systems smoothly, resulting in an adult-like ability to correct simple movements online (e.g. see Wilson & Hyde, 2013) while movement skills continue to develop into adolescence.

Research on the development of brain morphology provides important insights into the timescales over which perceptual-motor systems unfold. At a neural level, studies in healthy adults have implicated the posterior parietal cortices (PPC) in corrective hand movement during the course of goal-directed action (Gréa et al., 2002; Reichenbach, Bresciani, Peer, Bulthoff, & Thielscher, 2011; Reichenbach, Thielscher, Peer, Bülthoff, & Bresciani, 2014). In typically developing children, improvement in online control appears to coincide with patterns of neural maturation that include synaptogenesis, myelination, and formation of white matter networks (WMNs) (for reviews see Casey, Tottenham, Liston, & Durston, 2005; Chen, Liu, Gross, & Beaulieu, 2013; Collin & Van Den Heuvel, 2013; Spreng, Sepulcre, Turner, Stevens, & Schacter, 2013; Sripada, Kessler, & Angstadt, 2014; Ve´rtes & Bullmore, 2014). Of the various cortical and sub-cortical networks, peak periods of myelination and synaptic pruning are observed to occur last in frontal and parietal zones, shaped by both external (i.e., experiential learning) and internal/maturational growth factors (Casey, Getz, & Galvan, 2008). Similarly, development of dorsal attention and fronto-parietal WMNs is maximal during older childhood (10-13 years of age) (Sripada et al., 2014). This same fronto-parietal circuitry is critical to the control of goal-directed and target-directed motion (Gréa et al., 2002; Reichenbach et al., 2014)

The broad theory of *interactive specialisation* provides a parsimonious explanation of how different neural systems unfold and interact over time (Johnson, 2011; Johnson, 2013). Traditional models of brain-behaviour posit a number of separable brain systems that support a narrow range of behaviours, each unfolding under specific maturational timelines. In the case of motor control, for instance, this implies that specific processes/behaviours develop according to localised neural regions. However, neural networks are far more dynamic in their interaction than this model would suggest. A more parsimonious account is that separate systems (with individual growth trajectories) can impact the development of each system through a process of *interactive specialization* (Johnson, 2005, 2011; Johnson, 2013). To this end, recent behavioural and neurophysiological evidence indicates that the emergence of new, or more refined behaviour, is often the result of several brain regions/networks whose growth trajectories may differ, but yet support each other (Johnson, 2011). This theory has been applied quite persuasively in describing the development of behaviours as varied as linguistic processing, social cognition, and face perception (Johnson, 2011). We argue that co-development of online motor control and executive function (EF) is another important case in point.

In typically developing children, we have shown that the expression of rapid online control – supported by dorsal stream and parieto-cerebellar networks – appears to be constrained by concurrent demands on frontal executive systems (i.e. Ruddock et al., 2014). For relatively simple movements to visual perturbation (without an executive load), the capacity to enlist online control improves rapidly between 6 and 9 years of age, followed by steady but more modest growth into older childhood (Wilson & Hyde, 2013). Importantly, online control is based on predictive estimates of limb position. As such, predictive control for simple movements is a landmark achievement of development over early and middle childhood, an ability subserved by posterior visuomotor networks including posterior parietal cortex (Shadmehr et al., 2010)[1]. In contrast, the pattern of development differs when online corrections must be implemented under an executive (inhibitory) load. For anti-reach movements, the performance of mid-age children deteriorates relative to that of older children aged 10-12 years (Ruddock et al., 2014) and was more similar to the performance of younger children (aged 6-7 years).

The importance of EF to motor control is further supported by evidence that children with atypical motor development (i.e. Developmental Coordination Disorder; DCD) show deficits on tasks that involve the joint action of frontal executive and (dorsal) visuomotor systems. For example, in the case of the online control of reaching, recent research has shown that older children with DCD are able to reach to stationary targets as efficiently as age-matched peers, but they take longer to correct arm reaching following unexpected target displacement mid-movement (Hyde & Wilson, 2011a). From a neuro-computational

[1] The dorsal visuomotor network comprises the posterior parietal cortex (PPC) and its reciprocal connections to frontal and cerebellar cortices (Shadmehr et al., 2010). PPC is a prime site for processing forward internal models; these neurons are capable of re-mapping their receptive fields in anticipation of the sensory effects of an impending eye movement or goal-directed reach, for example (Shadmehr et al., 2010).

perspective, corrections of this type are predicated by the integrity of predictive control, an argument formalised as the *internal modelling deficit* (IMD) hypothesis of DCD (Adams, Lust, Wilson, & Steenbergen, 2014; Wilson et al., 2013). Hyde and Wilson (2013) also showed that for older children with DCD, the time taken to implement changes in movement trajectory mid-flight was similar to younger typically developing children (5-7 years old). This pattern suggested that poor predictive control in DCD may reflect a developmental delay of fronto-parietal systems rather than an abnormality.

In a recent cross-sectional study (Ruddock et al., 2015), we compared the ability of children with and without DCD to enlist inhibitory control while implementing online corrections. Using an anti-jump reaching task, children were instructed to reach and touch a target location in the hemispace opposite a cued location. While replicating earlier results for the double-jump reaching task (DJRT), it was also shown that children with DCD were further disadvantaged by the inhibitory load of the anti-jump condition. Importantly, this effect was moderated by age: younger (6-7 years) and mid-age (8-9 years) children with DCD showed substantial difficulties coupling online and inhibitory demands on anti-reach trials, whereas older children with DCD (10-12 years) showed a similar pattern of performance to age-matched TDC. This pattern suggested that immature coupling of cognitive (i.e., inhibitory) and motor control systems is linked to the movement skill problems of younger and mid-age children, while a different mechanism may explain the persistence of clumsiness in older children. However, our ability to make strong causal statements about the interaction of these systems was limited by the cross-sectional design. This was the motivation for modelling the development of cognitive and motor control functions using a sophisticated longitudinal design.

1.1 Growth curve modelling of typical and atypical motor development

Examining the motor performance of children longitudinally can be complicated by a range of factors including the amount of time needed to capture a suitable age, the cost of repeated testing, and attrition. However, recent innovations in statistical (multilevel) modelling, particularly the use of growth curve modelling (GCM), has afforded a number of flexible research designs in the area of child development. The influence of GCM is most apparent in the field of neural and cognitive development (e.g. Sansavini et al., 2014; Wiebe, Sheffield, & Espy, 2012). This technique is well suited for a range of longitudinal designs and is known for its flexibility in modelling non-linear changes. For example, cohort-sequential (or accelerated) designs provide an extremely efficient means of modelling developmental processes over extended age periods, and are amenable to GCM techniques where growth functions are readily resolved. To our knowledge, GCM has yet to be applied to the development of motor control in children.

The broad aim of our study was to model age-related change in the ability to couple online and executive control using a large sample of children. To capture developmental progression over the 6-12 year-old period, while limiting data collection to a 2-year period, we enlisted a cohort sequential design (CSD), and examined the growth patterns of TDC and DCD groups using model comparison techniques. CSDs enlist a set of adjacent age cohorts that are each tracked longitudinally over a limited time period, but in combination provide an extended age profile that can be analysed to reveal a common developmental trend (or growth function/curve). As such the combination of CSD and GCM is an extremely powerful and efficient means of examining developmental processes at various levels of function (neural, cognitive, and behavioural). Cohort sequential designs maximise the use of incomplete participant data and permit modelling of non-linear data distributions. In light of the suggestion that TDC experience rapid improvement in coupling online motor and executive systems during early and middle childhood, we predicted that a quadratic growth function would best capture developmental change. By comparison, we expected that the typical re-organisation in the coupling mechanism around middle childhood would be disrupted in children with DCD which would manifest as a linear trend on key chronometric and kinematic indices.

2. **Method**

2.1Participants

A group of 196 children was recruited for the study. Children from preparatory to sixth grade (or 6 to 12 years) were randomly selected from primary schools across two metropolitan cities. Figure 1 summarises the number of children assessed at each of five occasions of testing. The overall attrition rate between the first and last time of testing (2 years later) was 34 children (17%); among those were children who transitioned into secondary school after graduating from grade six. After screening assessments, the final sample size comprised 109 typically developing children (TDC) and 67 with DCD. Demographics for DCD and TDC groups are provided in Table 1.

[Insert Figure 1 about here]

[Insert Table 1 about here]

Motor proficiency was assessed using the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997). Consistent with the recommendations of the Diagnostic and Statistical Manual 5th Edition (American Psychiatric Association, 2013) and meeting research criteria (Blank, Smith-Engelsman, Polatajko, & Wilson, 2012), children were classified as DCD if their level of movement skill was below expectations for age and they scored less than the 15th percentile on a standardised test of motor proficiency (the MAND) at Time 1 (Noten, Wilson, Ruddock, & Steenbergen, 2014; Piek, Baynam, & Barrett, 2006; Ruddock et al., 2015) (Criterion A), their motor skill difficulties interfered with daily home and/or school curriculum activities (Criterion B), and these difficulties were evident before school age (Criterion C) as indicated on a parent/teacher pre-screening questionnaire. Children were excluded if the pre-screening questionnaire showed evidence of a previous or current developmental (ADHD, autism), physical (i.e. asthma, visual impairment, epilepsy, etc…), and/or neurological condition; this met Criterion D, notionally. Typically developing children were identified by a score above the 20th percentile (Hyde & Wilson, 2013). Since children were recruited from mainstream primary schools and were not attending remedial classes for academic skills, it was assumed that IQ scores were within normal range. Informed consent was obtained from all participants, parents and principals involved in the study and relevant ethics clearances were granted from government and tertiary institutions.

2.2 Apparatus

A Double-Jump Reaching Task (DJRT) paradigm was used to assess online control. The task was developed using VIRTOOLS Software (3DVIA, 2010) on a PC laptop running

Windows XP and projected on a black Samsung 40-inch touch screen with black bezel. The screen was placed on a height-adjustable table and positioned in portrait orientation, raised 10° from the horizontal plane.

Stimuli were presented on a dark background in order to minimise contrast interference. The display consisted of a round 'home base' (2.5cm in diameter), placed 5cm from the near edge of the screen and centred on a sagittal plane. Three yellow cue targets were positioned at -20°, 0°, 20° from a vertical line drawn directly from home base. To accommodate age-related differences in reach, the distance to each possible target location was scaled to 60% of average arm length based on age norms for young children (25cm; 6-7 years), mid-age children (28cm; 8-9 years), and older children (30cm; 10-12 years) (Gerver, Drayer, & Schaafsma, 1989).

The Zebris CMS10 (Noraxon, 2010) system was used to record arm reach and sampled at 200Hz. The device was clamped to the table and positioned at a height of 1 meter above the middle of the screen. A thin (1 mm) cord, 2 m in length, extended from the Zebris receiver to a small ultrasonic sensor (7mm in diameter) which was attached via an adhesive strip to the child's dominant index finger; the cord was also tethered to the wrist using an elastic band.

Procedure

The study was conducted over a 2 year period, with five occasions of testing each separated by 6 months. At each school, a quiet office was used for assessments, free from environmental distraction. Each room was darkened to minimise use of visual feedback from the moving hand during performance of the DJRT (Farnè et al., 2003). Hand preference was determined using the manual dexterity items of the MAND, and corroborated by both the child and by observation of hand use during writing. Each child was positioned directly in front of the screen as the kinematic sensor was attached to the dominant hand index finger and task instructions were explained.

Administration of the DJRT occurred across two sessions with the order of administration randomised: a standard 'jump' condition and a modified 'anti-jump' condition (see Figure 2 for a schematic of the conditions and trial types).

[Insert Figure 2 about here]

On the jump condition, children held their index finger on the green home base prior to commencing each trial. The imperative stimulus was a doubling in luminance of one of the two peripheral target locations, with simultaneous extinction of the home base. Each trial was programed with a random delay of 500-1500ms to prevent children from anticipating change in target illumination. Children were also instructed to *follow the target* and touch its centre as *quickly and accurately as possible*. A successful trial occurred when the cued target location was touched within its circular boundary which extinguished the light, accompanied by an auditory tone to indicate trial completion. For the jump condition, on 80% of all trials, the middle target remained lit until touched (*non-jump* trial) while on 20% of all trials the location of the target shifted (or jumped) at movement onset to either the left or right peripheral location (*jump* trial). At the completion of each trial, children returned their finger to the home base, ready for the next trial. The anti-jump condition was administered as a separate task but used the same method described for the jump condition; however, when target displacement occurred to a lateral location, children were instructed to *reach and touch the circle on the opposite side* (*anti-jump* trial).

Prior to each condition, the researcher demonstrated the action required for *non-jump*, *jump*, and *anti-jump* trials. Children were permitted 10 practice trials to familiarise themselves with the task; in rare cases children were given extra trials, if needed. Each condition comprised 80 trials administered in two blocks of 40 trials each (32 *non-jump* and 8 *jump*/*anti-jump*), programmed in a pseudo-random order across left and right target locations. Between conditions, children were provided with a 2 min rest. Total administration time of the task was approximately 15-20 minutes per child.

2.3 Measures

For all trials, movement time (MT) was recorded on the DJRT and only successfully completed trials were included in the analyses. Across the 5 test points, an average of 9 (14%) non-jump trials and 3 (18%) jump/anti-jump trials were removed from the DCD group, and 7 (11%) and 2 (13%) respectively from the control group. The effect of inhibitory load on online control was assessed using the difference in MT between anti-jump and jump trials ($AJMT_{diff}$). For anti-jump trials, there are two time points at which trajectory corrections occur. The first, automatic correction (ToC) was defined as the point at which the hand deviates from its dominant trajectory to the central target location and toward the peripheral cue (Hyde & Wilson, 2011b). A second correction (TOC2) then occurs when the hand is directed away from the cued location and toward the contralateral target location (Cameron, Cressman, Franks, & Chua, 2009). ToC2 reflects the integration of inhibitory control as part of the corrected movement plan as the hand is redirected toward the hemispace opposite the original cue. Both $AJMT_{diff}$ and the interval between the first (automatic) corrective movement and the second (inhibitory) correction of hand movement (i.e. ToC_{diff}) reflect the ability to enlist inhibitory control in the context of an online motor correction. All data were filtered through a fourth order Butterworth filter with a cut off of 10Hz. Movement trajectories were plotted on a 2D Cartesian plane using MATLAB software (Mathworks, 2010) and ToC and ToC2 values were determined by two independent raters (Ruddock et al., 2014).

2.4 Design and Analytic Approach

We combined a cohort-sequential (longitudinal) design (CSD) and growth curve modelling (GCM) to examine developmental trends in the ability to couple inhibitory and online control systems over the course of child development. A CSD – or accelerated design – enlists separate but overlapping age cohorts to test an overarching developmental trend (Duncan, Duncan, & Strycker, 2006). In our study, children were allocated to one of the 13 age cohorts (separated by 6-month increments), which together spanned a 6-year period from 6- to 12-years of age. CSDs maximise the use of incomplete participant data and has been shown to be more powerful and efficient than single-cohort designs in generating developmental data on specific age groups (Grammer, Coffman, Ornstein, & Morrison, 2013). As well, GCM offers a number of major advantages over traditional methods of analysing longitudinal data (such as repeated-measures ANOVA): (i) change in motor and cognitive functions over time is analysed at both a population and individual level which is consistent with theories of developmental psychology; (ii) flexibility is afforded in the treatment of the time variable (i.e., each child does not have to contribute measures over the entire age range of interest); (iii) missing data are accommodated readily under the assumption that they occur randomly; and (iv) modeling can be generalised to non-normal data. Latent growth curve modelling, in particular, enabled us to examine (predicted) non-linear developmental trajectories and differences between TDC and DCD groups (Bryk & Raudenbush, 1992; Singer & Willett, 2003).

Growth curves were analysed at two main levels: Level 1 examined within-person (or individual) change using Age as a predictor variable. This yields individual estimates for intercept and slope on the main outcome measures. All individual estimates are then combined for each age cohort. Cohort-specific trajectories are also plotted and 95% CIs were inspected for overlap at relevant age points. Possible cohort interactions with different change trends were tested using convergence estimates. A common model was then tested under the assumption that members of all 13 age cohorts follow a single underlying developmental trajectory (Duncan et al., 2006). For each dependent variable on the DJRT, linear, quadratic, and cubic growth patterns in the TDC and DCD samples were tested.

While there is some debate on the minimum number of observations per participant that are required to maintain adequate levels of model fit (Curran, Obeidat, & Losardo, 2010), we included all available data in order to ensure the most valid representation of our participant groups (Miers, Blöte, De Rooij, Bokhorst, & Westenberg, 2013). A minimum of three observations per cohort was set so as to prevent over- or under-inflation of mean values at each test point.

Outliers were analysed using a combination of standard regression diagnostics and influence statistics, which is designed to optimise the model fit (Schabenberger, 2004). Because extreme values can influence different parameters within the multi-level model (including estimates of fixed effects, covariance parameters, and fitted and predicted values), removal of data points based on standardised residuals alone can compromise model fit. As such, outliers were removed when two conditions were met: (i) standardised residual value > +/- 3.0 *and* (ii) analysis of individual and multiple data points revealed large values on influence statistics (e.g., *restricted likelihood distance*) (Schabenberger, 2004).

Data analysis was conducted using the PROC MIXED procedure of SAS version 9.3 software (SAS Institute, 2008), running on a Windows 7 platform. This procedure estimates for each child individual curve functions (i.e., slope and intercept) and, using a random effects approach, models the effect of cohort, age and their interaction, guarding against potentially high correlations from repeated measures of the same individuals over time (Anderson, Oti, Lord, & Welch, 2009). Model fit and comparison between models was assessed using goodness of fit indices, specifically the Bayesian Information Criterion (BIC).

This index is useful for comparing different models, with smaller values indicating better fit and a more parsimonious model, regardless of the absolute value. For each group (TDC and DCD), the trajectory of each outcome variable ($AJMT_{diff}$ and ToC_{diff}) was tested using polynomial analyses that assessed linear, quadratic and cubic trends in an unstructured covariance matrix. In this analysis, model parameters (i.e. age, cohort, and age*cohort) were tested for their sequential effect to determine the most appropriate growth curve solution (i.e. linear, quadratic, or cubic) using *-2log likelihood* statistic.

3. Results

3.1 Anti-jump Movement Time Difference

3.1.1 Descriptive overview. Plots of cohort values of $AJMT_{diff}$ for control and DCD are presented in Figure 3. Mean values for age (collapsed across cohorts) are presented in Table 2. Three children from the DCD group (one each from cohorts 1, 2, 3) were identified as outliers and removed from subsequent analyses. The plots show that difference scores for both groups decreased monotonically across the age, reflecting quicker response times across childhood on the difference between jump- and anti-jump trials.

[Insert Figure 3 about here]

[Insert Table 2 about here]

3.1.2 Model Fitting Analysis. For the TDC group, the best fitting growth curve included quadratic growth terms, indicating that TDC showed quick improvement in online corrections under tight inhibitory constraints with development, but growth decelerated over time into later childhood (−2LL = 4808.2, BIC = 4839.8). Adding a cubic term to the model did not results in a better fit.

In contrast, for the DCD group, the best fitting growth curve was linear, suggesting that there was only generalised improvement across childhood (−2LL = 2921.1, BIC = 2929.9). Adding quadratic and cubic terms to the model showed no improvement to the model fit.

3.2 Time of Correction difference

3.2.1 Descriptive overview. Plots of cohort values of ToC_{diff} for control and DCD are presented in Figure 4. Mean values for ToC_{diff} at each age are presented in Table 3. The plots show that time difference between ToC and ToC2 for both groups decreased across age, resulting in faster response times on anti-jump trials to engage a second (more deliberate) corrective movement.

[Insert Figure 4 about here]

[Insert Table 3 about here]

3.2.2 Model Fitting Analysis. The pattern of results for ToC*diff* was similar to AJMT*diff*. For the TDC group, the best fitting growth curve also included quadratic growth terms, indicating a steady rate of improvement on this measure of coupling up to middle childhood, followed by a shallower rate of improvement into later childhood (−2LL = 4374.6, BIC = 4400.7). The addition of a cubic term to the model did not result in a better fit.

For the DCG group, the best fitting curve solution was linear, indicating a shallow but consistent rate of improvement across childhood (−2LL = 2635.5, BIC = 2934.0). Adding quadratic and cubic terms to the model did not improve model fit.

3.3 Summary of Trend Analyses

Overall, both TDC and DCD groups showed an improvement in performance across childhood on key chronometric and kinematic measurements. For TDC, a curve with quadratic terms was found to be the best fit for AJMT*diff* and ToC*diff*, indicating that performance improves rapidly up until middle childhood followed by a more gradual but consistent improvement after this period. For the DCD group, a linear function provided the best fit on both AJMT*diff* and ToC*diff*; however, the rate of improvement was more gradual in comparison to the TDC group. On AJMT*diff*, the level of performance of 12 year old children with DCD was within 2 ms of TDC ($p > .10$) while on ToC*diff*, the difference was 23 ms ($p > .10$).

4. Discussion

The aim of this study was to model age-related changes in the coupling of online and executive control. Using a CSD that spanned the 6-12 year-old period, we examined the ability of TDC and DCD groups to perform online corrections under inhibitory constraints (i.e., anti-reach performance) using a double-jump paradigm. Overall, the pattern of performance for both groups showed improvement on key metrics across childhood. However, analysis of growth trajectories using GCM highlighted distinct fit solutions for TDC and DCD groups. For TDC on both AJMT*diff* and ToC*diff*, a quadratic trend was the most appropriate fit with evidence of rapid improvement in anti-reach performance up until middle childhood (around 8-9 years of age), followed by a more gradual level of improvement into late childhood and early adolescence. Both measures indicate the level of proficiency when enlisting inhibitory control to re-direct (online) a reaching movement away from a compelling visual cue. By comparison, for the DCD group, linear growth curves were found on both AJMT*diff* and ToC*diff* variables. A more moderate slope/linear function in DCD relative to TDC indicates a developmental lag (or more gradual unfolding) of the coupling between inhibitory and rapid online control systems. The implications of these results are taken up for discussion below.

4.1 Performance of Typically Developing Children

For TDC, developmental trajectories using GCM were similar on each of the two key performance metrics. Polynomial analysis on AJMT*diff* revealed that a quadratic growth curve was the most optimal fit. Here relative fit statistics (i.e., *-2log likelihood* and BIC) showed that adding a quadratic term to the model produced lower fit metrics and improved the model estimate. This method of model comparison is a valid means for comparing growth profiles (Zhang & Wang, 2009), and provides confidence in the pattern of results. Likewise, for ToC*diff* – also measuring the efficiency of the two-step correctional process for anti-jump trials – a quadratic trend was shown. In response to visual perturbations performed under an executive load, growth curves on these chronometric and kinematic indices show a fast reduction of AJMT in TDC between 6 and around 9 years of age, after which improvement continues but at a reduced rate. This pattern is suggestive of an important transition in the coupling of executive (inhibition) and motor systems, particularly during middle childhood; it represents a time when predictive (online) control is being re-organised to better accommodate and support movement complexity and flexibility (Desmurget & Grafton, 2003; Hyde & Wilson, 2011b).

It is telling that the coupling between online and inhibitory control systems emerges on a similar timescale to that of core executive processes per se (i.e., task switching, executive attention, and inhibition). With development, executive control exerts a more 'top-down' influence on the goal-directed behaviour of children, enabling the organisation of more flexible and complex responses in novel situations (Diamond, 2013). This progression is highlighted by mainstream research into children's cognitive development showing fast improvement of EF across primary school years, with some variation in the timescales of development between different aspects of EF (Anderson, 2002; Garon, Bryson, & Smith, 2008). These trajectories of change with age are also mirrored in recent morphological analyses of structural brain networks, also using growth curve modelling (Chen et al., 2013).

Our modelling of longitudinal data here for the TDC group are also consistent with and extend a recent cross-sectional study (Ruddock et al., 2014). In the first developmental study of its type investigating the coupling of inhibitory and online control, we showed that while children aged 8-9 years were able to implement standard online corrections on a DJRT with a level of efficiency comparable to that of older children (aged 10-12), their performance on anti-jump trials was compromised and resembled that of younger children (aged 6-7 years). The implication here was that predictive control shows rapid improvement up to middle childhood for simple online corrections but when inhibitory demands are superimposed on the task, performance is compromised, suggesting poor coupling. Our modelling work here is remarkably consistent with this pattern in showing a quadratic fit to be optimal in describing change with age. Our confidence in the integrity of this finding is strong as the longitudinal design provides one of the most robust tests of developmental processes. Support for this hypothesis is also consistent with other work showing reasonable levels of response inhibition per se by middle childhood, but only for simple tasks (Diamond, 2013; Iani, Stella, & Rubichi, 2014; Luna, Garver, Urban, Lazar, & Sweeney, 2004)

In terms of neuro-maturational development, levels of synaptic proliferation are particularly high during early and middle childhood, while rates of development in white matter networks are maximal during later childhood—these changes underpin the emerging capacity for frontal executive control (Johnson, 2013). Similarly, recent advances in brain network mapping, particularly 'growth connectomics' (Ve´rtes & Bullmore, 2014), indicate significant changes in brain architecture over childhood and associated graph metrics. Throughout childhood and adolescence, brain networks mature gradually from local, proximity-based connectivity patterns, to a more spatially distributed and topological integrative organisation supporting higher cognitive functioning. In other words, white matter networks are reshaped from early childhood to adolescence with increased global integration and decreased segregation. The connections between major modules of the connectome increase with age as long fibre pathways linking the modules mature together. For example, Chen and colleagues (2013) showed that most changes in white matter networks occur during late childhood (10-13 years); that is, specific modular hubs responsible for visual processing, EF, multisensory integration, and a so called default module are established during childhood, but are refined into adolescence. These changes would support greater functional coupling between fronto-parietal systems, for example, consistent with the pattern of changes we observe for older children on the anti-jump task.

In the case of flexible online control, the younger child must learn to couple (emerging) frontal executive systems to the more automatic online control systems of the dorsal stream, e.g., the fast response visuomotor channels of the premotor-parietal axis (Pisella, Binkofski, Lasek, Toni, & Rossetti, 2006). Hence, we expected to see slower performance around this period of development. The growth pattern on the kinematic measure of anti-jump performance (ToC_{diff}) also supports the hypothesis that younger and mid-aged children are less efficient at implementing online control when demands on inhibition are imposed. After a period of re-organisation during middle childhood, there was continued and progressive maturation of this coupling into older childhood, which provided a critical test of the patterns observed when age groups were compared cross-sectionally (Ruddock et al., 2015).

4.2 Coupling of Online Control and Inhibitory Systems in Children with DCD shows atypical Growth Patterns

In general, the DCD group performed less efficiently than TDC as reflected by their scores on both $AJMT_{diff}$ and ToC_{diff}. Inspection of the cohort plots indicates slower and more variable performance in children with DCD compared with TDC up to around 10-11 years of age, with some evidence that the developmental lag in performance of the DCD groups lessened in late childhood, a pattern confirmed by the magnitude of effect sizes for DCD-TDC comparisons on $AJMT_{diff}$ (Tables 2). Consistent with a visual inspection of trends on the chronometric ($AJMT_{diff}$) and kinematic (ToC_{diff}) measure of coupling – i.e., steady reduction on difference scores with age – a model comparison of polynomial trends showed that the best fitting growth curve was linear as indicated by *-2log likelihood* and BIC fit metrics. By late childhood, performance metrics for the DCD group were within the range observed for the TDC group. As such, we have agreement between earlier cross-sectional and current longitudinal data. Like the cross-sectional analysis of Ruddock and colleagues (2015), children with DCD require a more extended period of development to effectively couple online motor control and executive systems when completing anti-reach movements.

In terms of neural development, network connections between frontal and parietal systems that are necessary to support predictive and executive control and their coupling appears to require additional time to develop in DCD. This is consistent with some recent fMRI data showing hypoactivation along dorsal stream routes in children with DCD (Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009). Using a visually-guided tracking task that required high levels of predictive control, these authors showed under-activation in PPC and IPL in DCD as compared with controls. Structural MRI studies in ADHD (Sripada et al., 2014) and autism spectrum disorders (Travers et al., 2015) also show growth patterns that suggest developmental lags on cognitive and behavioural functions. For example, individuals with autism display a negative correlation between age and integrity of their white matter connections (for reviews see Dennis & Thompson, 2014; Travers et al., 2012). It is possible that similar lags in neural development may underpin the difficulties that younger and mid-aged children with DCD have in coupling online and executive control systems. By comparison, it appears that the motor difficulties experienced by the older children may not be a function of the ability to couple online motor and inhibitory control per se.

All this raises the issue of what exactly does explain the persistence of clumsiness in older children with DCD. It is likely that patterns of physical participation learned during earlier childhood are particularly hard to change. And, without meaning to sound trite, we know that without adequate levels of participation (viz learning experiences) obvious limits are imposed on the acquisition of skill. Compounding the issue of practice is the possibility of *learned non-use* in DCD, an interesting hypothesis that could be explored in future work. However, if the underlying control systems for motor prediction and coupling are emergent by older childhood, then one could argue that the motor system would be responsive to various forms of intensive training during this period. In the current study, the fact that older children with DCD showed similar difference scores to TDC does not suggest that ubiquitous functional coupling exists within this age group. In cases where older children with DCD do show poor coupling of control systems, a recent systematic review suggests that improving motor performance may be best addressed from task-oriented approaches (Smits-Engelsman et al., 2013).

4.3 Interactive Specialization is a Parsimonious Account of Behavioural Development

The pattern of performance on both key metrics for TDC reflects the time course over which different cortical zones unfold during child development. Developmental research shows that cognitive processes emerge over different time intervals, each with their own growth trajectory (Diamond, 2013; Johnson, 2011). However, each emerging process may take some time to be integrated efficiently with existing processes, whether they are perceptual-motor or other. In the case of EF, behavioural changes are associated with an increase in density of the cortical structures tied closely to the prefrontal cortex (PFC). When the raw architecture of neural networks first emerge there tends to be an adjustment (or re-organisation) phase in which new skills are incorporated by the performer (Johnson, 2013). In the case of coupling motor and cognitive processes, efficiency is the result of a combination of neural growth and experience-dependent plasticity along fronto-parietal and other associated networks (Casey et al., 2008; Johnson, 2011). Our growth curve modelling suggests that only by older childhood a high degree of efficiency is achieved in TDC, and that a period of re-organisation is needed during middle childhood. Diffusion tensor imaging studies (Collin & Van Den Heuvel, 2013; Tymofiyeva et al., 2013) also highlight the shift neural networks make from supporting proximally based regions to more expanded, distributed networks that are involved with specialised cognitive control. Our work here shows that this broad model of neuro-behavioural development (i.e., *interactive specialization*) can be applied well to cognitive-motor systems and their coupling, and points to its applications in other areas of behaviour where multiple systems are involved to enact increasingly complex skills. For example, examining patterns of development in kinematic markers necessary for fluid handwriting (Jolly & Gentaz, 2014; Jolly, Huron, & Gentaz, 2014). It is not surprising, then, to see non-linear changes in TDC with regards to performance on step-perturbation tasks; novel skills (i.e. engaging inhibitory control when online corrections are performed) are learned and incorporated into the motor system.

In terms of atypical development, the linear trends from the DCD group lend support to a delay in general growth patterns (Hyde & Wilson, 2013). A naïve assumption here would be that children with online motor control deficits *should* eventually show age appropriate skills once the underlying systems emerge. However, simply leaving poor motor coordination untreated, certainly in the case of younger and mid-age children with DCD, should not suggest spontaneous acquisition of motor skills and the absence of intervention; evidence shows that problems untreated persist into adulthood (Cousins & Smyth, 2003; Kirby, Edwards, & Sugden, 2011; Missiuna, Moll, King, King, & Law, 2007). The question here is what type of intervention (e.g., a combination of motor-cognitive approaches) is best suited when multiple systems may not be interacting as expected.

4.4 Limitations

No longitudinal study is immune from the threat of attrition. We acknowledge that using any type of value estimation (e.g. multiple imputations) may be advantageous in certain circumstances where missing data occur randomly, and in minimal proportions, to the overall date set (Graham, 2009). However, using such techniques on a large data set, particularly for developmental data where even simple behavioural measures can show large variance (Wilson et al., 2013), would likely provide estimated values that are inaccurate and could seriously undermine the validity of individual scores. In addition, a common threat to the internal validity of any study with recurring measurements is practice effects which have the potential to influence results. As tracking maturational changes requires repeated assessment, it is possible participants become familiarised with assessment materials and procedures (i.e., items on the MAND and conditions of DJRT), thus improving their performance over successive measurement points. However, to minimise this threat, we counterbalanced conditions on the DJRT. While this may not completely resolve the issue of assessment familiarisation, future studies could use parallel versions of the test.

Finally, one of the assumptions about EF and its role to ROC is that other EF processes are sufficiently mature enough to support other behaviours. In future, it may be worth modelling other measures of EF (e.g., switching, update), while also testing for IQ levels (as we assumed all children were within normal range based on the school they were recruited from), and try to co-vary online control metrics in an effort to identify risk factors in children who have deficits across cognitive domains and help streamline interventions in goal-directed action and skill.

4.5 Conclusion

Longitudinal modelling provides one of the strongest tests of developmental hypotheses. Modelling of this longitudinal dataset has extended our cross-sectional research and confirmed that the real-time coupling between online control and inhibitory systems follows an atypical pattern in DCD. For children without motor impairment, the pattern of performance on $AJMT_{diff}$ and ToC_{diff} variables conformed to a quadratic growth curve, with evidence of re-organisation of the coupling around middle childhood. Conversely, children with DCD displayed a more protracted period of development across both measures, as noted from the linear trajectories. Interpreted from the perspective of *interactive specialization*, multiple networks appear to support the fine tuning of anti-jump performance across childhood for TDC while more time is required to integrate the function of control systems in children with DCD.

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Tables

Table 1

Descriptive Statistics for Typically Developing Children (TDC) and Developmental Coordination Disorder (DCD) groups at Time 1

	Gender		Age (years)		Handedness	
	Girls	Boys	*M*	*SD*	Right	Left
TDC						
Age 6	19	9	6.44	0.37	26	2
Age 7	14	7	7.47	0.31	18	3
Age 8	11	10	8.39	0.31	21	0
Age 9	6	12	9.45	0.27	18	0
Age 10	8	7	10.33	0.26	15	0
Age 11	3	2	11.35	0.17	4	1
Age 12	0	1	12.25	0.00	1	0
DCD						
Age 6	4	3	6.43	0.61	6	1
Age 7	4	9	7.53	0.31	13	0
Age 8	2	9	8.56	0.35	10	1
Age 9	4	7	9.50	0.32	11	0
Age 10	9	6	10.55	0.26	13	2
Age 11	4	1	11.28	0.17	4	1

Note. TDC = Typically Developing Children; DCD = Developmental Coordination Disorder,

Table 2

Mean Values for $AJMT_{diff}$ at each age for TDC, DCD and Total Group

Age Group	TDC *M (SD)*	DCD *M (SD)*	Overall *M (SD)*	TDC vs DCD *Cohen's d*
Age 6	407 (200)	444 (175)	412 (194)	.30
Age 7	334 (168)	441 (184)	360 (177)	.63
Age 8	278 (136)	326 (149)	295 (142)	.65
Age 9	273 (131)	293 (151)	281 (139)	.14
Age 10	215 (93)	285 (126)	241 (112)	.66
Age 11	164 (92)	203 (137)	182 (116)	.34
Age 12	117 (72)	119 (71)	117 (69)	.03

Note. All values are in milliseconds. $AJMT_{diff}$ = Anti-jump Movement Time Difference Score; TDC = Typically Developing Children; DCD = Developmental Coordination Disorder.

Table 3

Mean Values (SD) for ToC_{diff} at each age for TDC, DCD and Total Group

	TDC	DCD	Overall	TDC vs DCD
Age Group	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*Cohen's d*
Age 6	326 (78)	354 (16)	329 (73)	.38
Age 7	279 (85)	296 (64)	283 (80)	.21
Age 8	221 (67)	240 (63)	227 (66)	.29
Age 9	202 (66)	215 (62)	207 (65)	.20
Age 10	166 (49)	194 (64)	177 (57)	.49
Age 11	139 (48)	157 (49)	148 (49)	.37
Age 12	106 (26)	129 (31)	121 (31)	.25

Note. All values are in milliseconds. ToC_{diff} = Time of correction difference score; TDC = Typically Developing Children; DCD = Developmental Coordination Disorder.

Figures Legends

Figure 1. Flow chart of participants available for testing at each time point across the study lifespan

Figure 2. Schematic overview of the double jump reaching task showing trial types across two conditions (standard jump and anti-jump).

Figure 3. Mean $AJMT_{diff}$ values for each age cohort for (a) TDC and (b) DCD groups on the double-jump reaching task

Figure 4. Mean ToC_{diff} values for each age cohort for (a) TDC and (b) DCD groups on the double-jump reaching task.

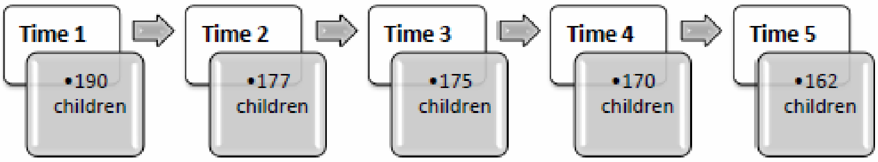
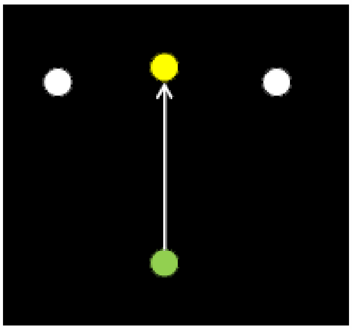


Figure 1. Flow chart of participants available for testing at each time point across the study lifespan

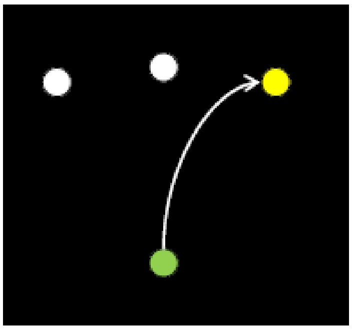
Condition A (standard jump trials)

Non-jump trial



The central target remains lit until touchdown.

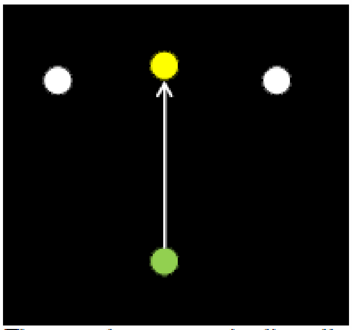
Jump trial



Target *jumps* to either peripheral location at finger lift off

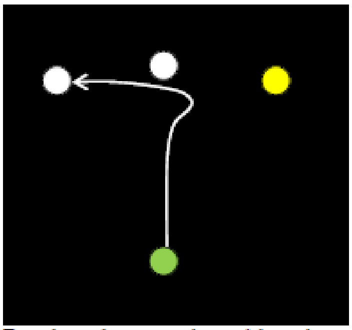
Condition B (with anti-jump trials)

Non-jump trial



The central target remains lit until touchdown.

Anti-jump trial



Reach to the contralateral location is required.

Figure 2. Schematic overview of the double jump reaching task showing trial types across two conditions (standard jump and anti-jump).

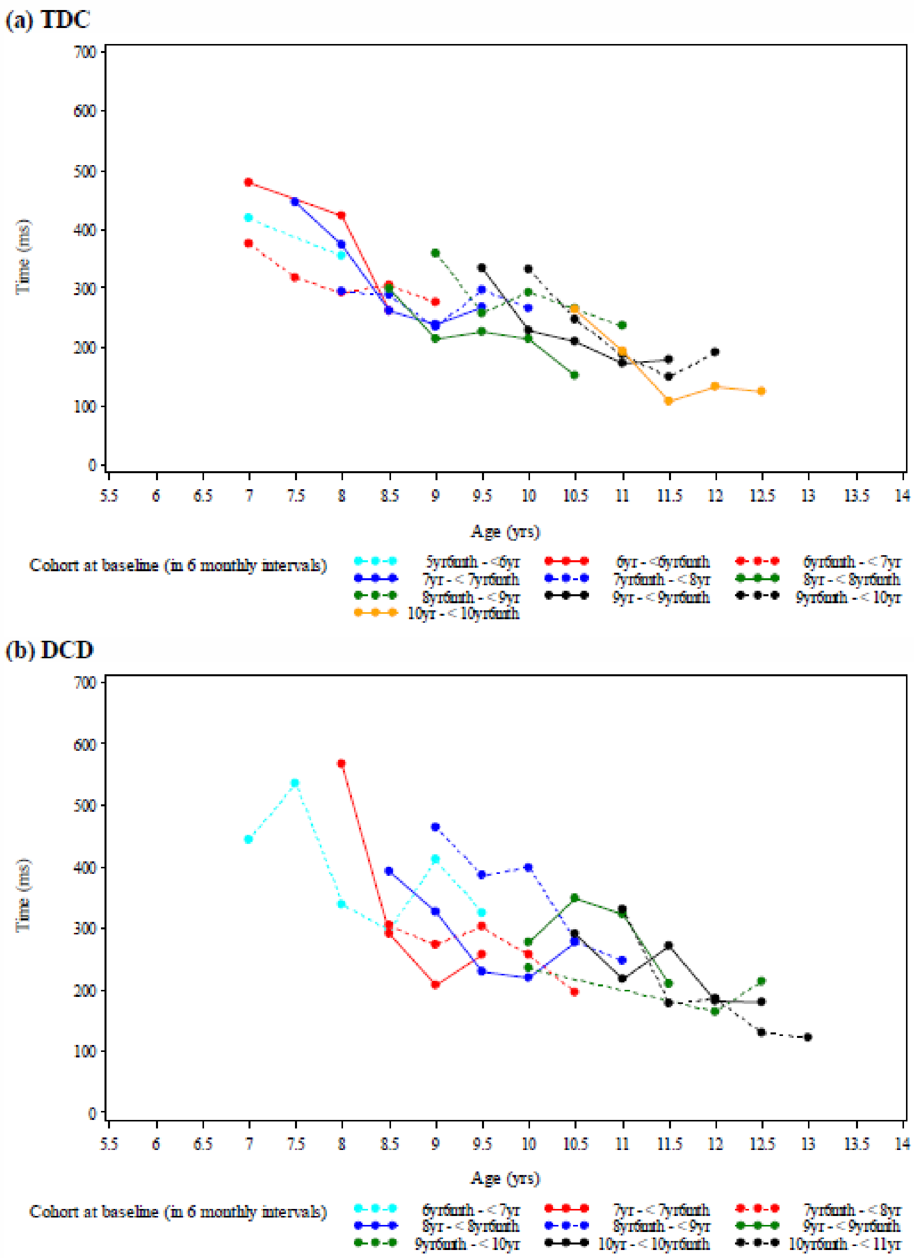


Figure 3. Mean AJMT$_{diff}$ values for each age cohort for (a) TDC and (b) DCD groups on the double-jump reaching task

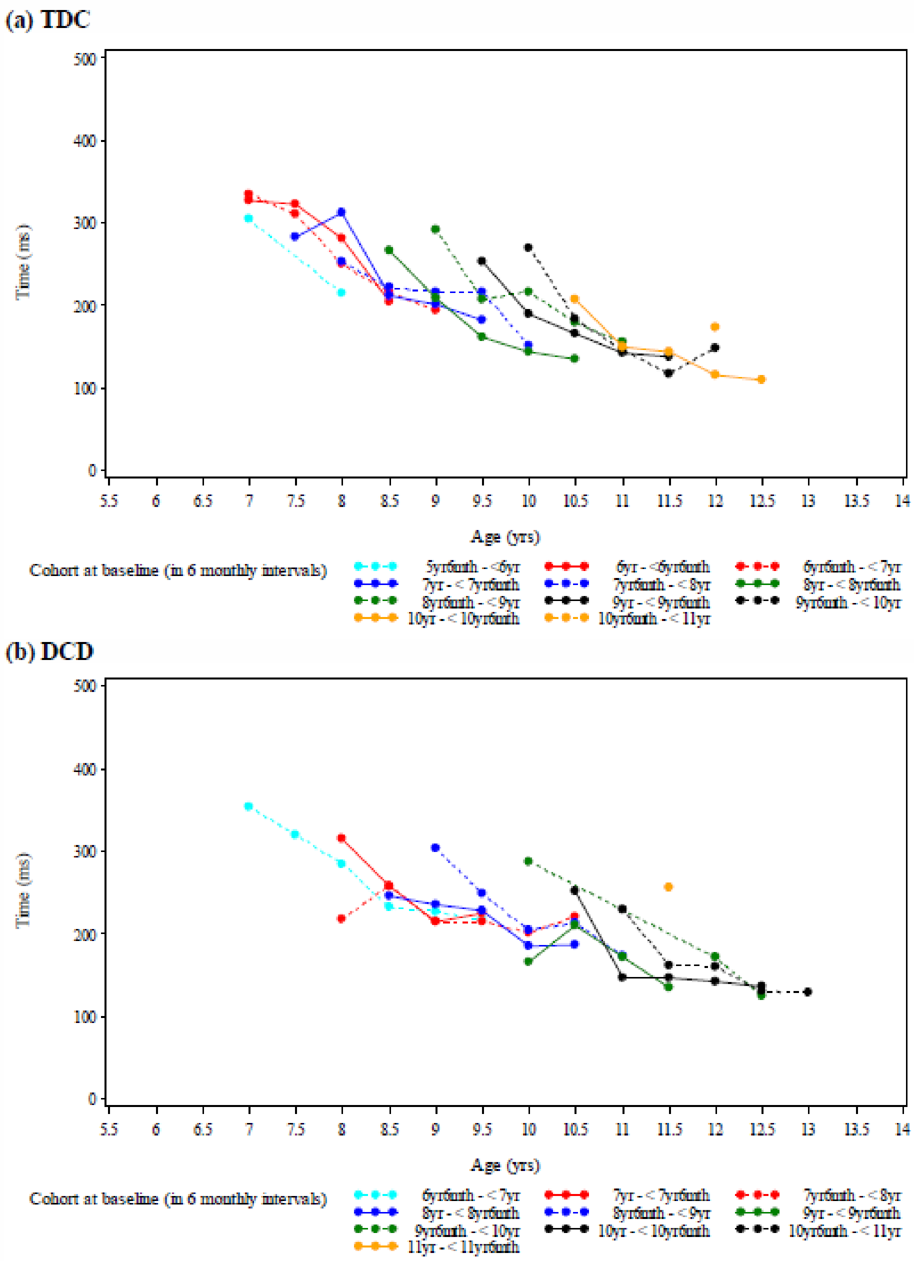


Figure 4. Mean ToC*diff* values for each age cohort for (a) TDC and (b) DCD groups on the double-jump reaching task