Shedding New Light on Developmental Coordination Disorder: An investigation of behavioural and neuroimaging evidence for mirror neuron system dysfunction

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ABSTRACT

Developmental coordination disorder (DCD) is a condition characterised by an inability to perform fine (hand writing and shoelace tying) and gross motor skills (playing sport and getting dressed) at an age appropriate level (American Psychiatric Association, 2013). It is one of the most common childhood movement disorders, affecting approximately 6% of school-aged children (American Psychiatric Association, 2013). Children with DCD experience movement difficulties that lead to activity limitations at home, school and in the community. The motor difficulties can extend to impact children’s emotional and social development, and often continue through adulthood. While, by its definition, no identifiable hard neurological signs (e.g., lesions) are associated with DCD, it is now well established that the motor difficulties experienced are in some way neurologically based (Brown-Lum & Zwicker 2015; Zwicker et al., 2009). Although neuroimaging in this population is an expanding area of research, limited exploration has been undertaken to explore the mechanisms of this disorder at a neurological level.

A cortical network that has recently been hypothesised to be associated with the movement difficulties characteristic of DCD is the mirror neuron system (MNS; Reynolds, Thornton et al., 2015; Werner, Cermak, & Aziz-Zadeh, 2012). The MNS is a fronto-parietal network of multimodal neurons in the central nervous system that supports learning via imitation and the internal representation of movement (motor imagery; Decety, 1996; Iacoboni & Dapretto, 2006). An exploration of the function of this system has the potential to explain the motor deficits characteristic of DCD, assist in assessment, and inform theoretical foundations of targeted intervention approaches in this population.

The research undertaken for this thesis addressed the question: are deficits in MNS function an underlying mechanism of DCD? To answer this question, this doctoral thesis is divided into three series (five studies), each adding to the understanding of MNS function in children with DCD. These series include: (1) a systematic review of current literature of MNS function; (2) behavioural level assessments of MNS function (imitation and motor imagery); and (3) neuroimaging studies of relative grey matter volumes (voxel-based morphometry) and MNS function (functional MRI). Although children with DCD were found to have deficits when performing behavioural tasks designed to assess MNS function, no deficits in this system were identified at neurological level. It is important to
note, however, that both imitation and motor imagery require the integration of multiple sensory systems and, at a neurological level, are also supported by systems and mechanisms beyond the MNS. Instead, this research suggests that reduced grey matter volume and activation in motor planning and attention regions may contribute to this disorder. Although deficits in MNS function were not identified, this thesis has identified other potential mechanisms contributing to DCD and has identified important future research directions. Further research on the underlying aetiology of DCD through genetics, in combination with neuroimaging research to increase our understanding of the underlying mechanisms through which it acts, will improve our understanding of this disorder and enable earlier detection and treatment.
EXECUTIVE SUMMARY

Imagine what it would be like to be born into a body unable to learn and perform the most basic movement tasks with ease, no matter how hard you tried. Imagine if it took you years to learn how to dress yourself and tie your shoes, to eat with a knife and fork, to hold a pencil and write legibly, or to throw and catch a ball. Imagine what it would be like to have your peers laugh and make fun of you because you run awkwardly, bump into things, or fall over. It is hard to imagine, isn’t it? For most of us, motor skills are learnt with considerable ease, and we take for granted our brain’s ability to translate our intentions into actions. For children with developmental coordination disorder (DCD), however, the process of learning movements is far from easy.

DCD is a condition characterised by impaired motor coordination and an inability to perform motor skills at an age appropriate level (American Psychiatric Association; APA, 2013). By its definition, no identifiable hard neurological signs (e.g., lesions) are associated with the disorder; however, it is agreed that the motor difficulties experienced are, in some way, neurologically based (Brown-Lum & Zwicker, 2015). Despite the relatively good understanding of the movement difficulties impacting children with DCD, there is still no clear understanding of the neural mechanisms associated with these impairments at either a structural or functional level, which limits early diagnosis and intervention. A cortical network that has recently been hypothesised to be associated with the movement difficulties characteristic of DCD is the mirror neuron system (MNS; Reynolds, Thornton et al., 2015; Werner, Cermak, & Aziz-Zadeh, 2012). The MNS is a fronto-parietal network of multimodal neurons in the central nervous system that supports learning via imitation and the internal representation of movement (motor imagery; Decety, 1996; Iacoboni & Dapretto, 2006). An exploration of the function of this system has the potential to explain the motor deficits characteristic of DCD, assist in assessment, and inform theoretical foundations of targeted intervention approaches in this population.

This doctoral thesis is divided into three series (five studies), each adding to the understanding of MNS function in children with DCD. These series include: (1) a systematic review of current literature of MNS function; (2) behavioural level assessments of MNS function (imitation and motor imagery); and (3) neuroimaging studies of grey matter volumes and MNS function.
The following is an overview of the studies presented within each of these series:

**Series One: Systematic literature review of MNS function in children with DCD**


**Series Two: Behavioural assessments of MNS function**


**Series Three: Neuroimaging studies of MNS structure and function**


In the first series of this thesis, a systematic review of MNS function in children and adults with DCD, examining both behavioural (imitation and motor imagery) and neuroimaging evidence is presented (Study 1). The review has been published in *Research in Developmental Disabilities* (Reynolds, Thornton et al., 2015). This study outlines the current evidence of MNS dysfunction in DCD and, in doing so, identifies gaps in the research which need to be explored to enable a more comprehensive understanding of the functioning of this neural system in this disorder. The review
provides the theoretical foundations (MNS dysfunction theory of DCD) and research direction for this thesis.

Thirty one articles met the inclusion criteria. Due to differences in outcome measures between studies and the variables reported, a narrative review was undertaken to synthesise findings from the studies. Preliminary evidence from this systematic review indicated a likely deficit in the functioning of the MNS in children and adults with DCD at behavioural and neurological levels. Although it was found to be well established that children with DCD display deficits imitating meaningful gestures (e.g., waving goodbye, brushing teeth), little research has explored novel, unlearned gestures. Preliminary evidence using assessment batteries consisting of limited items suggests that children with DCD also have a difficulty imitating novel gestures and sequences of gestures (Dewey & Kaplan, 1992; Goyen, Lui, & Hummel, 2011; Hill, 1998). As children with DCD experience difficulties acquiring new skills, further research to explore these types of gestures has the potential to provide a better reflection of the extent of imitation deficits in this disorder. Assessments that include novel and sequence gestures are likely to be more sensitive and a more accurate reflection of the motor learning process. In addition to imitation deficits, children and adults with DCD demonstrate different response patterns compared to controls when undertaking motor imagery tasks, providing further evidence to support MNS dysfunction. Assessments using more complex tasks are required to explore whether a motor imagery strategy can be maintained at increased levels of task difficulty, and to determine whether motor imagery deficits increase alongside task difficulty. In the neuroimaging literature, children with DCD were found to have reduced activation and connectivity of frontal, parietal and temporal MNS regions compared to controls (Debrabant, Gheysen, Caeyenberghs, Van Waelvelde, & Vingerhoets, 2013; Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009; Licari et al., 2015; McLeod, Langevin, Goodyear, & Dewey, 2014; Querne et al., 2008; Zwicker et al., 2010, 2011). These results should be interpreted with caution as the tasks utilised were not designed to explore MNS function; at the time of publication, no published neuroimaging studies had been designed specifically to explore MNS function. Based on the information presented in this review, there is evidence to implicate the MNS as possible cortical regions linked to DCD. The review also identified a need for further research to explore the MNS hypothesis in greater detail, particularly from a neuroimaging perspective.
The second series of this thesis aimed to provide some clarity surrounding equivocal findings in imitation and motor imagery deficits in children with DCD, behavioural markers of MNS dysfunction. The series consists of two studies. The first study (Study 2 of thesis), accepted for publication in the *Journal of Motor Behavior* (Reynolds et al., 2016), addresses the limited research into imitation of complex novel postures and sequences of gestures in probable DCD (pDCD). Fifty-eight boys (29 pDCD; 29 controls) aged 6-13 years were assessed using the postural praxis and sequencing praxis subtests of the Sensory Integration and Praxis Tests (Ayres, 1989). Children with pDCD were found to be slower to respond and less accurate than controls on both of the imitation tasks. Furthermore, group differences became more apparent with increasing task complexity. Because most movement skills, and many of the tasks we perform on a daily basis, are comprised of sequences of movements, this has important implications for children with DCD. There was considerable performance variability within the pDCD group, with some children displaying imitation scores within the normative range. Given the importance of imitation and visual learning for motor development, the difficulties in imitation displayed by some children with pDCD have the potential to impact on movement acquisition. These results provide support for the MNS hypothesis of DCD and suggest that interventions to target imitation may be beneficial for this population.

The second study in this series (Study 3 of thesis), published in *Human Movement Science* (Reynolds, Licari, Elliott et al., 2015), uses a complex hand rotation motor imagery paradigm to explore how the MNS and internal modelling may contribute to the motor impairments associated with DCD. The study also addresses task complexity in two ways: (1) determining whether motor imagery strategies can be used by children with DCD during more complex tasks, and (2) whether motor imagery deficits displayed by children with DCD compared to group age-matched controls are greater at increased levels of task complexity. Forty-four boys aged 7-13 years (22 pDCD; 22 controls) participated. Participants completed a complex hand rotation task in two conditions: with and without motor imagery instructions. Complex task paradigms, such as the use of both back and palm view across a number of angles, increase the likelihood of individuals adopting a motor imagery strategy (ter Horst et al., 2010), and so are likely to provide a more accurate assessment of MNS function. Stimuli were presented in two rotational axes – palm/back, and eight 45° rotational steps. Response patterns for both groups followed the biomechanical and postural constraints of actual movements, suggesting that both groups used motor imagery strategies to perform the task. Children with pDCD had slower and
less accurate responses to the hand stimuli than controls, with group differences increasing alongside task complexity. The response characteristics displayed by children with pDCD likely reflect a reduced capacity to mentally manipulate a body schema, and reduced visuo-motor processing capabilities. These results provide further behavioural evidence for the contribution of deficits in MNS function in DCD.

The third series in this thesis explores MNS function at a neurological level and comprises a volumetric study of brain structure and a functional activation study of MNS regions. Disruptions to development of grey matter have been linked to a range of related neurodevelopmental disorders which often co-occur with DCD (Boddaert et al., 2004; Brambilla et al., 2003; Carmona et al., 2005; Eckert et al., 2005; Kobel et al., 2010; Langevin, MacMaster, & Dewey, 2015; Nickl-Jockschat et al., 2012; Richlan, Kronbichler, & Wimmer, 2013; Silani et al., 2005; Valera, Faraone, Murray, & Seidman, 2007). Only two studies, however, have examined the potential contribution of brain grey matter macrostructural differences to DCD, both of these using measures of cortical thickness (Caeyenberghs et al., 2016; Langevin et al., 2015). The first study (Study 4 of this thesis), is a cross-sectional study that uses voxel-based morphometry (VBM) to assess grey matter volume differences in children with and without DCD, including regions within the MNS, using. VBM involves voxel-wise comparisons of grey matter volumes (modulated VBM data) and tests for differences anywhere in the brain (Mechelli, Price, Friston, & Ashburner, 2005). High-resolution structural MRI images were acquired from 44 children aged 8-12 years (22 DCD, 7.8 – 11.6 years; 22 controls, 8.3 – 12.0 years). No relative grey matter volume reductions were identified in MNS regions. Children with DCD were, however, found to have significant, large, right lateralised reductions in grey matter volume in the medial and middle frontal, and superior frontal gyri compared to controls. The addition of motor proficiency as a covariate explained the between-group GM volume differences, suggesting that grey matter volumes in motor regions are reflective of the level of motor proficiency. Grey matter volume reductions in frontal pre-motor regions may contribute to the motor difficulties characteristic of DCD. It is possible that intervention approaches targeting motor planning, attention, and executive functioning processes associated with these regions of reduced grey matter volume may result in functional improvements in children with DCD.

The second study of this series, and the final study of this thesis (Study 5), explores the MNS at a functional level in children with and without pDCD. This cross-sectional study
was undertaken as a follow up to the research undertaken by Reynolds and colleagues (Reynolds, Licari, Billington et al., 2015; Appendix A) exploring MNS cortical function in DCD. Nineteen children (10 pDCD; 9 controls) aged 8-13 participated in this study. A block design paradigm was used, and children performed an index finger adduction/abduction task during four MNS activation state conditions: (1) action observation; (2) motor imagery; (3) action execution; and (4) action imitation. Although children with pDCD had deficits in imitation and motor imagery at a behavioural level, no between group differences in MNS regions were identified during any of the task conditions. Consistent with our original study (Appendix A; Reynolds, Licari, Billington et al., 2015), the limited differences suggest that MNS dysfunction is unlikely to be an underlying mechanism of DCD. This study did reveal that children with pDCD had reduced activation in the thalamus, caudate and posterior cingulate compared to controls during the imitation condition. Reduced activation in these regions may suggest deficits in motor planning and attentional processes at a neurological level.

The evidence from the five studies demonstrated that although support for MNS dysfunction exists in the literature (Study 1), and at a behavioural level (Studies 2 and 3), dysfunction of this system is not supported at a neurological level. Based on the results from the structural MRI and fMRI studies, it is possible that reduced grey matter volume and activation pattern differences in motor planning and attention control regions may underlie the motor learning difficulties experienced by individuals with DCD. Although deficits in MNS function were not identified at a neurological level, this thesis has identified other potential mechanisms contributing to DCD. Further research into the underlying aetiology of DCD through genetics, in combination with neuroimaging research to increase our understanding of the underlying mechanisms through which it acts, will improve our understanding of this disorder and enable the development of intervention approaches targeting these processes.
The following is a list of publications, and conference abstracts and presentation to which the candidate has contributed during the course of her candidature.

**PEER REVIEWED PUBLICATIONS FROM THESIS**


**MANUSCRIPTS IN PREPARATION FROM THESIS**


**OTHER PEER REVIEWED PUBLICATIONS**


**ABSTRACTS, POSTERS, and PRESENTATIONS (Listed in chronological order)**


AWARDS

Sheila & Leslie Henderson Award for Originality, excellence of execution and ability to communicate research in Developmental Coordination Disorder, International Conference on Developmental Coordination Disorder (DCD11), Toulouse, France, July 2015

Most Outstanding Oral Presentation by a PhD Student, Symposium of Western Australian Neuroscience, Perth, Australia, April 2015

UWA Convocation Postgraduate Research Travel Award, 2014
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<tr>
<td>ACC</td>
<td>anterior cingulate cortex</td>
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<tr>
<td>ADHD</td>
<td>attention deficit hyperactivity disorder</td>
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<tr>
<td>ASD</td>
<td>autism spectrum disorder</td>
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<tr>
<td>BOLD</td>
<td>blood-oxygen-level dependent</td>
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<tr>
<td>DCD</td>
<td>developmental coordination disorder</td>
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<td>pDCD</td>
<td>probable developmental coordination disorder</td>
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<tr>
<td>DSM-5</td>
<td>Diagnostic and Statistical Manual of Mental Disorders (5th Ed.)</td>
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<tr>
<td>DTI</td>
<td>diffusion tensor imaging</td>
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<td>EEG</td>
<td>electroencephalography</td>
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<td>FC</td>
<td>functional connectivity</td>
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<tr>
<td>fMRI</td>
<td>functional magnetic resonance imaging</td>
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<tr>
<td>IFG</td>
<td>inferior frontal gyrus</td>
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<tr>
<td>IMD</td>
<td>internal modelling deficit</td>
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<tr>
<td>IPC</td>
<td>inferior parietal cortex</td>
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<td>IPL</td>
<td>inferior parietal lobule</td>
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<tr>
<td>M1</td>
<td>primary motor cortex</td>
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<tr>
<td>MABC</td>
<td>Movement Assessment Battery for Children</td>
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<td>MABC-2</td>
<td>Movement Assessment Battery for Children - 2</td>
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<tr>
<td>MFC</td>
<td>middle frontal cortex</td>
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<td>MI</td>
<td>motor imagery</td>
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<td>MNS</td>
<td>mirror neuron system</td>
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<td>MRI</td>
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<td>OFC</td>
<td>orbitofrontal cortex</td>
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<td>PIQ</td>
<td>praxis imagery questionnaire</td>
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<td>PMv</td>
<td>ventral premotor cortex</td>
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<td>PoCGy</td>
<td>postcentral gyrus</td>
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<td>PrCGy</td>
<td>precentral gyrus</td>
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<td>ROI</td>
<td>region of interest</td>
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<td>Abbreviation</td>
<td>Definition</td>
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<tr>
<td>rsfMRI</td>
<td>resting state functional magnetic resonance imaging</td>
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<td>SIPT</td>
<td>Sensory Integration and Praxis Tests</td>
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<tr>
<td>SLI</td>
<td>specific language impairment</td>
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<td>SMA</td>
<td>supplementary motor area</td>
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<td>superior temporal sulcus</td>
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<td>TD</td>
<td>typically developing</td>
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<tr>
<td>TPJ</td>
<td>temporo-parietal junction</td>
</tr>
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DECLARATION

I declare that this thesis is my own composition. All sources have been acknowledged throughout, and my contribution is clearly identified in the thesis. For any work presented in this thesis that has been co-published with other authors, I have the permission of all co-authors to include this work in my thesis.

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PhD Candidate

________________________________________________________________________________________________________________________
Assistant Professor Melissa K Licari
Principal and Coordinating Supervisor
STATEMENT OF CANDIDATURE CONTRIBUTION

This thesis contains published work and work prepared for publication which has been co-authored. The bibliographical details of the work and where it appears in the thesis are outlined below. A statement for each publication and prepared manuscript that clarifies the contribution of the student to the work is also provided below.


**Planning:** The candidate contributed to the conception of the review article, and development of the search terms and review protocol.

**Data Collection:** The candidate was the primary individual involved in the database searches, and managed the endnote library of citations. In addition, she was the primary reviewer of citations, reviewed all relevant articles, performed data extraction, and analysis and interpretation of the data.

**Manuscript:** The candidate prepared the first version of the manuscript and all the figures and tables. In addition, she was also responsible for revising manuscripts following circulation to co-authors. Finally, she led the preparation of journal review rebuttals and revisions.


**Planning:** The candidate contributed to the conception of the ideas, decisions surrounding the assessments utilised, and the development of the experimental design.

**Data Collection:** The candidate was the primary individual involved in the data collection, analysis, and interpretation of data.

**Manuscript:** The candidate prepared the first version of the manuscript and all the figures and tables. In addition, she was also responsible for revising manuscripts following
circulation to co-authors. Finally, she led the preparation of journal review rebuttals and revisions.


**Planning:** The candidate contributed to the conception of the ideas, decisions surrounding the assessments utilised, and the development of the experimental design.

**Data Collection:** The candidate was the primary individual involved in the data collection, analysis, and interpretation of data.

**Manuscript:** The candidate prepared the first version of the manuscript and all the figures and tables. In addition, she was also responsible for revising manuscripts following circulation to co-authors. Finally, she led the preparation of journal review rebuttals and revisions.


**Planning:** The candidate conceptualized and designed the voxel-based morphometry study.

**Data Collection:** The candidate was the primary individual involved in the data processing, analysis, and interpretation.

**Manuscript:** The candidate prepared the first version of the manuscript and all the figures and tables. In addition, she was also responsible for revising manuscripts following circulation to co-authors. Finally, she led the preparation of journal submission.

Planning: The candidate contributed to the conception of the ideas, decisions surrounding the fMRI protocol, and the development of the experimental design and fMRI scanning paradigm.

Data Collection: The candidate was the primary individual involved in the data-collection, processing, analysis, and interpretation.

Manuscript: The candidate prepared the first version of the manuscript and all the figures and tables. In addition, she was also responsible for revising manuscripts following circulation to co-authors. Finally, she led the preparation of journal submission.
CHAPTER 1: GENERAL INTRODUCTION

1.1 Introduction

Developmental coordination disorder (DCD) is a neurodevelopmental disorder characterised by impaired motor coordination and an inability to perform motor skills at an age appropriate level (American Psychiatric Association; APA, 2013). It is one of the most common childhood developmental disorders, affecting approximately 6% of school-aged children (APA, 2013; World Health Organisation, 2010). While the coordination difficulties are generally less severe than those seen in other movement related conditions (e.g., cerebral palsy), children with DCD experience activity limitations and participation restrictions at home, school and in the community; these limitations significantly impact their emotional and social development and place them at greater risk for depression, anxiety and low self-esteem (Jarus, Lourie-Gelberg, Engel-Yeger, & Bart, 2011; Zwicker, Harris, & Klassen, 2013). Although no studies have been undertaken to explore the direct economic cost of DCD to families and society (Cairney, 2015), there is undoubtably a significant cost associated with the extensive range of therapies used to treat this disorder, such as occupational therapy, physical therapy, speech therapy, and psychological services. In addition to therapy costs, the burden on family, education, and healthcare systems is unknown.

DCD is classified under the Motor Disorders subcategory of Neurodevelopmental Disorders in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5; APA 2013). Children diagnosed with DCD display impaired development of motor coordination, which is below that expected for their chronological age and opportunity for skill learning (Criterion A). The difficulties must significantly interfere with activities of daily living and academic achievement (Criterion B), and time of onset normally occurs early in the developmental period (Criterion C). The difficulties should not be attributed to intellectual or visual impairment, nor related to an identifiable neurological condition (e.g., cerebral palsy; Criterion D). There is a high level of co-occurrence with other neurodevelopmental disorders, including attention deficit hyperactivity disorder (ADHD), autism spectrum disorder (ASD), dyslexia, and specific language impairment with a potential for overlapping aetiologies of these disorders (APA, 2013; Blank, Smits-Engelsman, Polatajko, & Wilson, 2012). A dual diagnosis can be made if children display movement difficulties beyond what is normally associated with these behavioural
disorders. It has been demonstrated that children with DCD exhibit an extensive range of motor related deficits (for reviews of performance and hypothesised neurological deficits refer to Blank et al., 2012; Brown-Lum & Zwicker, 2015; Kashiwagi & Tamai, 2013; Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013; Zwicker, Missiuna, & Boyd, 2009); however, the underlying aetiology (e.g., genetics) and mechanisms (e.g., neurology) of the disorder remain largely unknown.

1.2 Mechanisms of developmental coordination disorder

While, by its definition, no identifiable hard neurological signs (e.g., lesions) are associated with DCD, it is now well established that the motor difficulties experienced are in some way neurologically based (Brown-Lum & Zwicker, 2015; Zwicker et al., 2009). Despite this, very little is known about the underlying neurological mechanisms, as limited neuroimaging studies have been undertaken to examine the suspected deficits in neurological functioning of this population. As a result, to date, hypotheses regarding the mechanisms underlying DCD have typically been drawn from behavioural studies.

With advancements in technology, recent research has utilised neuroimaging techniques such as magnetic resonance imaging (MRI; Caeyenberghs et al., 2016; Langevin, MacMaster, & Dewey, 2015) and diffusion tensor imaging (DTI; Debrabant et al., 2016; Langevin, MacMaster, Crawford, Lebel, & Dewey, 2014; Zwicker, Missiuna, Harris & Boyd, 2012;) to investigate brain micro- and macrostructure, and electroencephalography (EEG; Albaret & Chaix, 2001; de Castelnau, Albaret, Chaix, & Zanone, 2008; Lust, Geuze, Wijers, & Wilson, 2006; Pangelinan, Hatfield, & Clark, 2013; Tsai, Chang, Hung, Tseng, & Chen, 2012; Tsai, Pan, Cherng, Hsu, & Chiu, 2009), functional magnetic resonance imaging (fMRI; Debrabant, Gheysen, Caeyenberghs, Van Waelvelde, & Vingerhoets, 2013; Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009; Licari et al., 2015; Querne et al., 2008, Reynolds, Licari, Billington et al., 2015; Zwicker, Missiuna, Harris, & Boyd, 2010, 2011), resting state fMRI (rsfMRI; McLeod, Langevin, Goodyear, & Dewey, 2014, 2016), and single-photon emission computed tomography (SPECT; Mariën, Wackenier, De Surgeloose, De Deyn, & Verhoeven, 2010) to explore potential brain regions displaying functional abnormality. At a neurological level, although differences in activation patterns have been demonstrated in children with DCD, specific findings have been inconsistent, likely a result of different paradigms used during scanning and participant selection criteria. What is clear, however, is that the motor deficits characteristic of DCD are unlikely to be isolated to one brain region or system
(Brown-Lum & Zwicker, 2015; Zwicker et al., 2009). It has recently been hypothesised that a deficit in the functioning of the mirror neuron system (MNS), a cortical network involved in the learning of movement skills through imitation and internal representation of movement, may be an underlying mechanism linked to the movement difficulties associated with DCD (Reynolds, Thornton et al., 2015; Werner, Cermak, & Aziz-Zadeh, 2012).

**1.3 The mirror neuron system**

The MNS is a cluster of multimodal neurons in the central nervous system (CNS) with visual and motor properties (Fogassi & Gallese 2002) that fire when a person observes, imagines, or performs an action demonstrated by another (for MNS reviews refer to Cattaneo & Rizzolatti, 2009; Iacoboni, 2005; Iacoboni & Dapretto 2006; Iacoboni & Mazziotta 2007; Rizzolatti & Craighero, 2004; Rizzolatti, Fogassi & Gallese 2001). The MNS is thought to play an integrative role in observational learning and motor skill acquisition (Billard & Arbib 2002). It is proposed to be critical for imitation by simultaneously coding for the goals of actions, as well as the way in which they were performed (Billard & Arbib 2002; Heiser, Iacoboni, Maeda, Marcus, & Mazziotta, 2003; Iacoboni, 2005; Iacoboni et al. 1999; Iacoboni & Dapretto, 2006). The MNS is also active during motor imagery (the internal rehearsal of movement without any overt movement), a cognition state that has been demonstrated to assist the planning, acquisition, development and improvement of motor skills (Buccino, Solodkin, & Small, 2006; Decety, 1996). Dysfunction at any level within the MNS has the potential to disrupt motor skill learning and possibly lead to delays in motor development (Reynolds, Thornton et al., 2015).

Mirror neurons were first discovered in macaque monkeys, using single cell recordings in area F5 of the ventral premotor cortex (di Pellegrino, Fadiga, Fogassi, Gallese, & Rizzolatti, 1992; Fogassi & Gallese 2002; Gallese, Fadiga, Fogassi, & Rizzolatti, 1996), and subsequently within the prefrontal cortex (Gallese, Fadiga, Fogassi, & Rizzolatti, 2002). Numerous neurophysiological and brain imaging studies using transcranial magnetic stimulation (TMS), EEG, magnetoencephalography (MEG), positron emission tomography (PET), fMRI (e.g. Avikainen, Forss, & Hari, 2002; Buccino et al., 2001; Decety et al., 1997; Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Iacoboni et al., 1999; Kilner, Neal, Weiskopf, Friston, & Frith, 2009; Muthukumaraswamy, Johnson, & McNair 2004), and single cell recording (Mukamel, Ekstrom, Kaplan, Iacoboni, & Fried
2010) have provided indirect evidence that a somatotopically organized fronto-parietal MNS also exists in humans, with similar but possibly more evolved properties.

The homologous MNS areas in the human brain (see Figure 1.1) are thought to constitute the inferior parietal lobule (IPL; Arbib, Billard, Iacoboni, & Oztop, 2000; Rizzolatti & Craighero, 2004; Rizzolatti & Matelli, 2003), ventral premotor cortex (PMv; Buccino et al. 2001; Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Rizzolatti et al., 1996; Rizzolatti & Craighero, 2004), and pars opercularis of the inferior frontal gyrus (IFG; Brodmann’s area BA 44; Petrides & Pandya, 1994). The superior temporal sulcus (STS) is also thought to play an important role in visual input in the MNS. While not considered a primary MNS region per se (not active during motor execution), the STS is normally activated when observing biological movements (Allison, Puce, & McCarthy, 2000). This visual information is transferred to the IPL via the arcuate fasciculus and parallel tracts for specific kinaesthetic coding of the action. This information is then transferred to the IFG to define the goal of the action (inverse model; Arbib et al., 2000, Iacoboni, 2005; Iacoboni et al., 2001, Rizzolatti & Craighero, 2004). Efferent copies of the planned motor action are sent back to the STS for matching with the initial observed action (forward model; Iacoboni, 2005). The human MNS has been proposed to represent a ‘dynamic feedback control system’ (Schippers & Keysers, 2011, p. 40), which supports forward and inverse internal modelling, with a primary predictive control function.
1.4 The problem

Although we have a reasonably comprehensive understanding of the behavioural deficits characteristic of DCD, the underlying CNS mechanisms of DCD are not well understood. As a result, despite the many intervention approaches that have been trialled for DCD, they are often not evidence-based, with the long term impact of intervention programs unknown (Smits-Engelsman et al., 2013). A greater understanding of CNS structure and function in DCD may lead to the possibility of new evidence-based assessment and intervention strategies. One recent hypothesis is that a deficit in the functioning of the MNS contributes to the motor skill difficulties characteristic of DCD (Reynolds, Thornton et al., 2015; Werner et al., 2012). A greater understanding of the current literature, and behavioural and neurological correlates of MNS function in children with DCD is required to evaluate this hypothesis.
1.5 Study aims
The overarching aim of this research is to contribute to the exploration of possible underlying mechanisms associated with DCD. Specifically, the aim of this thesis is to explore the MNS dysfunction hypothesis of DCD from behavioural and neurological perspectives. It is hoped that this contribution will be able to inform future research to develop targeted patient-specific evidence-based intervention approaches for children with DCD to improve their motor skills and promote their participation at home, school, and in the community.

The specific research aims of this thesis are to:

- Systematically review the evidence related to MNS function in children with DCD.
- Assess behavioural measures of MNS function, including imitation and motor imagery, in children with and without DCD.
- Examine brain structure in children with DCD by examining grey matter relative volumes, both within and beyond the MNS, to inform brain structure-function relationships.
- Evaluate measures of neurological function to examine recruitment of MNS regions during motor imagery and imitation tasks in children with and without DCD.
- Identify other possible neural correlates of DCD.
- If possible, contribute evidence for the development of targeted interventions for children with DCD.

1.6 Significance of the studies
Children with DCD have motor coordination difficulties that impact many facets of their daily lives. To date, our understanding of this disorder has largely been based on behavioural research. There is currently a limited understanding of the underlying brain structure and function of children with DCD. By providing a greater understanding of the neurological mechanisms of DCD, and directions for future research, neuroimaging research has the potential to inform targeted interventions. This thesis explores one possible underlying mechanism, the MNS, recently proposed to be associated with movement difficulties characteristic of DCD by researchers involved in this project (Licari et al., 2015; Reynolds, Licari, Billington et al., 2015) and others (Werner et al.,
2012). Based on results of this research, potential directions for further research and translations into clinical practice are presented.

This research will add new knowledge to the current understanding of:

- Imitation of complex unlearned posture and sequence gestures, and motor imagery using a complex hand rotation paradigm in children with DCD in a MNS context.
- Whether grey matter volume differences exist between children with and without DCD that may contribute to functional activation differences.
- MNS region activation in children with DCD using fMRI.
- Other neural mechanisms that may be linked to this disorder.

1.7 Thesis outline

The introduction establishes subject matter for this doctoral thesis, and briefly introduces the research problem and approaches taken to address the problem. This thesis is presented as a series of individual studies addressing five individual, yet inter-related, research questions (Figure 1.2). The first study presents a systematic review of motor behaviour and neuroimaging literature regarding mirror neuron system function in children with DCD. This review provides background information for the theoretical foundations of this thesis. It identifies the questions and hypotheses for the subsequent research presented in the thesis. The second and third studies explore imitation and motor imagery performance, which are behavioural correlates of MNS function. The neuroimaging series includes structural and functional studies. The series are followed by detailed appendices, including one additional related paper on MNS function published by the candidate (Appendix A; Reynolds, Licari, Billington et al., 2015), published conference abstracts (Appendix B), plain language infographic summaries for stakeholders (Appendix C), and study information including ethics and assessments used (Appendix D). References lists for each article are presented at the end of each study, with all other references presented in a list following the discussion.

Although at times the presentation of independent papers may seem repetitive, it is felt that each paper should stand alone for ease of reading and publication purposes. Studies that have been published have been included in their published form. A synthesis of the results and discussion along with future research directions is presented at the end of this thesis.
Figure 1.2. Overview of thesis and research questions.
INTRODUCTION TO SERIES ONE: LITERATURE REVIEW

The first series of this thesis comprises one study published in Research in Developmental Disabilities, which is a systematic synthesis of current research in the area of MNS function in children and adults with DCD. The systematic review commences with an overview of DCD, the associated motor difficulties, and the clusters of performance deficits that have been identified in recent meta-analyses on the disorder (Reynolds, Thornton et al., 2015). A discussion of the MNS, and its role and hypothesised contribution to motor skill development and motor disorders is then provided. This study aimed to explore the current level of evidence for MNS deficits in children and adults with DCD at a motor behaviour and neurological level. In doing so, this paper has identified limitations in the previous research and provides research questions based on gaps within the current literature for the research carried out in subsequent chapters of this thesis.


The aims of this study are to:

- Systematically synthesise the literature in the area of MNS function in children with DCD.
- Explore the current level of evidence for MNS deficits in children with DCD at a motor behaviour and neurological level.
- Formulate future research questions based on gaps within the current literature.

It is hypothesised that there will be:

- Evidence to support a MNS deficit at a behavioural (imitation and motor imagery) level in children with DCD.
- Differences in reported activation patterns within MNS regions for children with and without DCD.
Limitations and delimitations

There are a number of limitations and delimitations of this systematic review.

- This review does not include psychosocial aspects of MNS function such as empathy or theory of mind. It only presents evidence for MNS dysfunction at a behavioural level through imitation and motor imagery, and at a neurological level exploring activation and connectivity of MNS areas.

- Only one reviewer screened articles at a title and abstract level, meaning that there was a potential for some studies to be missed. Two reviewers screened articles after this stage. Despite this, the whole review process was conducted twice (full searches and screening re-run to update for publication), reducing the potential for the omission of relevant articles.

- The systematic review uses a narrative summary approach rather than a meta-analytical approach. A meta-analysis of results was not possible as a result of the differences in outcome measures across studies.

- Effect sizes could not be calculated for all outcomes and tasks, as a result of the information presented in the original articles and/or the types of outcome measures presented.
CHAPTER 2: A SYSTEMATIC REVIEW OF MIRROR NEURON SYSTEM
FUNCTION IN DEVELOPMENTAL COORDINATION DISORDER:IMITATION,
MOTOR IMAGERY, AND NEUROIMAGING EVIDENCE

Review article

A systematic review of mirror neuron system function in developmental coordination disorder: Imitation, motor imagery, and neuroimaging evidence

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ABSTRACT

PURPOSE: The aim of this systematic review was to investigate the evidence of abnormal functioning of the mirror neuron system (MNS) in children and adults with developmental coordination disorder (DCD), through examination of imitation, motor imagery, and neuroimaging literature.

METHODS: The following databases were comprehensively searched for relevant articles: CINAHL Plus, Embase, MEDLINE, PsycINFO, Pubmed, and Web of Science. Full-text articles of all potentially relevant citations were obtained and assessed for eligibility by two authors. Outcome measures of interest at a motor behaviour level were any measures of imitation or motor imagery proficiency and, at a neurological level, were any measures of neural activity in MNS brain regions. Due to differences in outcome measures between studies and the variables reported, a narrative review was undertaken to synthesise findings from the studies.

RESULTS: Overall, 31 articles met the inclusion criteria. Children and adults with DCD display deficits imitating meaningful and novel gestures and demonstrate different response patterns to controls when undertaking complex motor imagery tasks. Children with DCD present reduced activation and connectivity of frontal, parietal, and temporal MNS regions.

CONCLUSIONS: Preliminary evidence indicates some deficit in the functioning of the MNS at a motor behaviour and neurological level. As no published neuroimaging studies have been designed specifically to explore MNS function, these results must be interpreted with caution. Further research to explore the MNS hypothesis in greater detail, particularly from a neuroimaging perspective, has the potential to provide information on the underlying mechanisms of DCD, inform future research into the aetiology of this disorder, and inform intervention approaches.

Abbreviations: BOLD, blood-oxygen-level dependent; DCD, developmental coordination disorder; pDCD, probable developmental coordination disorder; DSM-5, Diagnostic and Statistical Manual of Mental Disorders; DTI, diffusion tensor imaging; EEG, electroencephalography; fMRI, functional magnetic resonance imaging; IFG, inferior frontal gyrus; IPL, inferior parietal lobule; M1, primary motor cortex; MNS, mirror neuron system; ROI, region of interest; rsfMRI, resting state functional magnetic resonance imaging; STS, superior temporal sulcus.

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0891-4222/© 2015 Elsevier Ltd. All rights reserved.
Developmental coordination disorder (DCD) is a condition characterised by impaired motor coordination and an inability to perform and learn motor skills at an age appropriate level (American Psychiatric Association [APA], 2013). DCD is one of the most common childhood developmental disorders, affecting approximately 6% of school-aged children (APA, 2013; World Health Organisation [WHO], 2010). The poor motor performance displayed by children with DCD may present as persistent difficulty acquiring basic motor skills such as running, throwing, and catching, poor balance, and postural control, as well as difficulties associated with daily activities including tying shoelaces and handwriting (APA, 2013; Geuze, 2005; Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). In addition to the impaired fine and gross motor coordination experienced, individuals with DCD show marked neurodevelopmental immaturities and neurological soft signs, including choreiform and mirror movements (APA, 2013; WHO, 2010). Children with DCD experience activity limitations and participation restrictions at home, school, and in the community, significantly impacting their emotional and social development, and placing them at greater risk for depression, anxiety, and low self-esteem (Jarus, Lourie-Gelberg, Engel-Yeger, & Bart, 2011; Zwicker, Harris, & Klassen, 2013).

DCD is classified under the Motor Disorders subcategory of Neurodevelopmental Disorders in the Diagnostic and Statistical Manual of Mental Disorders (5th ed.; DSM-5) (APA, 2013), and as Specific Developmental Disorder of Motor Function (FB2) which falls under Pervasive and Specific Developmental Disorders, a subcategory of Developmental Mental, Behavioural and Neurodevelopmental Disorders in the International Classification of Diseases framework (WHO, 2010). Whilst by its definition, no identifiable hard neurological signs are associated with DCD, it has long been suspected that the motor difficulties experienced are neurologically based (Brown-Lum & Zwicker, 2015; Debrabant, Gheyens, Caeyenberghs, Van Waelvelde, & Vingerhoets, 2013; Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009; Langevin, MacMasters, Crawford, Lebel, & Dewey, 2014; Langevin, MacMaster, & Dewey, 2015; Licari et al., 2015; McLeod, Langevin, Goodyear, & Dewey, 2014; Querne et al., 2008; Zwicker, Missiuna, Harris, & Boyd, 2010, 2011, 2012). Very little is known about the underlying aetiology, as limited neuroimaging studies have been undertaken to examine the suspected deficits in neurological functioning of this population. As a result, to date, hypotheses regarding the neural correlates of DCD have typically been drawn from behavioural studies. With advancements in technology, recent research has utilised neuroimaging techniques such as functional magnetic resonance imaging (fMRI) (Debrabant et al., 2013; Kashiwagi et al., 2009; Licari et al., 2015; Querne et al., 2008; Zwicker et al., 2010, 2011), resting state fMRI (rsfMRI) (McLeod et al., 2014), and diffusion tensor imaging (DTI) (Langevin et al., 2014; Zwicker et al., 2012) to examine areas of potential neurological dysfunction.

A recent meta-analysis undertaken by Wilson et al. (2013) highlights the extensive range of difficulties children with DCD experience. Seven main task category clusters of movement deficits were identified, including the domain general clusters: internal (forward) modelling, rhythmic coordination, and executive function, and the domain-specific: control of gait and posture, control of reaching, catching and manual interception, and aspects of sensoriperceptual function. A separate meta-analysis suggests that children with DCD also have underlying visuo-motor translation deficits (Blank, Smits-Engelsman,
Dysfunction of several brain regions has been proposed to contribute to the movement difficulties characteristic of DCD (Brown-Lum & Zwicker, 2015; Zwicker et al., 2009). Deficits in motor adaptation (Cantin, Polatajko, Thach, & Jagal, 2007), postural control (Geuze, 2005), timing (Piek & Skinner, 1999), and visuo-motor tracking (Zwicker et al., 2011) implicate the cerebellum. Deficits in visuo-spatial processing and internal representation of movements (motor imagery and mental rotations) (Williams, Thomas, Maruff, Butson, & Wilson, 2006: Wilson, Maruff, Ives, & Currie, 2001: Wilson et al., 2004) suggest involvement of the parietal lobe. Difficulties in sequencing, motor control, motor learning, and coordination may be linked to basal ganglia dysfunction (Greenewegen, 2003). Involvement of the corpus callosum, the major neural pathway between the two cerebral hemispheres, which mediates information transfer, serving both an inhibitory and excitatory role, has also been suggested to account for deficits experienced in bimanual coordination (Sigmundsson, 2003). In addition, recent diffusion tensor imaging (DTI) studies have indicated reduced axial diffusivity of both the corticospinal tract (voluntary motor pathway) and posterior thalamic radiation (sensory pathway) of children with DCD compared to controls (Zwicker et al., 2012), as well as reduced fractional anisotropy in the superior longitudinal fasciculus and corpus callosum (Langevin et al., 2014). Based on motor behaviour research which suggests that deficits in a range of brain regions may underlie the movement deficits characteristic of DCD, further neuroimaging research in this population is required to gain a greater understanding of the underlying mechanisms.

A cortical network that has recently been hypothesised to be associated with the movement difficulties characteristic of DCD is the mirror neuron system (MNS) (Werner, Cermak, & Aziz-Zadeh, 2012; for MNS reviews, refer to Cattaneo & Rizzolatti, 2009; Iacoboni, 2005; Iacoboni & Dapretto, 2006; Iacoboni & Mazziotta, 2007; Rizzolatti & Craighero, 2004; Rizzolatti, Fogassi, & Gallese, 2001). The MNS is a cluster of multimodal neurons in the central nervous system that fire when a person observes and acts an action performed by another. It is thought to be our primary modality of learning skills through modelling behaviour and action (Iacoboni & Dapretto, 2006). The MNS circuit in humans is believed to incorporate the pars opercularis (BA44) of the inferior frontal gyrus (IFG) (Kilner, Neal, Weiskopf, Friston, & Frith, 2009), the adjacent ventral premotor cortex (PMv) (BA6) (Buccino et al., 2003; Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Rizzolatti et al., 1996), and the rostral inferior parietal lobule (IPL) (BA 39 and 40) (Arbib, Billard, Iacoboni, & Oztop, 2000; Caspers, Zilles, Laird, & Eckhorn, 2010; Rizzolatti & Craighero, 2004). These areas are activated during action observation, motor imagery, execution, and imitation. The superior temporal sulcus (STS) also plays an important role in visual input during action observation and imitation and is thought to code for goal-directed and meaningful actions (Jellema, Baker, Wicker, & Perrett, 2000; Perrett et al., 1989); however, STS neurons are not also activated during motor execution (Aziz-Zadeh, Koski, Zaidel, Mazziotta, & Iacoboni, 2006; Buccino, Solodkin, & Small, 2006). Whilst it is not therefore considered a true mirror area, the STS is thought to be connected with the MNS circuit via the arcuate fasciculus and parallel tracts (Catani, Jones, & ffytche, 2005; Iacoboni et al., 1999; Rizzolatti et al., 2001), transferring this visual information to the IPL for specific kinaesthetic coding of the action. This information is then transferred to the IFG to define the goal of the action (Arbib et al., 2000; Iacoboni, 2005; Iacoboni et al., 2001; Rizzolatti & Craighero, 2004). Efferent copies of the planned motor action are sent back to the STS for matching the planned with the observed action (Iacoboni, 2005). Together, these areas forming the human MNS have been proposed to represent a ‘dynamic feedback control system’ (Schippers & Keysers, 2011), supporting forward and inverse internal modelling, with a primary predictive control function.

The MNS is activated by observation of well-known meaningful, as well as novel meaningless and intransitive (non-object related) gestures (Buccino et al., 2001; Fadiga, Fogassi, Pavesi, & Rizzolatti, 1995; Maeda, Kleiner-Fisman, & Pascual-Leone, 2002; Patuzzo, Fiaschi, & Manganotti, 2003). Furthermore, the MNS codes simultaneously for the goals of actions, as well as the way in which they were performed; together, these features play an important role in learning via imitation (Rizzolatti & Craighero, 2004). It has been proposed that the MNS is partially an innate mechanism developed and modulated through experiential canalisation (Virji-Babul, Rose, Morricea, & Makan, 2012), and partially developed via Hebbian learning (Giudice, Manera, & Keysers, 2009). Generalist theories of imitation hypothesise imitation use and success are dependent on past experience (Brass & Heyes, 2005). Furthermore, activation of the human MNS appears to differ according to motor experience and motor competence (Calvo-Merino et al., 2005; Calvo-Merino, Grèzes, Gaser, Passingham, & Haggard, 2006). FMRI studies of MNS activation of professional dancers and piano players compared to controls during observation and mental imagery of dance sequences and piano playing demonstrated higher activation of MNS areas in experts (Calvo-Merino, Glaser, Grèzes, Passingham, & Haggard, 2005; Haslinger et al., 2005). It is not yet understood whether the differences in MNS activation reflect motor proficiency and repertoire, or whether the motor proficiency outcomes are a result of degree of MNS activation. Despite this, the suggestions that the MNS may be more active when the observer is watching actions which build on a part of their current motor repertoire has obvious consequences for individuals with movement dysfunction who are less proficient movers and typically have a smaller motor repertoire. Based on these MNS activation patterns, it is certainly possible that children with DCD could display reduced activation of MNS regions which may impact on their ability to imagine and imitate movements and therefore their capacity to learn motor skills.

In addition to its role in observational learning, the MNS is also active during motor imagery. Motor imagery is the internal rehearsal of movement without any overt movement, during which there is activation of the same neural and musculature regions that are active during physical execution of skills (Page, Levine, & Leonard, 2007). The use of motor
imagery, on its own, as well as in conjunction with traditional motor execution training, has been demonstrated to improve motor skill performance (Buccino et al., 2006) and to assist the acquisition and development of motor skills (Decety, 1996). Motor imagery is also used by most people during the planning phases of movements and is quite commonly utilised in the elite sport setting (Guillot, Debarnot, Louis, Hoyek, & Collet, 2010; MacIntyre & Moran, 2010). As a cognition state which activates the MNS, poorer performance on motor imagery tasks by individuals with DCD would suggest some underlying MNS dysfunction, and these motor imagery deficits may lead to delays in motor development (Lust, Geuze, Wijers, & Wilson, 2006).

Dysfunction of the MNS has been hypothesised to contribute to other neurodevelopmental disorders (e.g. Autism Spectrum Disorders [ASD]; Oberman et al., 2005) and movement-related conditions including ideomotor apraxia following focal lesions (Cattaneo & Rizzolotti, 2009), environmental dependency syndrome following frontal lesions, echopraxia (Rizzolotti, Fabbri-Destro, & Cattaneo, 2009), and possibly Tourette syndrome (Ganos, Ogrzal, Schnitzler, & Münchau, 2012). Current therapy for populations with movement-related conditions focuses on neurorehabilitation, exploiting the concept of neuroplasticity and the capacity of the brain to alter its structure and function at a neuronal level and reorganise neural networks in response to changing demands (Nilsson, Pelny, & Pekna, 2012). Given the suggested neurological underpinnings of DCD, interventions grounded in neurorehabilitation have the potential to improve motor learning in this population, particularly once a greater understanding of the neurology associated with DCD is gained.

Werner et al. (2012) proposed and drew support for the MNS hypothesis of DCD in a review based on a small selection of behavioural papers indicating imitation impairments, along with a comprehensive collation of neuroimaging studies which had been published at the time identifying differential activation of MNS regions in children with DCD during non-MNS activation tasks. The MNS hypothesis suggests that as a result of MNS involvement in imitation and general motor functioning, dysfunction of this system may underlie the motor deficits characteristic of this population. The evidence collected in their review demonstrated evidence to support the hypothesis that dysfunction of the MNS may be associated with this disorder. The aim of the review was to present the MNS dysfunction hypothesis, rather than to systematically review the evidence; the extent of supporting evidence is not explored, with only a small proportion of the relevant imitation papers drawn upon, and motor imagery deficits not included. Given that the MNS mediates imitation, action execution, and motor imagery, which all assist in skill learning, deficits in mirror neuron function may underlie the motor difficulties characteristic of DCD. This review aims to extend the initial proposal of MNS dysfunction in children with DCD, by systematically collating and reviewing the relevant behavioural (imitation and imagery) and neuroimaging literature to steer future research on the neural correlates of DCD.

If MNS dysfunction is found to be linked to DCD, we may be able to improve current intervention practices and target interventions towards improving MNS function. Motor skill rehabilitation programs based on activation of the MNS have included action observation treatment, motor imagery training, and mirror box therapy (for unilateral deficits) (Mulder, 2007). The premise behind all of these intervention paradigms is that action observation and motor imagery recruit the same neural circuits as motor execution (Mulder, 2007). In addition to improving motor performance, fMRI assessment of action observation and imagery rehabilitation programs demonstrates that these interventions induce neuroplastic changes with increased post-intervention MNS activation (Ertelt et al., 2007). Action observation and motor imagery training are of particular clinical relevance for individuals who are unable to physically perform a task (Mulder, 2007), and therefore of potential relevance in a DCD intervention context. Other intervention approaches currently used for children with DCD, such as the CO-OP (Missiuna, Mandich, Polatajko, & Malloy-Miller, 2001) also have potential to be used in an MNS intervention context; the addition of a motor imagery ‘imagine’ stage to the CO-OP paradigm (Polatajko et al., 2001) may also provide additional benefits.

2. Material and methods

This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement (Moher, Liberati, Tetzlaff, Altman, & The PRISMA Group, 2009). To identify whether a similar systematic review had been previously conducted, electronic searches were conducted in both the Cochrane and Database of Abstracts of Reviews of Effectiveness (DARE) databases, and in Google scholar. A comprehensive search of scholarly literature was conducted on 10 April 2014, with monthly search update notifications set up to identify any new articles added to the databases. The full search was updated on 26 June 2015 using the following electronic databases: CINAHL Plus (1982), Embase (1980–2015, Week 25), MEDLINE (In-Process & Other Non-Indexed Citations and MEDLINE 1946 to Present), PsycINFO (1806 to June Week 3 2015), Pubmed, and Web of Science. On each database, publications were searched from the earliest records until the most recent (Week 3, June 2015). Reference lists of selected articles were also reviewed for novel studies. The protocol for this review has not been registered or published.

2.1. Search

To assist with the development of the search terms and subsequent eligibility criteria for selection of studies, the review question (What is the evidence for abnormal functioning of the mirror neuron system (MNS) in children and adults with DCD?) was organised taking into account both the quantitative PICOS framework; Population, Intervention (exposure), Comparison, Outcome, Study design (Moher et al., 2009) and qualitative PICo framework: Population,
Interest. Context. Given that the review question was not a focused clinical assessment of a particular intervention, the search strategy was modified to ensure that all research relating to MNS function in children and adults DCD was identified. The search included Populations: Developmental Coordination Disorder (and other terms used to refer to this disorder, including minimal brain dysfunction, perceptual motor dysfunction, and developmental dyspraxia; Missiuna & Polatajko, 1995) and Exposure/Interest: the Mirror Neuron System, which encompassed MNS brain regions and performance correlates of MNS function (imitation and motor imagery). To ensure that any articles on the broad topic of MNS and DCD were identified Comparison: typically developing controls. Outcome: any measure of neurological function within MNS regions, imitation, and motor imagery measures, and Study Type: all study types presenting original data, were built into the eligibility criteria stage of the review. Studies were only included if they also assessed motor proficiency with a valid and reliable motor assessment. Studies which did not exclude children with comorbidities were included in the review when it was clear that all children fit the criteria for DCD. Only peer reviewed journal articles were considered for inclusion.

An initial orientation search was conducted to extract the key search terms, which were then finalised and adapted for each database. Keywords and MeSH heading search terms were truncated, exploded, and adjusted with the assistance of a librarian to comply with each of the databases (see Appendix 1 for full list of search terms). Searches were limited to ‘humans’, however, no language limits, age limits, or publication year limits were used. Reference lists of the included studies and relevant review articles were manually searched for additional articles which were not identified through the search.

2.2. Types of outcome measures

Motor behaviour outcome measures of interest were any measures of imitation or motor imagery proficiency. These included valid and reliable standardised assessments, such as the Sensory Integration and Praxis Tests battery, as well as non-standardised test batteries based on assessments administered in similar studies. Because a large number of assessments were non-standardised, and designed for individual studies, assessment tools were not included in the search strategy. Neurological outcome measures included blood oxygen level-dependent (BOLD) signal activation in MNS brain regions, Electroencephalography (EEG) measures in MNS brain regions were also explored when paired with behavioural MNS tasks. Cortical thickness of MNS regions was also explored.

2.3. Study selection

Citations from all six databases were downloaded to and managed using EndNote X5. Duplicate citation records were manually removed. Based on the eligibility criteria, one author (J.R.) screened all non-duplicate titles and abstracts, identified relevant articles, and excluded irrelevant citations. Full-text articles of all potentially relevant citations were obtained and assessed independently for eligibility by two authors (J.R. and A.T.). 100% agreement on article inclusion status was reached.

The same two authors followed the guidelines outlined in section seven of The Cochrane Handbook for Systematic Reviews of Interventions (Higgins & Deeks, 2008) for data extraction. An electronic Microsoft Excel data extraction form was designed to extract: year of publication, country of origin, study objective(s), study design, participants selection and characteristics (e.g. sample size, age, diagnoses), confounding controls, neuroimaging technique and scan sequence (where applicable), tasks performed and outcome measures, number of test administrators/assessors, blinding of test administrators/assessors, gender comparisons, analytical methods, reported statistics, effect sizes, Kmet score, key findings, and conclusions. Articles were given a study and report ID to link together multiple reports of the same study so that reviewed information was not duplicated in the review.

Two authors (J.R. and A.T.) independently evaluated the risk of bias and quality of each study, using the assessment tool developed by Kmet, Lee, and Cook (2004) (refer to Appendix 2 for detailed scoring, and Kmet et al., 2004 for scoring criteria). A third assessor (C.D.), reviewed the article by Licari et al. (2015), instead of A.T., who was an author of the paper. The assessment tool consists of 14 questions, guidelines for scoring quality, and a scoring system. Calculated Kmet scores were used to classify the quality of each study as either strong (>80%), good (70–79%), adequate (50–69%), or limited (<49%) (Lee, Packer, Tang, & Girdler, 2008). Discrepancies were resolved through discussion. Any potential conflicts of interest or biases were noted.

2.4. Synthesis of results and additional analyses

Due to differences in outcome measures between studies and the variables reported, a meta-analysis was not feasible. Therefore, a narrative review was undertaken to synthesise findings from the studies. Effect sizes for each study were calculated where possible using G*Power (3.1.2) software (Faul, Erdfelder, Lang, & Buchner, 2007) to determine the magnitude of imitation or motor imagery performance differences between children with and without DCD. Relevant effect sizes reported in text were also included. Effect sizes were not created for tasks where multiple variables were employed when assessing performance. Effect size was classified as small \( (d < 0.20) \), moderate \( (d = 0.20–0.80) \), or large \( (d > 0.80) \), as described by Cohen (Portney & Watkins, 2009).
3. Results

3.1. Study selection

Electronic searches yielded 5993 articles, after accounting for duplicates (8585 articles with duplicates) (Fig. 1). Upon review of the titles and abstracts, 5955 articles did not meet inclusion criteria. Most of the studies addressed topics not related to the subject of our review, such as apraxia in adults following stroke. Full texts of the remaining 38 articles were reviewed, and a total of 27 articles were considered to meet inclusion criteria. Reasons for exclusion of the 11 full text articles included: no control group, no movement assessments for either group, children with and without DCD pooled for analysis, the DCD group including children with other disorders such as ASD and intellectual impairments but not necessarily DCD, the use of the term dyspraxia to refer to children with deficits in gestural ability in the absence of coordination deficits, and
no relevant data presented (Fig. 1). A citation search of the eligible articles and monthly search update notification emails revealed an additional 11 articles that were assessed. Four of these articles met the inclusion criteria, taking the total to 31 articles. 100% agreement by the two reviewers on article inclusion was reached at this stage.

3.2. Study characteristics

The 31 articles included for review comprised 27 cross-sectional studies (29 reports) and one longitudinal study (two reports). Thirty-six articles assessed children with DCD and one article assessed adults with DCD. Tables 1, 3, and 5 provide information on study characteristics, including: citation, country in which the research was undertaken, objective(s) of the research, study design, neuroimaging technique (where appropriate), population and study size, tasks performed and outcome measures. Outcome tools were broken into measures at the levels of motor behaviour (‘behavioural studies’) and functioning of the brain (‘neuroimaging studies’). Behavioural outcomes included measures of imitation and motor imagery performance, whilst neuroimaging outcomes included BOLD signal activation, EEG measures, and cortical thickness in MNS brain regions. Only data relevant to children and adults with DCD and typically developing controls were considered in this review.

3.3. Imitation

Nine imitation articles based on seven data sets were included in the review (Tables 1 and 2). Of these, eight articles (six studies) reported data relating to representational (meaningful) gesture imitation based on non-standardised assessments. Three articles explored imitation of non-representational (non-meaningful) gestures. Of these, two articles employed non-standardised assessment batteries to explore novel gestures and sequences of gestures (Dewey & Kaplan, 1992; Hill, 1998), and one paper used the standardised praxis assessments from the Sensory Integration and Praxis Tests (S IPT) (Goyen, Lui, & Hummell, 2011). Of the imitation of non-representational gesture assessments, five of six studies identified group differences (Dewey, 1991, 1993; Dewey & Kaplan, 1992; Hill, 1998; Sinani, Sugden, & Hill, 2011; Zoia, Pelamatti, Cuttini, Casotto, & Scabar, 2002), with only one study not identifying a reduced level of performance in the group of children with DCD (Dewey, Cantell, & Crawford, 2007). Two of (Dewey & Kaplan, 1992; Goyen et al., 2011) three studies exploring non-representational gesture imitation report a reduced performance level by children with DCD; one assessment using a small battery of six simple gestures did not produce group differences, potentially because a ceiling effect was reached (Hill, 1998).

Imitation development and performance differences across age were explored in several studies. The development of praxis skills with age was explored by Hill, Bishop, and Nimmo-Smith (1998), where children with DCD performed at a similar level to younger typically developing controls. In contrast, when comparing children with DCD to younger, yet also motor level matched children, Sinani et al. (2011) identified differences in performance, rather than purely a developmental delay in the development of praxis. The relationship between imitation proficiency and age was also examined by Zoia et al. (2002) who identified a significant increase in imitation performance with age ($p < 0.001$). Furthermore, they identified the difference in performance of the five simple gestures between children with DCD and control children to be less marked with increasing age.

Gender comparisons were undertaken in four reports (Dewey et al., 2007; Dewey & Kaplan, 1992; Sinani et al., 2011; Zoia et al., 2002). Only Zoia et al. (2002) identified gender differences in the imitation of gestures, with males performing significantly worse than females. The uneven ratios of males:females and small sample of females in most research prohibited gendered comparisons. No assessment of imitation performance in relation to the severity of DCD, or correlation between movement proficiency and imitation performance was undertaken in any of the imitation literature.

3.4. Motor imagery

Fourteen motor imagery articles based on 12 studies were included in the review (Tables 3 and 4). One of these (Lust et al., 2006) also incorporated the use of EEG. Seven articles (six studies) reported data relating to indirect explicit (asked to use motor imagery) assessment methods including the Praxis Imagery Questionnaire (Sinani et al., 2011; Wilson et al., 2001), visually guided pointing tasks (VGPT) (Katschmarissy, Cairney, Maruff, Wilson, & Currie, 2001; Lewis, Vance, Maruff, Wilson, & Cairney, 2008; Maruff, Wilson, Trebilcock, & Currie, 1999; Williams, Omizzolo, Galea, & Vance, 2013; Wilson et al., 2001), and an imagined reaching task (Cacola, Gabbard, Ihana, & Romero, 2014). Eight articles (seven studies) explored indirect implicit (the task itself elicits a motor imagery strategy) measurement of motor imagery using hand laterality (Decoainck, Spitaels, Fias, & Lenoir, 2009; Lust et al., 2006; Noten, Wilson, Ruddock, & Steenbergen, 2014; Williams et al., 2011, 2013, 2006; Williams, Thomas, Maruff, & Wilson, 2008; Wilson et al., 2004) and whole body rotation (Williams et al., 2006, 2008) tasks.

All five studies that employed VGPTs identified deficits in performance of imagined tasks. The imagined reaching study indicated motor imagery deficits emerged as the task difficulty increased (Cacola et al., 2014), with a moderate effect size for the more difficult task ($d = 0.70$). The two Praxis Imagery Questionnaire studies, both report differences, with one reporting overall deficits and deficits on the subtests position and action (Sinani et al., 2011), and the other reporting differences on the kinaesthetic subtest (Wilson et al., 2001). Hand laterality results are less consistent; a small number of reports suggest the use of non-motor imagery strategies (Williams et al., 2013; Wilson et al., 2004) or decreased engagement in a motor imagery
<table>
<thead>
<tr>
<th>Report Id</th>
<th>Reference</th>
<th>Country</th>
<th>Objective</th>
<th>Study design</th>
<th>Population</th>
<th>Tasks: measure of imitation</th>
<th>Outcome measures</th>
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<tbody>
<tr>
<td>1.1</td>
<td>Dewey (1991)</td>
<td>Canada</td>
<td>To investigate praxis and sequencing skills in children with sensorimotor dysfunction (using tests of symbolic, representational gestures, and action sequences); to investigate the effect of input modality (verbal command/imitation) on the performance of single limb gestures and action sequences</td>
<td>Cross sectional</td>
<td>48 children (42 males, 6 females), 5.3–8.10 years, $\bar{x}$ (SD) = 6.75 (0.87) years</td>
<td>Representational Gestures Praxis Test: six transitive and four intransitive limb gestures performed to verbal command and imitation</td>
<td>A 0–3 scale of gestural performance, and an analysis of error types</td>
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<tr>
<td>2.1</td>
<td>Dewey (1993)</td>
<td>Canada</td>
<td>To investigate the relationship between limb and orofacial praxis in children with developmental motor deficits; to examine developmental trends in gestural representation and the types of errors demonstrated by normally developing children and children with developmental motor deficits</td>
<td>Cross sectional</td>
<td>102 children (68 males, 34 females), 6.0–10.11 years, $\bar{x}$ (SD) = 8.5 (1.43) years; DCD: 51 children (44 males, 7 females); TD controls: 51 children (24 males, 27 females)</td>
<td>Representational Gestures Praxis Test: six transitive limb gestures, six intransitive limb gestures, and six orofacial gestures to verbal command and to imitation</td>
<td>A 0–3 scale of gestural performance, and an analysis of error types</td>
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<td>2.2</td>
<td>Dewey and Kaplan (1992)</td>
<td>Canada</td>
<td>To analyse praxis skills of children with developmental motor deficits under several task demands: representational nature of the gesture (representational vs nonrepresentational), type of limb gesture (transitive vs intransitive), input modality (command vs imitation), movement complexity (single gestures vs sequence of gestures), and movement system (limb vs orofacial)</td>
<td>Cross sectional</td>
<td>102 children (68 males, 34 females), 6.0–10.11 years, $\bar{x}$ (SD) = 8.5 (1.43) years; DCD: 51 children (44 males, 7 females); TD controls: 51 children (24 males, 27 females)</td>
<td>Representational Gestures Praxis Test: six transitive limb gestures, six intransitive limb gestures, and six orofacial gestures to verbal command and imitation; Nonrepresentational Gestures Test: six hand/limb and four orofacial gestures; Sequencing gestures test: combined intransitive limb and orofacial gestures</td>
<td>A 0–3 scale of gestural development, and an analysis of error types</td>
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<tr>
<td>3.1</td>
<td>Dewey et al. (2007)</td>
<td>Canada</td>
<td>To make comparisons and examine the differences in gestural skill and errors between ASD and DCD; to distinguish between children with ADHD who also met the criteria for DCD and those that did not</td>
<td>Cross sectional</td>
<td>238 children (181 males, 57 females), 5.0–18.0 years; DCD: 46 children (28 males, 18 females), $\bar{x}$ (SD) = 11.7 (3.6) years; DCD + ADHD: 38 children (26 males, 12 females), $\bar{x}$ (SD) = 11.3 (1.7); TD controls: 78 children (59 males, 19 females), $\bar{x}$ (SD) = 11.3 (2.4) years; ASD: 49 children (43 males, 6 females), $\bar{x}$ (SD) = 10.2 (3.4) years; ADHD: 27 children (25 males, 2 females), $\bar{x}$ (SD) = 12.0 (2.3) years</td>
<td>Representational Gestures Praxis Test: six transitive and six intransitive gestures to verbal command and imitation</td>
<td>A 0–3 scale of gestural development, and an analysis of error types</td>
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<td>4.1</td>
<td>Goyen et al. (2011)</td>
<td>Australia</td>
<td>To investigate the association of sensorimotor processing skills and DCD in extreme preterm children</td>
<td>Cross sectional (matched case-control)</td>
<td>100 children, 8 years; Preterm: 50 children (21 with DCD, 29 without DCD), $\bar{x}$ (SD) = 8.8 (0.2) years (born between 1st Jan 1992 and 10th May 1992); TD controls: 50 children, $\bar{x}$ (SD) = 8.8 (0.4) years</td>
<td>Sensory Integration and Praxis Test: Praxis subtests (Postural Praxis, Sequencing Praxis, and Oral Praxis)</td>
<td>SIPT standardised scores</td>
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<tr>
<td>5.1</td>
<td>Hill (1998)</td>
<td>England</td>
<td>To compare the nature of motor difficulties of children with DCD and SLI, and the extent to which they be regarded as being dyspraxic; to compare performance of the clinical groups with typically developing peers and younger control children</td>
<td>Cross sectional</td>
<td>72 children (43 males, 29 females), 5–13 years; DCD: 11 children (8 males, 3 females), $\bar{x}$ (SD) = 9.3 (1.4) years; TD controls: 25 children (14 male, 11 female), $\bar{x}$ (SD) = 9.8 (1.5) years; younger controls: 17 children (9 male, 8 female), 5–6 years, $\bar{x}$ (SD) = 5.8 (0.4) years; SII: 19 children (12 male, 7 female), $\bar{x}$ (SD) = 9.9 (1.9) years</td>
<td>Represenational Gestures Praxis Test: six transitive and six intransitive gestures to verbal command and imitation; Non-representational Gestures Test: six meaningless hand postures, Sequencing gestures test: six sequences of hand postures</td>
<td>Representational gestures: scored 0 for incorrect, 1 for correct. Single postures: on a 0–2 scale, Sequence imitation: 0–3 scale</td>
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<td>5.2</td>
<td>Hill et al. (1998)</td>
<td>England</td>
<td>To investigate patterns of error production to characterise and compare praxis skills in DCD and SLI and to consider whether errors were similar to adult apraxia; to investigate inter-rater reliability of the error categorisation to determine whether it would be possible to establish a reliable method of classifying, qualitative aspects of children's representational gestures; to explore the qualitative characteristics of responses</td>
<td>Cross sectional</td>
<td>72 children (43 males, 29 females), 5–13 years; DCD: 11 children (8 males, 3 females), $\bar{x}$ (SD) = 9.3 (1.4) years; TD controls: 25 children (14 male, 11 female), $\bar{x}$ (SD) = 9.8 (1.5) years; younger controls: 17 children (9 male, 8 female), 5–6 years, $\bar{x}$ (SD) = 5.8 (0.4) years; SII: 19 children (12 male, 7 female), $\bar{x}$ (SD) = 9.9 (1.9) years</td>
<td>Represenational Gestures Praxis Test: six transitive and six intransitive gestures to verbal command and imitation</td>
<td>Correct performance, error types</td>
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<td>Report Id</td>
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<td>6.1</td>
<td>Sinani et al. (2011)</td>
<td>United Kingdom</td>
<td>To compare the familiar transitive and intransitive gestural performance across modalities and praxis imagery between two groups of children with DCD, one selected from schools (sDCD) and another from clinics (cDCD) with typically developing age-matched children; to allow a direct comparison of transitive and intransitive gestural performance across modalities and between sDCD and cDCD groups; to compare the transitive and intransitive gestural performance across modalities and between the two DCD groups with two younger typically developing groups</td>
<td>Cross sectional</td>
<td>118 children (76 males, 42 females): school DCD (sDCD): 26 children (15 males, 11 females), 9–11 years, $\bar{x}$ (SD) = 118.2 (6.9) months; clinical DCD: 19 children, (14 males, 5 females), 9–11 years, $\bar{x}$ (SD) = 124.1 (1.3) months; TD controls: 24 children (16 males, 8 females), 9–11 years, $\bar{x}$ (SD) = 121.1 (6.9) months; younger controls (MA1): 23 children (14 males, 9 females), 5–6 years, $\bar{x}$ (SD) = 71.0 (4.2) months; younger controls (MA2): 26 children (17 males, 9 females), 4–5 years, $\bar{x}$ (SD) = 57.1 (4.4) months</td>
<td>Representational gestures praxis test: 12 transitive and 12 intransitive gestures to: (i) verbal command, (ii) reciprocal imitation, (iii) verbal command plus kinesthesia, (iv) tactile plus object use, (v) object use</td>
<td>Performance on representational gesture test</td>
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<td>7.1</td>
<td>Zoia et al. (2002)</td>
<td>Italy</td>
<td>To investigate the extent to which gesture performance depends on input modality and whether gestural development patterns differ in children with and without developmental coordination disorder (DCD); to explore whether gesture performance depends on the input modality; to explore which input modalities facilitate gestural performance at different ages and whether there are differential maturation patterns in the use of the different input modalities; to identify if children with DCD show a gestural development pattern similar to typically developing children</td>
<td>Cross sectional</td>
<td>140 children (123 males, 17 females), 5–10 years; DCD: 35 children (29 males, 6 females), 5–6 years; 10 children, 7–8 years; 15 children, 9–10 years; TD controls: 105 children (94 males, 11 females), 5–6 years; 43 children, 7–8 years; 50 children, 9–10 years; 12 children</td>
<td>Representational gestures praxis test: 17 transitive gestures performed to: (i) imitation (only first five items used), (ii) visual plus tactile modality, (iii) visual modality, (iv) verbal modality</td>
<td>0 if incomplete, inappropriate, incorrectly sequenced, or not executed at all, 1 if correct</td>
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Abbreviations: ADHD, attention deficit hyperactivity disorder; ASD, autism spectrum disorders; DCD, developmental coordination disorder; cDCD, clinical DCD; sDCD, school DCD; MA1, 5–6-year-olds; MA2, 4–5-year-olds; $\bar{x}$, mean; SD, standard deviation; SLI, specific language impairment; TD, typically developing.
Table 2  
Motor behaviour study results: imitation.

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<tr>
<td>1.1 Dewey, 1991</td>
<td>Representational Gestures Praxis Test (six transitive and four intransitive limb gestures; verbal command and imitation); performance on a 0–3 scale</td>
<td>Transitive: significant group differences ( (p &lt; 0.001) ): SMD and MP &lt; NC, SMD and MP not significantly different. Intransitive: significant group differences ( (p &lt; 0.013) ): SMD &lt; NC, MP between SMD and NC and not significantly different from either. Motor Sequencing Test: significant main effect for group ( (p &lt; 0.001) ): SMD &lt; MP and NC, MP &lt; NC</td>
<td>N/A (mean % correct presented on graph; no SD)</td>
<td>63.64</td>
<td>SMD demonstrated deficits in the performance of symbolic, representational gestures, and action sequences. MP group only performed lower than NC for transitive gestures. For single gestures, all groups performed better to verbal command rather than imitation</td>
<td>Statistics for imitation of gestures not reported separately (imitation/command combined)</td>
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<p>| 2.1 Dewey, 1993 | Representational Gestures Praxis Test (six transitive and six intransitive limb gestures, six orofacial gestures; verbal command and imitation); performance on a 0–3 scale, error types | Significant group differences for transitive gestures ( (p &lt; 0.001) ), intransitive gestures ( (p &lt; 0.05) ), and orofacial gestures ( (p &lt; 0.001) ); NC &gt; MP (imitation/verbal command combined); MP group performed intransitive gestures better to imitation than command ( (p &lt; 0.0125) ). Transitive gestures: multivariate effect for group ( (p &lt; 0.001) ), MP &lt; NC: correct responses ( (p &lt; 0.001) ) ( k^{<em>} = 1.57, NC k^{</em>} = 2.43 ), action errors ( (p &lt; 0.001) ) ( MP k^{<em>} = 98, NC k^{</em>} = 45 ), movement errors ( (p &lt; 0.05) ) ( MP k^{<em>} = 53, NC k^{</em>} = 30 ), and postural errors ( p &lt; 0.05 ) ( MP k^{<em>} = 1.60, NC k^{</em>} = 1.17 ). Intransitive gestures: multivariate effect for group ( p &lt; 0.001 ), MP &lt; NC: Correct responses ( p &lt; 0.001 ) ( MP k^{<em>} = 3.20, NC k^{</em>} = 4.21 ), action errors ( p &lt; 0.001 ) ( MP k^{<em>} = 1.11, NC k^{</em>} = 0.60 ), movement errors ( p &lt; 0.005 ) ( MP k^{<em>} = 0.15, NC k^{</em>} = 0.05 ). Orofacial gestures: multivariate effect for group ( p &lt; 0.001 ), Correct responses ( p &lt; 0.001 ) ( MP k^{<em>} = 3.39, NC k^{</em>} = 4.12 ), action errors ( p &lt; 0.001 ) ( MP k^{<em>} = 1.54, NC k^{</em>} = 0.72 ). Group differences and developmental trends to imitation: multivariate main effect for group ( p &lt; 0.001 ), and the multivariate linear age effect were significant ( p &lt; 0.001 ) | Transitive: ( d = 1.275, r = 0.537 ), Intransitive: ( d = 0.1225, r = 0.061 ), Ororal: ( d = 0.762, r = 0.356 ) (from 1992 paper) | 63.64 | NC performed better than MP for transitive, intransitive and orofacial gestures. MP greater number of errors than NC. Age-related performance on transitive and intransitive limb gestures was linear; NC performed better than MP at all ages | Same participant cohort and data reported in 2.2 and Dewey and Kaplan (1994) Performance to command/imitation not separated for statistical analysis |</p>
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<tr>
<td>2.2</td>
<td>Dewey &amp; Kaplan, 1992</td>
<td><strong>Representational Gestures Praxis Test</strong> (six transitive and six intransitive limb gestures, six orofacial gestures; verbal command and imitation): performance on a 0–3 scale</td>
<td>Transitive (18): DCD: $\bar{x} = 14.27$, $SD = 2.08$, NC: $\bar{x} = 16.43$, $SD = 1.19$; Intransitive (18): DCD: $\bar{x} = 16.94$, $SD = 2.03$, NC: $\bar{x} = 17.14$, $SD = 1.10$</td>
<td>Representational: Transitive: $d = 1.275$, $r = 0.537$; Intransitive: $d = 0.1225$, $r = 0.061$; Orofacial: $d = 0.762$, $r = 0.356$; Nonrepresentational: Sequence Preferred Limb: $d = 0.775$, $r = 0.361$, Sequence Non-Preferred Limb: $d = 0.613$, $r = 0.293$, Sequence Orofacial: $d = 0.343$, $r = 0.169$, Sequencing: N/A</td>
<td>68.18</td>
<td>NC performed better than MP for all praxis tasks. Transitive gestures performed more poorly than intransitive gestures. MP less accurate to command compared to imitation. NC performed better than MP for sequences imitation</td>
<td>Same participant cohort and representational gestures data reported in 4.1, and Dewey and Kaplan 1994 (not included in review)</td>
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<td><strong>Nonrepresentational Gestures Test</strong> (six hand/limb and four orofacial gestures): hand/limb; performance on a 0–2 scale (orofacial)</td>
<td>Nonrepresentational orofacial gestures (12): (covariate: age) trend towards MP group ($\bar{x} = 9.55$, $SD = 1.44$) performing worse than NC group ($\bar{x} = 10.02$, $SD = 1.3$) ($p &lt; 0.10$)</td>
<td>Significant group differences ($p &lt; 0.001$, partial $\eta^2 = 0.333$). DCD + ADHD ($\bar{x} = 29.2$, $SE = 0.36$) SE = 0.5) &lt; TD group ($\bar{x} = 31.1$, $SE = 0.41$)</td>
<td>86.36</td>
<td>DCD did not show deficits in imitation of gestures compared to TD. TD performed marginally better than DCD + ADHD for gesture to imitation. No difference between performances of transitive/intransitive. Gestural skills of the older group of individuals with DCD tested may have matured to normal levels</td>
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<td><strong>Sequencing Gestures Test</strong> (two-five gestures: intransitive limb, orofacial gestures): 0 for incorrect, 1 for correct</td>
<td>Sequencing Gestures (age and PPVT-R as covariates): significant multivariate main effect for group ($p &lt; 0.004$)</td>
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<td>3.1</td>
<td>Dewey et al., 2007</td>
<td><strong>Representational Gestures Praxis Test</strong> (six transitive and six intransitive gestures; verbal command and imitation): performance on a 0–3 scale, error types</td>
<td>Significant group differences ($p &lt; 0.001$, partial $\eta^2 = 0.333$). DCD + ADHD ($\bar{x} = 29.2$, $SE = 0.36$) SE = 0.5) &lt; TD group ($\bar{x} = 31.1$, $SE = 0.41$)</td>
<td>Partial $\eta^2 = 0.333$; (mean and standard error presented)</td>
<td>86.36</td>
<td>DCD did not show deficits in imitation of gestures compared to TD. TD performed marginally better than DCD + ADHD for gesture to imitation. No difference between performances of transitive/intransitive. Gestural skills of the older group of individuals with DCD tested may have matured to normal levels</td>
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Table 2 (Continued)

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| 4.1       | Goyen et al., 2011 | Sensory Integration and Praxis Test (Postural Praxis, Sequencing Praxis, Oral Praxis subtests): SIPT scores: performance on a 0–2 scale | Postural Praxis: significant group differences ($p < 0.001$); preterm DCD (median = 0.48, IQR = 1.025, 0.215) < control (median = 0.71, IQR = -0.1, 1.14), difference between preterm DCD and preterm no DCD (median = 0.06, IQR = -0.48, 0.79) approached significance ($p = 0.038$, 0.017 adjusted significance level)
Sequencing Praxis: significant group differences ($p < 0.004$); preterm DCD (median = 0.14, IQR = -0.57, 0.865) < control (median = 0.96, IQR = 0.34, 1.28), difference between preterm DCD and preterm no DCD (median = 0.33, IQR = 0.355, 1.345) approached significance (0.023, 0.017 adjusted significance level)
Oral Praxis: significant group differences ($p < 0.03$); preterm DCD (median = 0.16, IQR = 0.935, 0.865) < control (median = 0.52, IQR = 0.26, 0.98) (preterm no DCD: median = 0.35, IQR = 0.25, 0.82) | N/A (median and interquartile ranges presented) | 90.91 | Trend towards poorer visual processing and praxis in preterm children, particularly for preterm children with DCD. Controls performed better than preterm DCD for imitation. Differences in imitation assessments approached significance between preterm DCD and preterm no DCD (May have reached significance with larger sample) |
<p>| 5.1       | Hill, 1998 | Representational Gestures Praxis Test (six transitive and six intransitive gestures; verbal command and imitation): 0 for incorrect, 1 for correct. Nonrepresentational Gestures Test (six meaningless hand postures): performance on a 0-2 scale. Sequencing gestures test (six hand gestures sequences): performance on a 0-3 scale. | Representational Gestures: significant effects of group ($p &lt; 0.001$), gesture type ($p &lt; 0.001$), and response condition ($p &lt; 0.001$); DCD &lt; controls for transitive and intransitive gesture imitation ($p &lt; 0.001$). Nonrepresentational and sequencing gestures: no significant group differences ($p &gt; 0.1$) (ceiling effect acknowledged). Better performance for single compared to multiple gestures ($p &lt; 0.001$); no group x task (single/multiple gesture) interaction ($p &gt; 0.1$) | N/A (means and SD provided on graph only) | 86.36 | Representational Gesture Imitation: DCD and SLI greater number of errors than TD; DCD and SLI groups performed a similar number of errors to each other and to younger, motor matched, control group. Performance of all children was significantly worse in transitive compared to intransitive conditions and poorer to verbal command than imitation. Same population and assessments as 5.2 Hill, Bishop and Nimmo-Smith 1998; Ceiling effect for nonrepresentational and sequencing tasks. |</p>
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<td>5.2</td>
<td>Hill et al., 1998</td>
<td>Representational Gestures Praxis Test (six transitive and six intransitive gestures; verbal command and imitation): correct performance, error types</td>
<td>At least a trend towards children with DCD producing more of each of the four main errors than age-matched controls in all cases: body-part-as-object, external configuration, internal configuration, and spatial orientation. Children in all groups produced errors of similar types; differences only in the frequency with which they were observed. DCD performed similarly to SLI and younger control groups. Performance to imitation reduced, but did not eliminate, error production when compared to command.</td>
<td>N/A (% of group making error type presented in table and graph)</td>
<td>86.36</td>
<td>DCD, SLI and younger controls made similar types of errors. Only difference between the groups was frequency with which errors were displayed. Children with DCD may have immature praxis development. Gesture errors can be classified using error types derived from the adult literature.</td>
<td>Same population and assessments as in 5.1 Hill, 1998; Praxis test from 2.1 Dewey, 1993.</td>
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<td>6.1</td>
<td>Siani et al., 2011</td>
<td>Representational gestures praxis test (12 transitive and 12 intransitive gestures: verbal command, reciprocal imitation, verbal command plus kinaesthesia, tactile plus object use, object use): performance on a 0–3 scale</td>
<td>Transitive (36): significant group differences (p &lt; 0.001): sDCD (\bar{x} = 24.5, SD = 2.8, n = 22.3), cDCD (\bar{x} = 28.6, SD = 2.5) (p &lt; 0.001), sDCD &gt; 4–5 years (\bar{x} = 20.1, SD = 2.8) (p &lt; 0.001)</td>
<td>Transitive gesture imitation: TD/sDCD: (d = 1.545, r = 0.611), TD/cDCD: (d = 2.470, r = 0.777), Intransitive gesture imitation: TD/sDCD: (d = 1.006, r = 0.449), TD/cDCD: (d = 2.224, r = 0.743)</td>
<td>90.91</td>
<td>cDCD and sDCD impaired for both types of gestures for most modalities in comparison to their TD peers. Developmental dyspraxia is one symptom characterising DCD. Children with DCD recruited from different settings (school vs. clinic) have praxic problems that may be explained by the involvement of different underlying mechanisms. Pathology, rather than purely a developmental delay in the development of praxis, probably exists based on differences of performance of the younger groups motor matched with the DCD groups.</td>
<td>Not controlled for gender (boys performed better than girls)</td>
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<td>7.1</td>
<td>Zoia et al., 2002</td>
<td>Representational gestures praxis test (five transitive gestures: imitation, visual plus tactile modality, visual modality, verbal modality)</td>
<td>Significant group differences: TD &gt; DCD (p &lt; 0.001), OR of 0.2</td>
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<td>Performance increased significantly with age (p &lt; 0.001). Group differences less marked with increasing age.</td>
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<td>5–6 years: no difference between control (x̄ = 4.3, 95% CI = 4.0–4.7, 76%) and DCD (x̄ = 2.7, 95% CI = 2.3–3.1, 54%) (p = 0.054)</td>
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<td>DCD group had had difficulty integrating information deriving from different sensory systems (hearing, kinetic, touch, vision) into a stable motor representation and difficulty using verbal input.</td>
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<td>9–10 years: controls (x̄ = 4.8, range = 4–6) &gt; DCD (x̄ = 3.3, range = 2–7), 66% (p &lt; 0.05)</td>
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<td>Performance remained significantly less elevated than age-matched controls with increasing age (p &lt; 0.001). Group differences less marked with increasing age.</td>
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**Abbreviations:** ADHD, attention deficit hyperactivity disorder; DCD, developmental coordination disorder; cDCD, clinical DCD; sDCD, school DCD; IQR, interquartile range; MP, motor problem; NC, normal controls; OR, odds ratio; PPVT-R, Peabody Picture Vocabulary Test–Revised; SLI, specific language impairment; SMD, sensorimotor dysfunction; TD, typically developing.
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<td>8.1</td>
<td>Cacola et al., 2014</td>
<td>USA</td>
<td>To explore motor imagery in children with DCD using an estimation of reach paradigm that combines action representation and extension of space with tools; to determine differences in accuracy with two tool lengths and arms; to examine behaviour with the &quot;switch&quot; of conditions associated with extending and retracting spaces (change from arm to tool and tool to arm)</td>
<td>Cross sectional</td>
<td>36 children (20 males, 16 females), 6–13 years; DCD: 18 children (10 males, 8 females), 6–13 years, $\bar{x}$ (SD) = 9.83 (2.5) years; TD controls: 18 children (10 males, 8 females), 6–13 years, $\bar{x}$ (SD) = 9.0 (2.3) years</td>
<td>Reach estimation task: reach distance estimations with their arm and with tools 20 and 40 cm in length</td>
<td>Accuracy</td>
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<td>9.1</td>
<td>Deconinck et al., 2009</td>
<td>Belgium</td>
<td>To investigate motor imagery in children with DCD; to explore the modulating or interference role of posture on judgment of hand laterality in a mental rotation task; to investigate the notion that children with DCD show a reduced capacity of internally simulating movements of their own body or motor imagery</td>
<td>Cross sectional</td>
<td>26 children (22 males, 4 females); DCD: 13 children (11 males, 2 females), $\bar{x}$ (SD) = 9.0 (0.7) years; TD controls: 13 children (11 males, 2 females), $\bar{x}$ (SD) = 9.3 (0.7) years</td>
<td>Hand laterality task: Rotational axes: 2 (palm and back view in separate, with congruent posture), Rotational steps: 4 (–90°).</td>
<td>Response time, accuracy</td>
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<tr>
<td>10.1</td>
<td>Hyde et al., 2014</td>
<td>Australia</td>
<td>To provide preliminary insights into the integrity of motor imagery in adults with probable developmental coordination disorder</td>
<td>Cross sectional</td>
<td>59 young adults (28 males, 31 females); 19–35 years; pDCD: 12 young adults (2 males, 10 females), $\bar{x}$ (SD) = 22.17 (4.65) years; TD controls: 47 young adults (26 males, 21 females), $\bar{x}$ (SD) = 22.06 (1.95) years</td>
<td>Hand laterality task: Rotational axes: 2 (palm and back view), Rotational steps: 8 in 45° increments (5 practice followed by 80 tests)</td>
<td>Response time, accuracy</td>
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<td>11.1</td>
<td>Katschmarsky et al., 2001</td>
<td>Australia</td>
<td>To examine forward modeling of efference copy in children with DCD who showed impairments in motor imagery, using a double-step saccade test; to test the hypothesis that children with DCD who experience deficits in motor imagery have difficulty processing the visual spatial consequences of intended movements</td>
<td>Cross sectional</td>
<td>20 children, 7–11 years; DCD: 10 children, 7–11 years, $\bar{x}$ (SD) = 5.5 (1.1) years; TD controls: 10 children, 8–11 years, $\bar{x}$ (SD) = 10.0 (1.3) years</td>
<td>Visually guided pointing task: 80 mm vertical time with the closest edge of target box 30 mm from line; 10 target widths</td>
<td>VGPT: movement duration time for real and imagined movements</td>
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<td>12.1</td>
<td>Lewis et al., 2008</td>
<td>Australia</td>
<td>To determine whether motor impairments in ADHD, combined type alone, DCD alone, ADHD combined type and comorbid DCD may arise from disruption to a common set of cognitive functions and their related neural substrate; to compare the extent to which processes that depend on the forward modelling of efference copy are impaired in children with DCD and in children with ADHD-C who also have DCD (ADHD-C/DCD) by measuring the ability to generate imagined movement sequences in both groups</td>
<td>Cross sectional</td>
<td>58 children (40 males, 18 females), 8–12 years; DCD: 15 children (10 males, 5 females), 8–12 years; ADHD-C/DCD: 14 children (10 males, 4 females), 8–12 years; TD controls: 15 children (10 males, 5 females), 8–12 years; ADHD-C: 14 children (10 males, 4 females), 8–12 years</td>
<td>Visually guided pointing task: 80 mm vertical time with the closest edge of target box 30 mm from line; 5 target widths</td>
<td>Movement duration time for real and imagined movements</td>
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<td>13.1</td>
<td>Maruff et al., 1999</td>
<td>Australia</td>
<td>To examine the relationship between real and imagined movements in children with DCD to help determine the nature of cognitive and motor impairments</td>
<td>Cross sectional</td>
<td>44 children (22 males, 22 females), 108–131 months; DCD: 24 children (12 males, 12 females), 108–130 months, ( \bar{x} = 117 ) months; TD controls: 20 children (10 male, 10 female), 108–131 months, ( \bar{x} = 115.9 ) months</td>
<td>Visually guided pointing task: 80 mm vertical time with the closest edge of target box 30 mm from line; 5 target widths</td>
<td>Movement duration time for real and imagined movements</td>
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<td>14.1</td>
<td>Noten et al., 2014</td>
<td>The Netherlands</td>
<td>To explore action planning and motor imagery in children with DCD</td>
<td>Cross sectional</td>
<td>82 children (36 male, 46 female), 7–12 years, ( \bar{x} ) (SD = 10.3(1.4) years; DCD: 21 children (11 male, 10 female), ( \bar{x} = 10.4 ) years; TD controls: 56 children (22 male, 34 female), ( \bar{x} = 10.3 ) years</td>
<td>Hand laterality task with MI instructions: Rotational axes: 2 (back and palm in separate runs. Rotational steps: 6 angles in 60’ (each run 5 practice followed by 36 trials: steps, 2 hands, 3 repetitions)</td>
<td>Response time, mean accuracy</td>
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<td>6.1</td>
<td>Sinani et al., 2011</td>
<td>United Kingdom</td>
<td>To compare praxis imagery between two groups of children with DCD, one selected from schools (sDCD) and another from clinics (cDCD) with typically developing age-matched children (AMC); compare praxis imagery between sDCD and cDCD groups; to compare praxis imagery between the two DCD groups with two younger typically developing groups</td>
<td>Cross sectional</td>
<td>118 children (76 males, 42 females): School DCD (sDCD): 26 children (15 males, 11 females), 9–11 years, $\bar{x}$ (SD) = 118.2 (6.9) months; Clinical DCD: 19 children, (14 males, 5 females), 9–11 years, $\bar{x}$ (SD) = 124.1 (1.3) months; TD controls: 24 children (16 males, 8 females), 9–11 years, $\bar{x}$ (SD) = 121.1 (6.9) months; younger controls (MA1): 23 children (14 males, 9 females), 5–6 years, $\bar{x}$ (SD) = 71.0 (4.2) months; younger controls (MA2): 26 children (17 males, 9 females), 4–5 years, $\bar{x}$ (SD) = 57.1 (4.4) months</td>
<td>Praxis Imagery Questionnaire: kinaesthetic, spatial position, action and object subscales</td>
<td>Performance on representational gesture test; performance on Praxis Imagery Questionnaire</td>
</tr>
<tr>
<td>15.1</td>
<td>Williams et al., 2006</td>
<td>Australia</td>
<td>This study aimed to test the internal modelling deficit (IMD) hypothesis of DCD using the mental rotation paradigm</td>
<td>Cross sectional</td>
<td>36 children (18 males, 18 females), 7–11 years; DCD: 18 children (9 male, 9 female), $\bar{x}$ (SD) = 9.7 (0.7) years; TD controls: 18 children (9 male, 9 female), $\bar{x}$ (SD) = 9.2 (1.4) years</td>
<td>Hand laterality task (with and without motor imagery instructions): rotational axes: 1 (back view). Rotational steps: 8 (45° increments from 0°), 5 practice trials followed by 40 test trials. Repeated twice, without MI instructions and second time with MI instructions; Whole-body rotation task: Determine whether it was a left or right arm the person was holding out or across the body. Rotational steps: 8; 5 practice trials followed by 40 test trials</td>
<td>Response time, mean accuracy</td>
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<tr>
<td>Report Id</td>
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<td>Objective</td>
<td>Study design</td>
<td>Population</td>
<td>Tasks: measure of motor imagery</td>
<td>Outcome measures</td>
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<td>16.1</td>
<td>Williams et al., 2008</td>
<td>Australia</td>
<td>To explore whether children with varying degrees of motor impairment differ in their ability to perform motor imagery tasks</td>
<td>Cross sectional</td>
<td>63 children, 7–11; DCD-S: 21 children (9 males, 12 females), 7–11 years; ( \bar{x} ) (SD) = 9.4 (0.7) years; DCD-M: 21 children (14 males, 7 females), 7–11 years; ( \bar{x} ) (SD) = 9.8 (1.0) years; TD controls: 21 children (9 males, 12 females), 7–11 years, ( \bar{x} ) (SD) = 9.4 (1.3) years</td>
<td>Hand laterality task (with and without motor imagery instructions): rotational axes: 1 (back view)</td>
<td>Response time, mean accuracy</td>
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<td>16.2</td>
<td>Williams et al., 2011</td>
<td>Australia</td>
<td>To explore the motor imagery ability of children with hemiplegia, whilst comparing them to children with DCD and their typically developing peers; to compare deficits in the whole-body transformation task, which is more complex and less likely to produce ceiling effects in our comparison group to the hand rotation</td>
<td>Cross sectional</td>
<td>63 children (29 males, 35 females), 7–13 years; DCD: 21 children (9 males, 12 females), 7–11 years; ( \bar{x} ) (SD) = 9 years 5 months (8 months); TD controls: 21 children (9 males, 12 females), 7–11 years, ( \bar{x} ) (SD) = 9 years 5 months (1 year 4 months); Mild spastic hemiplegia: 21 children (10 males, 11 females), 8–13 years, ( \bar{x} ) (SD) = 10 years 4 months (1 year 6 months)</td>
<td>Hand laterality task: rotational axes: 1 (back view), Rotational steps: 8 in 45° increments (5 practice followed by 40 test trials); Whole-body rotation task: Determine whether it was a left or right arm the person was holding out or across the body. Rotational steps: 8, 5 practice trials followed by 40 test trials</td>
<td>Response time, mean accuracy</td>
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<td>17.1</td>
<td>Williams et al., 2013</td>
<td>Australia</td>
<td>To determine whether inattention was greater in ADHD + DCD than in ADHD alone; To determine whether motor imagery deficits observed in DCD were present in ADHD + DCD</td>
<td>Cross sectional</td>
<td>69 children (43 males, 26 females), 7–12 years; DCD: 10 children (6 males, 4 females), 7.05–10.51 years, ¯x (SD) = 8.45 (1.01) years; ADHD + DCD: 16 children (14 males, 2 females), 7.32–11.33 years, ¯x (SD) = 9.0 (1.65) years; TD controls: 18 children (10 males, 8 females), 7.56–11.84 years, ¯x (SD) = 10.20 (1.31) years; ADHD: 14 children (8 males, 6 females), 8.19–12.86 years, ¯x (SD) = 10.11 (1.41) years</td>
<td>Visually guided pointing task: 80 mm vertical time with the closest edge of target box 30 mm from line; 10 target widths; Hand laterality task: Rotational axes: 1 (back view), Rotational steps: 8 in 45° increments (5 practice followed by 40 tests)</td>
<td>VGPT: movement duration time for real and imagined movements; Hand laterality task: response time, mean accuracy</td>
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<td>18.1</td>
<td>Wilson et al., 2004</td>
<td>Australia</td>
<td>To test whether children with DCD have difficulties in generating an accurate visuospatial representation of an intended action, using a mental rotation motor imagery paradigm</td>
<td>Cross sectional</td>
<td>34 children (23 males, 11 females), 8–12 years; DCD: 16 children (11 males, 5 females), 8–12 years, ¯x (SD) = 10 years, 4 months (19 months); TD controls: 18 children (12 males, 6 females), 8–12 years, ¯x (SD) = 10 years (19 months)</td>
<td>Hand laterality task: Rotational axes: 2 (back and palm view), Rotational steps: 8 (45° increments from 0°), 80 test trials. Could see hands—hands not covered</td>
<td>Response time and mean accuracy</td>
</tr>
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<td>19.1</td>
<td>Wilson et al., 2001</td>
<td>Australia</td>
<td>To replicate earlier findings that timing of imagined movement sequences in children with DCD do not conform to conventional speed-accuracy trade-off; to examine (using a weight manipulation) whether this deficit was also attributable to inaccurate programming of relative force</td>
<td>Cross sectional</td>
<td>40 children, 97–141 months; DCD: 20 children (12 males, 8 females), 97–141 months, ¯x = 119.3 months; TD controls: 20 children, 97–136 months, ¯x = 120.3 months</td>
<td>Visually guided pointing task: 80 mm vertical time with the closest edge of target box 30 mm from line; 10 target widths; load and no load condition; Praxis Imagery Questionnaire: kinaesthetic, spatial position, action and object subscales</td>
<td>VGPT: Movement duration time for real and imagined movements; PIQ: number of correct responses</td>
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Abbreviations: ADHD, attention deficit hyperactivity disorder; ADHD-C, ADHD combined type; DCD, developmental coordination disorder; cDCD, clinical DCD; pDCD, probable DCD; sDCD, school DCD; MI, motor imagery; ¯x, mean; SD, standard deviation; TD, typically; VGPT, visually guided pointing task.
Table 4
Motor behaviour study results: motor imagery.

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<tr>
<th>Report Id</th>
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<th>Tasks and outcome measures</th>
<th>Key results</th>
<th>Effect sizes</th>
<th>Kmet score (%)</th>
<th>Key findings</th>
<th>Comments</th>
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<tr>
<td>8.1</td>
<td>Capola et al., 2014</td>
<td>Reach estimation task: accuracy</td>
<td>20 cm tool task: No significant effect for condition or group &lt; condition 40 cm task: Accuracy: Significant effect for condition (p &lt; .001, $\eta^2 = .18$) and group (p &lt; .001, $\eta^2 = .17$); TD (M = 77.61, SD = 17.02) &gt; DCD (M = 63.95, SD = 21.71)</td>
<td>$\eta^2 = .18$ TD/DCD: d = 0.70, r = 0.30</td>
<td>90.91</td>
<td>DCD group less accurate using 40 cm tool; possible that additional information such as processing metric length may have constrained the ability of children with DCD to effectively mentally represent the action</td>
<td>Participants asked to kinaesthetically &quot;feel&quot; themselves executing the movement</td>
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<td>9.1</td>
<td>Deconinck et al., 2009</td>
<td>Hand laterality task: accuracy, response time</td>
<td>Accuracy: DCD = 81.2%, TD = 95.0% (p &lt; .001, $\eta^2 = .17$), DCD &gt; errors than TD children. Group = Hand - Participant. Posture = Hand &gt; more efficient judging medial compared to lateral rotations. Controls significantly more efficient than pDCD (p = 0.001), $\eta^2 = .505$; DCD &gt; TD for accuracy. Effect of rotation interacted hand and group (p = 0.002, $\eta^2 = .18$)</td>
<td>Accuracy: $\eta^2 = .517$</td>
<td>72.73</td>
<td>Imagined rotation were influenced by the biomechanical complexity of actual movements and hand posture. DCD longer response times and lower accuracy scores: indicate a lack of quality of the MI processes</td>
<td>Not specified whether mean RT calculated with all or only correct responses. Appears to be all</td>
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<td>10.1</td>
<td>Hyde et al., 2014</td>
<td>Hand laterality task: IS: mean response time/ accuracy</td>
<td>Orientation: pDCD (M medial = 19.59, M lateral = 23.34, 63 ms, p = 0.040) and TD (M medial = 13.51, M lateral = 158.56, 63 ms, p = 0.001); more efficient judgment medalled to lateral rotations. Controls significantly more efficient than pDCD (p &lt; .001). Stimulus view: pDCD (M back = 1959.62 ms, M palm = 2475.77 ms, p = 0.010) and TD (M back = 1315.21 ms, M palm = 1642.71 ms, p = 0.001); more efficient judgment back compared to palm view. Controls significantly more efficient than pDCD (p &lt; .001)</td>
<td>Orientation: $\eta^2_p = .029$, p &lt; .001</td>
<td>90.91</td>
<td>Young adults with pDCD and controls engaged in an MI strategy. Young adults with pDCD were significantly less efficient than controls in using an MI strategy</td>
<td>Mean RT calculated with correct and incorrect responses</td>
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<td>11.1</td>
<td>Katschmarsky et al., 2001</td>
<td>VGPT: movement duration time for real and imagined movements</td>
<td>All impairments: DCD = 10/14 individuals, TD = 0/10 individuals. (Classified as having impaired MI if Pearson’s correlation between ID and target width was less than 0.20 on imagined trials of the VGPT. Conversely, subjects were considered to have no impairment in MI if Pearson’s correlation between ID and target width was greater than 0.30 on the VGPT.)</td>
<td>N/A (graph of Pearson’s r values for real and imagined conditions)</td>
<td>72.72</td>
<td>10/14 children with DCD displayed MI deficits. No TD children showed MI deficits. DCD imagined movements did not conform to physiological speed accuracy trade-off constraints. DCD with MI deficits demonstrated impairment ability to program saccades on the bases of efference copy</td>
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<td>12.1</td>
<td>Lewis et al., 2008</td>
<td>VGPT: movement duration time for real and imagined movements</td>
<td>Real movements: logarithmic regression had best fit for control ($r^2 = 0.94$) and DCD ($r^2 = 0.87$) groups. Imagined movements: logarithmic regression had best fit for control group ($r^2 = 0.80$). Neither the logarithmic ($r^2 = 0.28$) nor linear ($r^2 = 0.09$) function provided good fit for the relationship between movement duration and target width for imagined movements in the DCD group. Group x condition: no difference between groups for the slopes of real movements. For imagined movements, average slope in the DCD group was different to the other groups ($p &lt; 0.005$).</td>
<td>N/A (linear and logarithmic regression for each group and comparison)</td>
<td>68.18</td>
<td>DCD showed deficits in MI and did not conform to speed accuracy trade-off for imagined movements; ADHD-C/DCD and ADHD-C/no motor impairments showed normal MI abilities, although slower</td>
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<td>13.1</td>
<td>Maruff et al., 1999</td>
<td>VGPT: movement duration time for real and imagined movements</td>
<td>Real movements: logarithmic regression had best fit for the control ($r^2 = 0.91$, $p &lt; 0.001$) and DCD ($r^2 = 0.92$, $p &lt; 0.001$) groups. Imagined movements: logarithmic regression had best fit for control group ($r^2 = 0.90$, $p &lt; 0.001$) but did not improve on the linear fit ($r^2 = 0.41$, $p &lt; 0.001$) for the DCD group ($r^2 = 0.21$). Movement duration for real movements was correlated with the movement duration for imagined movements in the control group ($r = 0.94$, $p &lt; 0.001$) but not in the DCD group ($r = 0.51$, $p = 0.19$).</td>
<td>Correlation between real and imagined movements: TD $r = 0.94$, DCD $r = 0.51$</td>
<td>90.91</td>
<td>DCD showed deficits in MI and did not conform to speed accuracy trade-off for imagined movements; imagined movements not constrained by the same physiological and environmental factors that govern executed movements in DCD</td>
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<tr>
<td>14.1</td>
<td>Noten et al., 2014</td>
<td>Hand Laterality task (WI): accuracy, response time</td>
<td>Back view (4 DCD and 12 TD excluded): no significant differences between control and DCD groups; significant interaction between orientation, hand laterality and group ($p = 0.034$). Significant effect of orientation ($p &lt; 0.001$) for TD, while only a trend of orientation ($p = 0.086$) for DCD. Palm view (4 DCD and 6 TD excluded): Main effect of group ($p = 0.002$) laterality x orientation x group yielded significant effect of group ($p = 0.005$); DCD slower response times</td>
<td>N/A (RT and SD for each angle presented on graph)</td>
<td>68.18</td>
<td>Both groups conformed to biomechanical constraints. Effect of orientation was stronger in control group suggesting greater engagement in MI strategy. Slower response times for palm view in DCD, suggesting more compromised as task complexity increases. No correlation between MI and action planning in either group</td>
<td>Mean RT calculated with correct responses only</td>
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<tr>
<td>6.1</td>
<td>Sinani et al., 2011</td>
<td>Praxis Imagery Questionnaire (kinaesthetic, spatial position, action and object subscales); accuracy/correct responses</td>
<td>Total score (max = 48): significant group differences $p &lt; 0.01$. Age matched TD ($x = 39.9, SD = 3.7$) more accurate than sDCD ($x = 37.0, SD = 4.0$) and cDCD ($x = 35.8, SD = 5.3$), $p &lt; 0.01$. sDCD more accurate than 5–6 years ($x = 33.9, SD = 3.5$), $p &lt; 0.01$. Kinaesthetic subscale (max = 12): no group differences ($p = 0.032$). Position subscale (max = 12): significant group differences ($p &lt; 0.001$). Age matched TD ($x = 11.0, SD = 1.3$) more accurate than cDCD ($x = 9.7, SD = 1.5$), $p &lt; 0.01$. sDCD ($x = 10.0, SD = 1.8$) more accurate than 5–6 years ($x = 9.5, SD = 1.5$), $p &lt; 0.01$. Action subscale (max = 12): significant group differences ($p &lt; 0.001$). TD age matched ($x = 10.3, SD = 1.4$) more accurate than cDCD ($x = 9.0, SD = 1.4$), $p &lt; 0.01$. sDCD ($x = 9.3, SD = 1.7$) more accurate than 5–6 years ($x = 8.0, SD = 1.3$), $p &lt; 0.01$. Object subscale (max = 12): no group differences ($p = 0.123$).</td>
<td>Total PIQ: TD/dsDCD: $d = 0.753$, TD/cDCD: $d = 0.897$, TD/sDCD: $d = 0.929$</td>
<td>90.91</td>
<td>Children with DCD had difficulty answering praxis imagery questions that involved complex motor acts (e.g. using a pair of scissors, pencil, etc.) on the basis of internal representation.</td>
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<td>15.1</td>
<td>Williams et al., 2006</td>
<td>Hand Laterality task (NI and WI) and whole body rotation: accuracy, response time</td>
<td>Hand Laterality task: Accuracy: NI: no significant difference between groups or angle × group interaction ($p = 0.75$). WI: DCD significantly less accurate ($p = 0.034$, $r^2 = 0.134$), no angle × group interaction ($p = 0.30$). Response time: NI/WI: no differences between groups. No angle × group interaction for NI ($p = 0.40$), or WI ($p = 0.32$). Slope (Response time $ms$): NI: no significant multivariate effect for group ($p = 0.33$), no significant univariate effects for slope ($p = 0.076$), intercept ($p = 0.23$) or $r^2$ ($p = 0.44$). Whole body: Accuracy: DCD significantly less accurate than TD ($p = 0.004$, $r^2 = 0.218$). No angle × group interaction ($p = 0.05$). Response time: effect for group approached significance ($p = 0.068$, $r^2 = 0.095$). DCD faster. No angle × group interaction ($p = 0.34$). No significant multivariate effect for group for regression estimates ($p = 0.20$). Significant difference between groups for intercept ($p = 0.037$, $r^2 = 0.122$). TD: $x$ (SD) = 3008.04 (722.75) slower than DCD: $x$ (SD) = 2188.5 (1225.37). TD/DCD: $d = 0.218$ (NI: $d = 0.218$, WI: $d = 0.218$)</td>
<td>Hand Laterality: Accuracy: NI $r^2 = 0.134$, Whole Body: Accuracy: $r^2 = 0.218$</td>
<td>81.81</td>
<td>Partial support for atypical hand laterality performance pattern by DCD. No significant group differences for response time or accuracy without MI instructions; children with DCD were unable to benefit from explicit MI instructions (TD significantly more accurate than DCD following MI instructions). DCD less accurate and barely above chance for whole-body task.</td>
<td>Differences once imagery instructions introduced; alphanumeric rotation to control for visual imagery. Mean RT calculated with correct and incorrect responses.</td>
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<tr>
<td>16.1</td>
<td>Williams et al., 2008</td>
<td><strong>Hand Laterality task (NI and WI) and whole-body rotation task: accuracy, response time</strong></td>
<td><strong>Hand Laterality:</strong> Accuracy: NI (± SD): DCD-S: 80.45% (19.51%), DCD-M: 87.39 (11.01); TD: 91.60 (13.55); effect for group-approached significance (p = 0.062, ( \eta^2 = 0.089 )) with trend towards DCD-S less accurate than TD (p = 0.051). No group × angle interaction (p = 0.39).</td>
<td>NI: accuracy (trend towards significance, ( \eta^2 = 0.330 ))</td>
<td>77.27</td>
<td>Hand laterality: DCD-S generalised MI deficits (less accurate than TD and DCD-M). DCD-M capable of performing simpler transformations, but less successful at task difficulties increased. DCD-S showed little benefit from MI instructions, DCD-M increased minimal accuracy, controls benefited. Whole body: Accuracy decreased in both DCD groups. DCD-S more accurate than TD at all angles other than 180° (0°, p = 0.0002, 45°, p &lt; 0.001, 90°, p &lt; 0.001, 135°, p = 0.0026) and slower than DCD-M at 135° (p = 0.041). DCD-M group significantly slower to respond than TD at all angles other than 180° (0°, p = 0.002, 45°, p &lt; 0.001, 90°, p &lt; 0.001). Response Time: NI significantly slower to respond than TD at all angles other than 180° (0°, p = 0.0002, 45°, p &lt; 0.001, 90°, p &lt; 0.001, 135°, p = 0.0026) and slower than DCD-M at 135° (p = 0.041). DCD-M group significantly slower to respond than TD at 45°, p = 0.033 and 90°, p = 0.011.</td>
<td>Same data as 16.2, Williams et al., 2011 for DCD-S group Mean RT calculated with correct and incorrect responses.</td>
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<tr>
<td>16.2</td>
<td>Williams et al., 2011</td>
<td>Hand Laterality task and whole body rotation task: accuracy, response time</td>
<td>Hand Laterality: Accuracy: DCD ( \bar{x} = 81.0% ) TD ( \bar{x} = 95.7% ), Significant group effect (( p = 0.004, n^2 = 0.17 )): DCD significantly less accurate than TD (( p = 0.015 ))&lt;br&gt;Response time: After partialling out the variance associated with age, no significant interaction between group and angle (( p &gt; 0.05 ))&lt;br&gt;Whole Body Task: Accuracy: DCD ( \bar{x} = 85.0% ) TD ( \bar{x} = 49.0% ), Significant effect for group (( p &lt; 0.001, n^2 = 0.32 )): DCD significantly less accurate than TD (( p &lt; 0.001 ))&lt;br&gt;Response time: Effect for angle significant for DCD (( p = 0.050, n^2 = 0.159 )) but not TD (( p = 0.89 ))</td>
<td>Hand Laterality Accuracy: ( n^2 = 0.17 )&lt;br&gt;Whole Body Accuracy: ( n^2 = 0.32 )</td>
<td>95.45</td>
<td>MI deficits exist in children with DCD.&lt;br&gt;Accuracy in both tasks reduced for DCD group, and response time was atypical for the whole-body task, suggesting DCD group attempted to rotate to upright rather than perform an egocentric transformation&lt;br&gt;Same data as 16.1 Williams et al., 2008: the DCD-S group&lt;br&gt;Mean RT calculated with correct and incorrect responses</td>
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<tr>
<td>17.1</td>
<td>Williams et al., 2013</td>
<td>VCPT: movement duration time for real and imagined movements&lt;br&gt;Hand Laterality task: accuracy, response time</td>
<td>VCPT: Real movements: relationship between real movement duration and target width was described well by logarithmic function for control (( r^2 = 0.97, p = 0.002 )) and DCD (( r^2 = 0.97, p = 0.002 )) groups&lt;br&gt;Imagined movements: Logarithmic function provided good fit and target width for DCD group (( r^2 = 0.91, p = 0.0011 )). Logarithmic function did not provide good fit for relationship between imagined movement duration and angle in both DCD groups (( r^2 = 0.55, p = 0.151 )).&lt;br&gt;Correlation between real and imagined movements: TD: ( k (SD) = 0.88, r^2 = 0.57 ), DCD: ( k (SD) = 0.47(1.00), r^2 = 0.36 )&lt;br&gt;Hand Laterality: Accuracy (all angles): TD (SD): DCD: ( 0.68 (0.10), TD: 0.96 (0.15) ). Significant effect for group (( p &lt; 0.001, n^2 = 0.37 )): TD &gt; DCD (( p = 0.007 ))&lt;br&gt;Response time: No group differences (( p &gt; 0.75 )), no group * angle interaction (( p = 0.46 )). DCD group only group to not respond faster to medially compared to laterally rotated hands</td>
<td>Correlation between real and imagined movements: TD: ( r^2 = 0.57 )&lt;br&gt;DCD: ( r^2 = 0.36 )</td>
<td>90.91</td>
<td>DCD showed deficits in MI and did not conform to speed accuracy trade-off for imagined movements&lt;br&gt;Reduced accuracy for DCD. DCD did not respond faster to medially compared to laterally rotated hands (biomechanical constraints). DCD may not have engaged in MI because of deficits (may have used visual imagery), or MI was not restricted by the biomechanical limitations&lt;br&gt;Mean RT calculated with correct and incorrect responses</td>
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<tr>
<td>18.1</td>
<td>Wilson et al., 2004</td>
<td>Hand Laterality task: accuracy, response time</td>
<td>Accuracy: responses followed a similar pattern in both groups: no significant effect for angle group or group * angle interaction (( p &gt; 0.10 ))&lt;br&gt;Response time: significant group * angle interaction (( p = 0.049 ))&lt;br&gt;Mean regression estimates for linear fit of participant mean response times as a function of angle of rotation: Greater trade off in time (for angle) for TD: Slope TD (slope ( k (SE) = 3.565 (0.48) )) = DCD (slope ( k (SE) = 0.902 (0.90) )) (( t = 2.61, p = 0.016 )). No significant difference for fit (( p = 0.096 )).&lt;br&gt;TD: ( r^2 (SE) = 0.605 (0.08) ), DCD: ( r^2 (SE) = 0.408 (0.09) )</td>
<td>N/A (mean RT and accuracy for each angle presented on graph; group mean regression estimates for linear fit of RT by angle)</td>
<td>81.81</td>
<td>Significant difference in the response pattern between control children and children with DCD; Unlike TD, DCD responses did not conform to physical and biomechanical constraints; Children with DCD used an alternate strategy to TD controls&lt;br&gt;Could see hands (not covered). Children have a visual comparison during task&lt;br&gt;Mean RT calculated with correct and incorrect responses</td>
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<tr>
<td>Report Id</td>
<td>Reference</td>
<td>Tasks and outcome measures</td>
<td>Key results</td>
<td>Effect sizes</td>
<td>Kmet score (%)</td>
<td>Key findings</td>
<td>Comments</td>
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<td>19.1</td>
<td>Wilson et al., 2001</td>
<td>VGPT: movement duration time for real and imagined movements</td>
<td>Praxis Imagery Questionnaire (kinaesthetic, spatial position, action and object subscales): accuracy/correct responses</td>
<td>VGPT: For the control group, the logarithmic regression gave the best fit for the data for both real (no load: $R^2 = 0.939, p &lt; 0.001$) and imagined conditions (no load: $R^2 = 0.797, p &lt; 0.001$, load: $R^2 = 0.735, p &lt; 0.001$). For the DCD group the logarithmic regression gave best fit for real movements (load: $R^2 = 0.887, p &lt; 0.001$, no load: $R^2 = 0.773, p &lt; 0.001$), however neither the linear (no load: $R^2 = 0.099$, load: $R^2 = 0.058$) nor logarithmic (no load: $R^2 = 0.277$, load: $R^2 = 0.190$) regressions were significant for the imagined conditions. Duration of movement (real and imagined): slower in the DCD than controls ($p = 0.003$). Movement durations generally slower under load compared with no-load condition ($p &lt; 0.001$). Significant group × condition × load interaction ($p &lt; 0.001$). High correlation between real and imagined movement duration in TD under load ($r = 0.89, p &lt; 0.01$) and no-load ($r = 0.88, p &lt; 0.01$) condition, not significant in DCD for either load ($r = 0.47, p = 0.172$) or no-load ($r = 0.63, p = 0.051$). Correlation between real and imagined movements: Control: Load: $r = 0.89$, $p &lt; 0.01$; No-load: $r = 0.88$, $p &lt; 0.01$. DCD: Load: $r = 0.47$, $p = 0.172$; No-load: $r = 0.63$, $p = 0.051$.</td>
<td>72.73</td>
<td>DCD impaired ability to generate internal representations of volitional movements and simple gestures. Both real and imagined movements of controls obeyed Fitts law, whereas only real movements of DCD did. Addition of a weight slowed movements in TD, but not DCD. Although weight slowed overall duration of imagined movement it did not affect relative timing, suggesting that force and timing of imagined movements, like real movements, are programmed independently. The effect of external load on TD mirrored that observed in normal adults.</td>
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</table>
strategy (Noten et al., 2014), whilst others suggest the use of a motor imagery strategy albeit less effective (Deconinck et al., 2009; Williams et al., 2006, 2008) or even slightly yet not significantly different response patterns (Lust et al., 2006). Williams et al. (2006, 2008) report differences in response patterns emerging following the presentation of overt motor imagery instructions. Both studies using whole body rotation assessments (Williams et al., 2006, 2008) report deficits in performing this task. Effect sizes were not calculated for these tasks due to the complexity of the data analysis for this task across multiple variables.

The relationship between motor imagery proficiency and severity of movement difficulties in children with DCD was examined by Williams and colleagues (2008), who found motor imagery impairments to be greater for individuals who displayed a greater level of motor impairment. Lastly, two studies by Williams et al. (2006, 2008) examined changes in response patterns following the provision of motor imagery instructions. Children with DCD, particularly those with greater movement difficulties, had a reduced level of benefit from imagery instructions.

The relationship between age and motor imagery proficiency was not examined or discussed directly. Age was included as a covariate (ANCOVA) in two studies (Deconinck et al., 2009; Williams et al., 2011) to partial out the variance attributable to age. No direct gender comparisons were made in the motor imagery literature.

3.5. Neuroimaging

Nine neuroimaging articles based on eight studies were included in the review (Tables 5 and 6). Of these, one used EEG (Lust et al., 2006), six used fMRI (Debrabant et al., 2013; Kashiwagi et al., 2009; Licari et al., 2015; Querne et al., 2008; Zwicker et al., 2010, 2011), one used rsfMRI (McLeod et al., 2014), and one measured cortical thickness (Langevin et al., 2015). The EEG paper explored parietal activation and rotation-related negativity (electrodes placed over the parietal lobe) during a mental rotation motor imagery task. None of the fMRI studies specifically explore MNS function, however they report activation differences between children with and without DCD in MNS regions. Despite not specifically examining MNS function, a number of tasks used in the fMRI paradigms involved observing, following and responding to visual cues on screen, which may have involved activation of the MNS. Two reports by Zwicker et al. (2010, 2011) examined changes in neurological activity following training of a joystick tracing task.

3.6. Risk of bias in individual studies, risk of bias across studies, and assessment of methodological quality

The methodological risk of bias and quality in selected studies ranged from adequate to strong (54.54–100%) (see Tables 2, 4, and 6). Exact agreement between the two raters for the Kmet scale was 81.90%. Discrepancies were resolved through discussion, following which the agreement rate between the two raters was 100%.

No conflicts of interest were reported in any of the studies. The majority of the studies adequately reported objectives and participant characteristics and had appropriate sample sizes, determined by achieving significant results. A methodological issue surrounding a number of papers (both motor behaviour and neuroimaging) is group selection procedures. Some studies excluded children with comorbidities, some included comorbid groups (DCD + ADHD), and others do not report comorbidity status. Comorbidities, including Autism Spectrum Disorders, have the potential to confound results, given imitation deficits have been observed in this population (Vivanti & Hamilton, 2014; Vivanti, Trembath, & Dissnayake, 2014; Williams, Whitten, & Singh, 2004). A small number of studies omit movement testing for the control group (Dewey, 1991, 1993; Dewey & Kaplan, 1992). Given prevalence estimates of DCD in the general population of around 6%, a randomly selected control sample will likely include a small number of individuals with DCD. This point is evident in the study by Goyen et al. (2011) where four children (8% of control group) were within the DCD range on the Movement Assessment Battery for Children (Henderson & Sugden, 1992). Studies which performed no movement proficiency testing for either clinical or control groups were excluded.

It was also considered important that studies attempt to control for the confounding variables of age and gender. These variables were considered important as evidence suggests that both imitation (Zoa et al., 2002) and motor imagery (Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009) improves with age, and that there are differences in imitation performance between genders (Chipman & Hampson, 2006, 2007). Age was reported to be matched in four studies (Dewey, 1991, 1993; Dewey et al., 2007; Goyen et al., 2011) and was incorporated as a covariate in a selection of studies (Dewey, 1991, 1993; Dewey et al., 2007). The recruitment ratio of males females was rarely standardised within groups, with females with DCD frequently recruited in a very small number. This likely reflects the higher prevalence of males in DCD clinical populations, however does prohibit gender analyses being undertaken. Only seven studies matched participants for gender (Caçola et al., 2014; Debrabant et al., 2013; Deconinck et al., 2009; Dewey, 1991; Lewis et al., 2008; Williams et al., 2011, 2006). The often greater number of females in the control compared to DCD group is a limitation of a number of studies. Not matching participants for gender has the potential to confound the results given the literature suggesting gender differences in imitation proficiency, with females performing better than males, and displaying stronger imitative responses in a number of studies (Chipman & Hampson, 2006, 2007; Dinberg & Lundquist, 1990; Nagy, Kompagne, Orvos, & Pal, 2007). Due to the subjective nature of imitation and motor imagery measures (both standardised and non-standardised), it was considered important that these measures be scored by examiners who were blinded to participant’s diagnostic status. Only one study reported blind authors (Sinani et al., 2011), and two additional reported that the assessors were blinded to the purpose of the study (Hill et al., 1998; Zoa et al., 2002).
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<tr>
<th>Report Id</th>
<th>Reference</th>
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<tr>
<td>20.1</td>
<td>Debrabant et al., 2013</td>
<td>Belgium</td>
<td>To explore the neural correlates of predictive motor timing in children with and without DCD</td>
<td>Cross sectional</td>
<td>34 children (28 males, 6 females), 7–10 years; DCD: 17 children (14 males, 3 females), 7–10 years; ( \bar{x} ) (SD) = 9.4 (0.6) years; TD Controls: 17 children (14 males, 3 females), 7–10 years; ( \bar{x} ) (SD) = 9.2 (0.9) years.</td>
<td>fMRI</td>
<td>Block design reaction time task</td>
<td>Behavioural: Response time performance (ms), Percentage anticipatory responses; Neuroimaging: BOLD response</td>
</tr>
<tr>
<td>21.1</td>
<td>Kashiwagi et al., 2009</td>
<td>Japan</td>
<td>To use a visuomotor task during fMRI to detect the mechanisms underlying clumsiness in children with developmental coordination disorder (DCD)</td>
<td>Cross sectional</td>
<td>24 children (24 males), 9–12 years; DCD: 12 children (12 males), 9–12 years; ( \bar{x} ) (SD) = 129.4 (11.6) months; TD Controls: 12 children (12 males), 9–12 years; ( \bar{x} ) (SD) = 125.3 (11.9) months</td>
<td>fMRI</td>
<td>Visually guided tracking task: tracked a horizontally moving target by manipulating a joystick</td>
<td>Behavioural: distance between the target and cursor, change in velocity of cursor; Neuroimaging: BOLD response activation–MR signal changes</td>
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<tr>
<td>22.1</td>
<td>Langevin et al. (2015)</td>
<td>Canada</td>
<td>To investigate the effect of comorbid motor and attention problems on cortical thickness patterns. To identify whether cortical thickness alteration patterns for comorbid disorders are distinct from those of single disorders</td>
<td>Cross sectional</td>
<td>48 children (27 males), 8–17 years; DCD: 14 children (5 males, 9 females), ( \bar{x} ) (SD) = 9.75 (1.58) years; ADHD: 10 children (8 males, 2 females), ( \bar{x} ) (SD) = 9.7 (2.25) years; DCD + ADHD: 10 children (6 males, 4 females), ( \bar{x} ) (SD) = 9.75 (1.25) years; DCD, DCD + ADHD: ADHD: 34 children (19 males, 15 females), 8–17 years, ( \bar{x} ) = 9.75 years; Comparison: 14 children (8 males, 6 females), 8–17 years, ( \bar{x} ) (SD) = 11.75 (3.00) years</td>
<td>MRI</td>
<td>Two T1 weighted structural MRI scan</td>
<td>Cortical thickness index values</td>
</tr>
<tr>
<td>23.1</td>
<td>Licari et al., 2015</td>
<td>Australia</td>
<td>To investigate cortical activation patterns contributing to increased motor overflow in children with DCD; To reveal cortical areas that may contribute to poor movement execution and abundant motor overflow</td>
<td>Cross sectional</td>
<td>26 children (26 males), 9–12 years; DCD: 13 children (13 males), 9–12 years; ( \bar{x} ) (SD) = 9.6 (0.8) years; TD controls: 13 children (13 males), 9–12 years; ( \bar{x} ) (SD) = 9.3 (0.6) years</td>
<td>MRI</td>
<td>Block design right-hand finger sequencing and hand-clenching tasks</td>
<td>Behavioural: contralateral motor overflow using motion sensor glove; Neuroimaging: BOLD response</td>
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<tr>
<td>Report Id</td>
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<td>24.1</td>
<td>Lust et al., 2006</td>
<td>The Netherlands</td>
<td>To explore the parietal involvement in DCD with EEG measures; to explore whether children with DCD are less sensitive to mental rotation compared to matched control children, at a behavioural level (RT and errors) and at a rotation related negativity level; to identify if there is evidence of parietal involvement</td>
<td>Cross sectional</td>
<td>31 participants: 17 children (14 males, 3 females), 8–12 years, 14 adults (7 males, 7 females), 19–26 years; DCD: 10 children (9 males, 1 female), 9–11 years, $\bar{x}$ = 10.4 years; TD controls: 7 children (5 males, 2 females), 8–12 years, $\bar{x}$ = 9.6 years; 14 adults (7 males, 7 females), 19–26 years, $\bar{x}$ = 22.4 years</td>
<td>EEG</td>
<td>Hand laterality paradigm</td>
<td>Behavioural: response time and errors; EEG: Mental rotation-related negativity in the EEG. (If children with DCD do not engage motor imagery, a shallower trade-off function is expected between rotation angle and RRN above motor regions (P3 and P4). This is because when children with DCD perform the hand rotation task from a third-person view, they will not specifically activate motor areas of the cortex.)</td>
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<tr>
<td>25.1</td>
<td>McLeod et al., 2014</td>
<td>Canada</td>
<td>To investigate the functional connections of the motor network in children with DCD and/or ADHD compared to typically developing controls, with the aim of identifying common neurophysiological substrates</td>
<td>Cross sectional</td>
<td>69 children (50 males, 19 females), 8–17 years; DCD: 7 children (5 males, 2 females), $\bar{x}$ (SD) = 13.0 (2.5) years; DCD + ADHD: 18 children (14 males, 4 females), $\bar{x}$ (SD) = 11.5 (3.0) years; TD Controls: 23 children (11 males, 12 females), $\bar{x}$ (SD) = 11.3 (2.8) years; ADHD: 21 children (20 males, 1 female), $\bar{x}$ (SD) = 12.5 (2.9) years</td>
<td>rsfMRI</td>
<td>Resting state sequence (staring at a cross on screen)</td>
<td>BOLD response (functional connectivity with M1)</td>
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<tr>
<td>26.1</td>
<td>Querne et al., 2008</td>
<td>France</td>
<td>To assess the impact of DCD on effective connectivity applied to a putative model of inhibition using fMRI; to test the hypothesis that the functional coupling between fronto-striatal and parietal components of the attentional and executive network might be altered in children with DCD</td>
<td>Cross sectional</td>
<td>19 children (14 males, 5 females), 8.0–12.9 years; DCD: 9 children (7 males, 2 females), 8.0–12.9 years, $\bar{x}$ (SD) = 9.9 (1.8) years; TD controls: 10 children (7 males, 3 females), 8.2–11.6 years, $\bar{x}$ (SD) = 10.0 (1.1) years</td>
<td>fMRI</td>
<td>Go-NoGo Task</td>
<td>Behavioural: Response times; Neuroimaging: BOLD response</td>
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<td>27.1</td>
<td>Zwicker et al., 2010</td>
<td>Canada</td>
<td>To determine whether patterns of brain activity differ between children with and without DCD while performing a motor task</td>
<td>Cross sectional (pretest data)</td>
<td>14 children (10 males, 5 females), 8.6–12.6 years; DCD: 7 children (6 males, 1 female), 8.6–12.3 years; ( \bar{x} ) (SD) = 10.8 (1.5) years; TD controls: 7 children (4 males, 3 females), 8.6–12.6 years; ( \bar{x} ) (SD) = 10.9 (1.5) years</td>
<td>fMRI</td>
<td>Joystick trail tracing task: A fine-motor task adapted from the original MABC, the flower-shaped trail tracing task using a joystick</td>
<td>Behavioural: average time per trace, tracking error (number of times out of trace area); Neuroimaging: BOLD response</td>
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<td>27.2</td>
<td>Zwicker et al., 2011</td>
<td>Canada</td>
<td>To investigate whether children with DCD were able to demonstrate changes in skilled motor performance as evidenced by increased accuracy on a trail-tracing task and/or shifts in patterns of brain activation following task specific practice</td>
<td>Post-intervention (pre-post-intervention design)</td>
<td>14 children (10 males, 5 females), 8.6–12.6 years; DCD: 7 children (6 males, 1 female), 8.6–12.3 years; ( \bar{x} ) (SD) = 10.8 (1.5) years; TD controls: 7 children (4 males, 3 females), 8.6–12.6 years; ( \bar{x} ) (SD) = 10.9 (1.5) years</td>
<td>fMRI</td>
<td>Task: A fine-motor task adapted from the original MABC, the flower-shaped trail tracing task using a joystick early practice and retention test following three days of training outside of the scanner Protocol: Early task practice (Day 1) and retention test (Day 5) inside a 3-T Philips MRI scanner. Three days (Days 2–4) of tracing practice outside scanner between two scanning sessions (scheduled within two weeks of one another). During practice, children completed the same amount of tracing-task as on fMRI days (four, 2-min blocks per day)</td>
<td>Behavioural: average time per trace, tracking error (number of times out of trace area); Neuroimaging: BOLD response</td>
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Abbreviations: ADHD, attention deficit hyperactivity disorder; BOLD, blood-oxygen-level dependent; DCD, developmental coordination disorder; EEG, electroencephalography; fMRI, functional magnetic resonance imaging; M1, primary motor cortex; MR, magnetic resonance; RRN, rotation-related negativity; RT, response time; \( \bar{x} \), mean; SD, standard deviation; TD, typically developing.
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<tr>
<td>20.1</td>
<td>Debrabant et al., 2013</td>
<td>fMRI</td>
<td>Block design RT task: Neuroimaging: BOLD response</td>
<td>TD: Neural effects of increased timing uncertainty were localised by contrasting unpredictive versus predictive visual pacing condition (unpredictive &gt; predictive) in right IFG (Region = IFG, side = R, BA = 10/11, x = 24, y = 42, z = 6, t = 4.71, voxels = 140). Region = IFG, side = R, BA = 47, x = 32, y = 27, z = 12, t = 4.52, voxels = 40). DCD: No RT benefit from predictive visual pacing (reaction times did not differ between conditions). No significant activations yielded from 'predictive &gt; unpredictive' and 'unpredictive &gt; predictive' contrasts. No significant DCD &gt; TD activation. Unpredictive &gt; predictive contrast: TD higher activation than DCD in right TPJ (IPL and caudal STS) (Region = TPJ, side = R, BA = 40, x = 59, y = 50, z = 30, t = 4.40, voxels = 25).</td>
<td>100.00</td>
<td>Activation contrast unpredictive &gt; predictive: TD &gt; DCD in: right DLPFC, the left posterior cerebellum (crus I), and right tempo-parietal junction (TPJ) (BA40–48).</td>
<td>Differences are in a small number of voxels (small area)</td>
</tr>
<tr>
<td>21.1</td>
<td>Kashiwagi et al., 2009</td>
<td>fMRI</td>
<td>Visually guided tracking task (tracked horizontally moving target with joystick): Neuroimaging: BOLD response, activation (MR signal changes)</td>
<td>Tracking versus watching contrast: 'control greater than DCD' showed differences in left hemisphere activation (voxel level: p &lt; 0.001, cluster level with correction for multiple comparisons: p &lt; 0.05): SPL and IPL in left PPC and left PoCGy. Left IPL (BA 40), z value = 3.83, x = −36, y = −52, z = 50. No significant 'DCD greater than control activation MR signal changes in left IPL negatively correlated with task performance (smaller distances were closer to the target) (r = −0.413, p &lt; 0.05). DCD had poor performance and less activation than TD in left PPC and PoCGy during visuomotor task. Brain dysfunction in these areas may result in motor difficulty in DCD.</td>
<td>75.00</td>
<td>DCD had poor performance and less activation than TD in left PPC and PoCGy during visuomotor task. Brain dysfunction in these areas may result in motor difficulty in DCD.</td>
<td>DCD: 3 had ADHD; 3 had dyslexia; 2 had ADHD and dyslexia</td>
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<td>22.1</td>
<td>Langoven et al., 2015</td>
<td>T1 weighted structural MRI</td>
<td>Comparison &gt; DCD: no significant differences in MNS regions (only right temporal pole). Comparison &gt; DCD + ADHD: right caudal middle frontal, x = 2.80, y = 2.59, p = 0.05; right pars opercularis, x = 2.88, y = 2.77, p = 0.03, right pars triangularis, x = 2.91, y = 2.71, p = 0.003, right precentral, x = 2.64, y = 2.48, p = 0.03, right rostral middle frontal, x = 2.78, y = 2.61, p = 0.03. DCD &gt; DCD + ADHD: right precentral, x = 2.67, y = 2.48, p = 0.01, right pars opercularis, x = 2.94, y = 2.77, p = 0.022, right pars triangularis, x = 2.95, y = 2.71, p = 0.003. ADHD &gt; DCD + ADHD: right pars triangularis, x = 2.92, y = 2.71, p = 0.013, right rostral middle frontal, x = 2.80, y = 2.61, p = 0.022, right precentral, x = 2.65, y = 2.48, p = 0.033. More widespread differences in frontal, parietal, and temporal lobe cortical thickness were identified in children with comorbid DCD + ADHD relative to children with either disorder alone. Children with DCD alone demonstrated reduced cortical thickness relative to the comparison group only in the right temporal pole.</td>
<td>77.27</td>
<td>More widespread differences in frontal, parietal, and temporal lobe cortical thickness were identified in children with comorbid DCD + ADHD relative to children with either disorder alone. Children with DCD alone demonstrated reduced cortical thickness relative to the comparison group only in the right temporal pole.</td>
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Table 6 (Continued)

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<tr>
<td>23.1</td>
<td>Icati et al., 2015</td>
<td>MRI</td>
<td>Block design finger sequencing and hand clenching task: Neuroimaging BOLD response</td>
<td>Sequencing &gt; Clenching (minimal overflow observed during clenching contrast task): extensive activation in left frontal lobe BA 6, and left parietal lobe BA 40 during both tasks. Significantly greater activation of right PCCy (BA 6) during finger sequencing task. Group &lt; condition contrasts: Finger sequencing task: Control &gt; DCD: left superior frontal gyrus (BA 9), k = 157, x = -7, y = 53, z = 23 and left IFG (BA 44), k = 113, x = -50, y = 7, z = 6. DCD &gt; Control: right PCCy (BA 3), k = 59, x = 20, y = -35, z = 58. Hand clenching task: no significant group activation differences</td>
<td>9500 DCD displayed greater levels of motor overflow than TD controls on both functional tasks</td>
<td>DCD displayed decreased activation in the left IFG, an area playing a role in observation and imitation of hand movements</td>
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</table>

24.1 Lust et al., 2006 | EEG | Hand laterality task: Behavioral: accuracy, response time EEG: Mental rotation related negativity | Hand laterality task: Accuracy: TD = 94.5%, DCD = 91%. No significant group difference (p = 0.17) Response time: No group differences for median RTs per rotation angle (p = 0.64). TD averaged 65 ms faster than DCD (95% CI range: 227 to 357 ms). EEG: No main group effect (p = 0.27) for mean amplitude at parietal electrodes (P3, P4, and Pz). DCD amplitudes in RRN interval averaged 3 μV smaller than TD. No group difference (p = 0.71) for peak latency in RRN interval. Peak latency in DCD averaged 554 ms after stimulus presentation, compared with 565 ms in TD. If not engaging in motor imagery, expect shallower trade-off function between rotation angle and RRN above motor regions (P3 and P4), because performing hand rotation from third-person view will not specifically activate motor areas of the cortex | 54.54 No differences between DCD and TD in sensitivity to rotated stimuli. TD and DCD responded according to the physical and biomechanical task constraints. No significant difference in overall RT between the DCD children and their controls. No group effects for EEG measures at parietal electrodes. Children used a mix of motor and visual imagery | Given lack of differences in M1 observed, would not expect EEG differences in this sample |

25.1 McLeod et al., 2014 | rsfMRI | Resting state sequence (fixation cross): BOLD response (FC with M1) | Functional connectivity with M1: DCD < controls: Right IFG PCCy, Z score = 2.93, x = 54, y = 12, z = 2, BA = 44, 45; Left IFG PCCy, Z score = 2.76, x = -54, y = 10, z = 2, BA = 13, 44; DCD + ADHD < controls: Right motor cortex, Z score = 3.32, x = 62, y = 2, z = 26, BA = 6, ADHD < DCD: Right IFG, Z score = 2.79, x = 48, y = 20, z = 16, BA = 44, left IFG, Z score = 2.72, x = 56, y = 10, z = 2, BA = 44; DCD + ADHD > DCD: Left premotor cortex, Z score = 3.25, x = -26, y = -12, z = 70, BA = 6, Right IFG, Z score = 3.10, x = 52, y = 12, z = 4, BA = 44. DCD > Controls: none reported | 8000 DCD demonstrated decreased FC with M1 than TD in: bilateral IFG, right frontal operculum cortex, right supramarginal gyrus, bilateral insular cortices and superior temporal gyri. Subcortical structures exhibiting decreased FC include: bilateral caudate, right nucleus accumbens, pallidum and putamen. DCD did not exhibit increased FC with M1 in any region. TD had increased FC between M1 and bilateral motor and sensorimotor cortices as age increased; children with DCD and/or ADHD did not. Increasing FC with age between M1 and frontal and parietal regions involved in executive functions, memory and visuospatial imagery in children with DCD. DCD + ADHD group: absence of increased FC with age between M1 and any brain structures suggests brain development in children with co-occurring attention and motor disorders could be disrupted to a greater extent | >50% (n = 12) of control group female; only 7 females in clinical groups combined
<table>
<thead>
<tr>
<th>Report Id</th>
<th>Reference</th>
<th>Imaging technique</th>
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<tr>
<td>26.1</td>
<td>Querne et al., 2008</td>
<td>MRI</td>
<td>Go/NoGo Task: Neuroimaging; BOLD response</td>
<td>Similar cerebral regions activated in DCD and TD groups: ACC (BA 32, SMA (BA 6), OFC (BA 47), insula (BA 13), MFC (BA 46), IPC (BA 40) and striatum. Non-constrained model cannot be rejected, so model comparison between the control and DCD groups undertakes. Difference between $x^2$ of non-constrained model and $x^2$ of constrained model ($[x^2\text{diff}, = 20.05, p = 0.003]$) indicated a difference between control and DCD group models. Right hemisphere: anterior network connection between MFC and ACC significantly higher in TD than DCD. Top-down connection from MFC to IPC significant, in a positive direction in TD, and significant, in a negative direction in DCD. Posterior network connection between ACC and IPC in DCD was dramatically reinforced in children with DCD compared to TD, especially in the left hemispheric network. Positive path coefficient from IPC to MFC was higher in DCD than TD, whereas path coefficient from MFC to IPC was strongly negative in DCD. These modifications of the coupling between MFC and IPC observed in DCD seem to be more pronounced in the left than right hemispheric network.</td>
<td>55.00</td>
<td>FC between striatum and IPC very low in the right hemispheric network in DCD, when it was positive in TD. Influence exerted by ACC on IPC was dramatically reinforced in children with DCD compared to TD, especially in the left hemispheric network. Positive path coefficient from IPC to MFC was higher in DCD than TD, whereas path coefficient from MFC to IPC was strongly negative in DCD. These modifications of the coupling between MFC and IPC observed in DCD seem to be more pronounced in the left than right hemispheric network.</td>
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<tr>
<td>27.1</td>
<td>Zwicker et al., 2010</td>
<td>MRI</td>
<td>Joystick trail-tracing task: Neuroimaging; BOLD response</td>
<td>BOLD response: DCD &gt; TD, $p &lt; 0.01$: left IPL (BA 40, volume = 2719 $\mu$m, $x$ = 40, $y$ = 39, $z$ = 46), right PrCGy, right medial frontol gyrus (BA 6, volume = 473 $\mu$m, $x$ = 12, $y$ = 24, z = 68); TD &gt; DCD, $p &lt; 0.01$: left HG (BA 47, volume = 468 $\mu$m, $x$ = 38, $y$ = 22, z = 10)</td>
<td>75.00</td>
<td>DCD group used different network of brain regions compared to TD. DCD activated almost twice as many brain regions as those recruited by TD to accomplish task, suggesting DCD had to direct more effort to achieve motor performance similar to their peers.</td>
<td>Same data collection as 27.2: Data for Ax 1</td>
</tr>
<tr>
<td>27.2</td>
<td>Zwicker et al., 2011</td>
<td>MRI</td>
<td>Joystick trail-tracing task: (Early task practice (Day 1) and retention test (Day 5) inside 3-T Philips MRI scanner. Three days (Day 2–4) of skilled motor practice (tracing outside the scanner) between scans): Neuroimaging; BOLD response</td>
<td>Significant interaction in percent signal change between group and Time (early practice, retention test) ($p &lt; 0.005$, corrected). TD &gt; DCD, $p &lt; 0.005$: right IPL (BA 40, volume = 3761 $\mu$m, $x$ = 39, $y$ = 47, $z$ = 41), left IPL (BA 40, volume = 320 $\mu$m, $x$ = 27, $y$ = 41, $z$ = 55), left IPL (BA 40, volume = 306 $\mu$m, $x$ = 40, $y$ = 37, $z$ = 45); Compared to TD children, children with DCD showed lower percent signal change at both early practice and retention in all brain regions</td>
<td>75.00</td>
<td>DCD demonstrated different pattern of activation to TD in a number of brain regions: dorsolateral prefrontal cortex, inferior parietal lobule, and cerebellum. Reduced IPL activation in DCD (IPL role in processing sensory information and visual feedback; sensory feedback has been shown to play important role in learning new motor skills)</td>
<td>Same data collection as 27.1: Data for Ax 1 and Ax 5</td>
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**Abbreviations:** ACC, anterior cingulate cortex; ADHD, attention deficit hyperactivity disorder; BOLD, blood-oxygen-level dependent; DCD, developmental coordination disorder; EEG, electroencephalography; FC, functional connectivity; fMRI, functional magnetic resonance imaging; IFG, inferior frontal gyrus; IPC, inferior parietal cortex; IPL, inferior parietal lobule; M1, primary motor cortex; MFC, middle frontal cortex; MR, magnetic resonance; OFC, orbitofrontal cortex; PMv, adjacent ventral premotor cortex; PrCGy, postcentral gyrus; POGy, precentral gyrus; RDN, rotation-related negativity; RT, response time; ¯x, mean; SMA, supplementary motor area; SPL, superior parietal lobule; STS, superior temporal sulcus; TD, typically developing; TPJ, temporo-parietal junction.
3.7. Results of individual studies and synthesis of results

Results, statistical analyses reported on outcome measures, and calculated effect sizes are presented in 2, 4, and 6. Seven papers (five data sets) suggest representational gesture deficits with effect sizes ranging from $d = 0.12$–2.47. One report using a similar assessment in an older adolescent population ($8.6$–16.0 years, $M = 11.7$ years) suggests no representational gesture deficits (Dewey et al., 2007). Possibly more reflective of MNS deficits, two of three papers reporting on imitation of novel gestures support deficits in this area, with effect sizes ranging from $d = 0.34$–0.78 (Dewey & Kaplan, 1992; Goyen et al., 2011); a ceiling effect exists in the third (Hill, 1998). A greater level of variation of results exists within the implicit and explicit motor imagery literature. There is strong support for deficits in motor imagery from VGTs (Katschmarsky et al., 2001; Lewis et al., 2008; Maruff et al., 1999; Williams et al., 2013; Wilson et al., 2001), imagined reaching tasks (Cacola et al., 2014) and whole body rotation paradigms (Williams et al., 2006, 2008), and mild support from hand laterality (Deconinck et al., 2009; Lust et al., 2006; Noten et al., 2014; Williams et al., 2011, 2013, 2006, 2008; Wilson et al., 2004) and questionnaire assessments (Sinani et al., 2011; Wilson et al., 2001).

At a structural level, Langene et al. (2015) identified no differences in cortical thickness of MNS regions in children with DCD alone compared to controls (differences only in right temporal pole), but reduced cortical thickness in the right pars opercularis, pars triangularis, and middle frontal regions amongst numerous other regions, in children with comorbid DCD and ADHD. All fMRI studies report differences in activation patterns, in general, and differences in activation patterns in MNS regions (Debrabant et al., 2013; Kashigawa et al., 2009; Licari et al., 2015; Zwicker et al., 2010, 2011). These results are not entirely consistent across studies, with both decreased (Debrabant et al., 2013; Kashigawa et al., 2009; Licari et al., 2015) and increased (Zwicker et al., 2010) activation in MNS regions reported in children with DCD relative to controls. Both reduced (McLeod et al., 2014; Querne et al., 2008) and increased (Querne et al., 2008) connectivity with MNS regions has also been identified. Given that no fMRI or rsfMRI studies have specifically explored MNS function, these results need to be interpreted in this context with caution. No meta-analysis of results was performed.

4. Discussion

Support for an MNS deficit hypothesis in DCD can be drawn from literature at both motor behaviour and neurological levels. At a motor behaviour level, strong support exists for deficits in imitation of representational learned gestures, with preliminary evidence also suggesting children with DCD experience difficulties imitating non-representational, novel gestures. The level of deficit and response pattern differences presented within the motor imagery literature is slightly less consistent, however provides support for at least mild impairments in motor imagery for children and adults with DCD. Although not specifically exploring MNS function, neuroimaging evidence indicates differences in brain activation patterns at a motor behaviour level, strong support exists for deficits in imitation of representational learned gestures, with reduced (Zwicker et al., 2010, 2011) and mild support from hand laterality (Deconinck et al., 2009; Lust et al., 2006; Noten et al., 2014; Williams et al., 2011, 2013, 2006, 2008; Wilson et al., 2004) and questionnaire assessments (Sinani et al., 2011; Wilson et al., 2001).

At a structural level, Langevin et al. (2015) identified no differences in cortical thickness of MNS regions in children with DCD alone compared to controls (differences only in right temporal pole), but reduced cortical thickness in the right pars opercularis, pars triangularis, and middle frontal regions amongst numerous other regions, in children with comorbid DCD and ADHD. All fMRI studies report differences in activation patterns, in general, and differences in activation patterns in MNS regions (Debrabant et al., 2013; Kashigawa et al., 2009; Licari et al., 2015; Zwicker et al., 2010, 2011). These results are not entirely consistent across studies, with both decreased (Debrabant et al., 2013; Kashigawa et al., 2009; Licari et al., 2015) and increased (Zwicker et al., 2010) activation in MNS regions reported in children with DCD relative to controls. Both reduced (McLeod et al., 2014; Querne et al., 2008) and increased (Querne et al., 2008) connectivity with MNS regions has also been identified. Given that no fMRI or rsfMRI studies have specifically explored MNS function, these results need to be interpreted in this context with caution. No meta-analysis of results was performed.

4.1. Imitation

Imitation ability of children with DCD has typically been assessed in a praxis context which traditionally assesses learned or skilled transitive tool use actions and occasionally incorporates symbolic (meaningful) intransitive gestures (Steinman, Mostofsky, & Denckla, 2010). The majority of assessments of representational gestures indicate that children with DCD have poorer imitative gestural performance when compared to controls (Dewey, 1991, 1993; Dewey & Kaplan, 1992; Hill, 1998; Hill et al., 1998; Sinani et al., 2011; Zoia et al., 2002), with only one study finding no group differences (Dewey et al., 2007). While the use of small assessment batteries is characteristic of these studies in general, the assessment battery in the study by Dewey et al. (2007) included only six transitive (e.g. brush your teeth with a toothbrush, comb your hair with a comb) and six intransitive gestures (e.g. cross your fingers, wave goodbye) of a simple nature. It is likely that the very similar performance of the two groups represented a ceiling effect, based on the fact that these gestures are all well known and probably performed a lot in daily life. Furthermore, research on transitive (object/tool related) and intransitive (non-object related) representational gestures indicates that in addition to impaired performance for familiar representational gestures, children with DCD perform similarly to younger control groups (Hill et al., 1998; Sinani et al., 2011). While this research does suggest an imitation impairment, traditional apraxia models are likely not the best way to explore imitation performance in developmental disorders.

While the evidence for deficits in imitation of representational gestures in children with DCD is strong (Dewey, 1993; Dewey & Kaplan, 1992; Sinani et al., 2011), difficulties in the performance of learned skills and a delayed acquisition of motor skills are characteristics of DCD. Whilst these assessments are beneficial in the assessment of praxic ability, it is possible that these test batteries reflect the delayed skill acquisition characteristic of DCD rather than deficits in imitation as such. This should be taken into consideration when examining this literature with reference to MNS function.

Imitation of non-representational novel gestures and sequences are typically not included in assessments of praxic ability. Although imitation of novel actions is likely of greatest relevance with reference to the MNS, the majority of work has explored imitation of meaningful actions and learned skills. Despite this, the exploration of imitation in a praxis context precedes the current MNS literature (Steinman et al., 2010). More recent work has incorporated the use of
non-representational unlearned gestures (Goyen et al., 2011). These types of assessments which include both reliable standardised assessments and non-standardised test batteries, incorporate both single novel meaningless gestures (e.g. SIPT postural praxis (Ayres, 1989): full body postural gestures such as one hand on side of head, other hand on hip, head and trunk leaning, and non-standardised assessments: an open hand, a clenched fist with little finger extended), as well as sequences of novel movements (e.g. close fist, thump sideways on table, open hand, slap palm down on table, and combinations of intransitive limb gestures and orofacial gestures). Only three articles in this review incorporate such assessments (Dewey & Kaplan, 1992; Goyen et al., 2011; Hill, 1998), with only one of these using standardised assessment batteries (Goyen et al., 2011).

Based on their assessment of sensorimotor skills of extremely preterm or extremely low birth weight children with and without DCD, Goyen et al. (2011) undertook a comprehensive assessment of imitation proficiency and suggested that deficits in praxis contribute to the motor deficits associated with DCD. The group of preterm children with DCD scored significantly lower than age-matched controls on five of the six praxis subtests (excluding verbal command) of the standardised SIPT. Three of these subtests incorporate non-representational imitation: the postural praxis; oral praxis; and sequencing praxis. As the study was primarily exploring differences between extremely preterm/lower birth weight children and children born at full term with normal birth weight, a small number of children with probable DCD (4 children, 8%) were included in the control group. While this percentage is reflective of the prevalence of DCD in the general population, this may have led to an underestimation of differences. The results of this study indicate that the assessment of MNS function using outcome measures of novel non-meaningful gesture imitation appears a promising direction. These assessments may be more likely than representational gesture tasks to reflect MNS function, as they are an accurate reflection of imitation proficiency rather than a reflection of reporting non-difficulties (e.g. ‘all right’). Further support for the premise that children with DCD have some level of motor imagery deficits. Despite most literature recognising a generalised motor imagery deficit, not all individuals with DCD have been included in the results section of this review. Based on the limited studies examining novel single and sequence gestures, it is clear that further research utilising a larger number of complex and novel gestures is required to explore MNS function and imitation of non-representational gesture imitation and sequence imitation in children with DCD.

4.2. Motor imagery

Further support for an MNS deficit can be drawn from work demonstrating that both children with DCD and adults with probable DCD (pDCD) have motor imagery deficits. In a meta-analysis performed by Wilson et al. (2013), large weighted Cohen’s $d$ effect sizes were calculated for both explicit ($d_w = 2.43)$ and implicit ($d_w = 0.84$) motor imagery performance categories. It is thought that an internal representation strategy is both required and utilised to complete these explicit and implicit motor imagery tasks (Adams et al., 2014; Wilson et al., 2013). Motor imagery research in children and adults with DCD has focused on exploring the internal modelling deficit hypothesis (Adams et al., 2014; Wilson et al., 2013), which proposes motor deficits stem from an inability to utilise internal models to predict movement outcomes prior to the availability of sensorimotor feedback (Wolpert, 1997). The internal modelling deficit hypothesis and MNS hypothesis are not mutually exclusive hypotheses (Kilner, Friston, & Frith, 2007; Miall, 2003). Similar to the imitation literature, the majority of literature supports the premise that children and adults with DCD have some level of motor imagery deficits. Despite most literature recognising a generalised motor imagery deficit, not all individuals with DCD have been found to perform poorly on motor imagery tasks (Wilson et al., 2001, Wilson et al., 2013), with some studies reporting no difficulties in adopting a motor imagery strategy, albeit less efficient (Deconinck et al., 2009; Lust et al., 2006), or difficulties in only some individuals with DCD (Katschmarsky et al., 2001). The differences in results between studies have likely arisen as a result of the different assessments employed and their levels of complexity, differences in analysis techniques (e.g. for hand rotation analysing all or analysing only correct responses), and individual differences in severity of DCD and motor impairments.
One of the assessments used to examine motor imagery in the DCD is the Praxis Imagery Questionnaire, which requires participants to imagine the performance of object-related actions. The test comprises four subtests, each of which assess four varying components of the same internal representation (e.g. ‘using scissors to cut paper’): (i) kinaesthetic: body joint movements; (ii) position–position of body parts in space; (iii) action–body part movements; and (iv) object–physical appearance (size and shape) of objects (Wilson et al., 2001, p. 138). Wilson et al. (2001) created a child-modified version of the Florida Praxis Imagery Questionnaire (Ochipa et al., 1997), for use with Australian 7–10-year-olds, while Sinani et al. (2011) used a version based on both Florida Praxis Imagery Test (Ochipa et al., 1997), and Wilson and colleagues’ (2001) Praxis Imagery Questionnaire. The results across the two studies were not consistent, with Sinani et al. (2011) indicating an overall praxis imagery deficits in clinical and school-based DCD groups, as well as higher scores on the position and action subscales in the clinical DCD group. In contrast, Wilson et al. (2001) identified deficits, albeit slight, only in the kinaesthetic subscale. In both of these studies, the scores were high for both children with DCD and typically individuals, possibly indicating a ceiling effect.

The strongest evidence, and most consistent support for motor imagery deficits in the DCD population comes from VGPTs (Katschmarsky et al., 2001; Lewis et al., 2008; Maruff et al., 1999; Williams et al., 2013; Wilson et al., 2001). Visually guided pointing tasks assess motor imagery proficiency by exploring the relationship between the chronometry of real and imagined pointing movements to different sized targets, and whether these conform to speed accuracy trade-off (Fitts’ Law) physiological constraints. This explicit motor imagery task is based on observations that neural activation and biomechanical and physiological task constraints are similar during both mental rehearsal and actual execution of motor acts in neurotypical individuals (Jeannerod, 2001; Sirigu et al., 1996). A prominent aspect of response patterns on VGPTs suggests that children with DCD are unable to accurately internally visualise motor acts. The four studies that used linear and/or logarithmic regression to explore the relationship between real or imagined movement time and index of difficulty based on target size all indicate that the logarithmetic functions fit the movement time data for both real and imagined movements of typically developing children, indicating both real and imagined movements conform to physiological constraints (Lewis et al., 2008; Maruff et al., 1999; Williams et al., 2013; Wilson et al., 2001). In contrast, the linear and logarithmic curves only fit real movements of children with DCD (Lewis et al., 2008; Maruff et al., 1999; Williams et al., 2013; Wilson et al., 2001). The lack of fit for imagined movements in children with DCD suggests that in contrast to typically developing controls, the imagined movements of children with DCD do not conform to speed–accuracy constraints. The same response patterns emerge when exploring the addition of a weighted load condition (Wilson et al., 2001). Despite regression analyses providing strong support in explicit motor imagery tasks, it is possible that regression analysis of group means may mask individual differences in task performance.

The correlation between real and imagined movements has also been explored in two papers (Williams et al., 2013; Wilson et al., 2001) and used as a screening measure in a third (Katschmarsky et al., 2001), as described below. Whilst still in support of group differences, analysis of individual’s real/imagined movement time correlations (Katschmarsky et al., 2001; Williams et al., 2013; Wilson et al., 2001) demonstrates a higher degree of variation in the VGPT data than is evident from group regression analysis. In support of decreased correlation between real and imagined movements, Williams et al. (2013) also identified a much higher correlation between real and imagined movements for typically developing controls (r² = 0.57) than children with DCD (r² = 0.36). Together, these demonstrate differences in motor imagery, and a difficulty using a motor imagery strategy, which could in part provide an explanation for the movement deficits characteristic of DCD. A further avenue of support for motor imagery deficits comes from hand laterality (Deconinck et al., 2009; Hyde et al., 2014; Lust et al., 2006; Noten et al., 2014; Williams et al., 2011, 2006, 2008; Wilson et al., 2001) and whole body rotation tasks (Williams et al., 2011, 2006, 2008). These paradigms are common implicit assessments of motor imagery proficiency which lend partial support for motor imagery deficits, providing evidence for differences in the use of motor imagery strategies between children with and without DCD. Both behavioural and neuroimaging data suggest that hand rotation paradigms are valid for the assessment of motor imagery ability (Lust et al., 2006). Despite being accurately able to determine whether a motor imagery strategy is being used, hand rotation paradigms have resulted in less consistent response patterns than VGPTs (Williams et al., 2008). It is likely that these differences arise in part from the variations in the complexity of the hand laterality paradigms that have been used between studies.

Differences in hand laterality paradigms across studies exist at a number of levels. For example, the use of one (back view) or two (back and palm views) rotational axes, number of rotational steps, the use or omission of motor imagery instructions, and vision or occlusion of hands have the potential to have a large impact on the response patterns. Furthermore, while articles typically present results concerning group response time, accuracy and angle - response time interactions, there is no consistent method for the inclusion or exclusion of trials. Some studies include all responses when analysing response times, in comparison to others which use only correct responses. It is also likely that differences in findings are a result of the profiles of motor impairment of the individual children involved in the studies (Williams et al., 2008). Despite these methodological issues, the current body of hand laterality literature does suggest at least mild impairments in motor imagery for children with DCD.

It appears that differences in motor imagery proficiency become more apparent as the task complexity increases (Noten et al., 2014; Williams et al., 2008). Based on paradigm differences, some studies are more likely than others to identify differences in motor imagery. One would expect to observe greater differences in a paradigm incorporating back and palm view than one including only back view, as the greater number of rotational axes leads to an increased level of complexity (ter Horst, van Lier, & Steenbergen, 2010). Future work exploring motor imagery ability in children with DCD should
incorporate a high level of complexity, to ensure any existing deficits are identified and to minimise the potential for ceiling effects.

Hand and whole body rotation paradigms support different response patterns between children with and without DCD on implicit motor imagery tasks and lend some support for the engagement in different strategies. Because it is biomechanically more challenging to perform lateral (turning the hand outwards) compared to medial (inwards) rotations, if a motor imagery strategy is employed, lateral responses would be expected to be slower and/or less accurate. A small number of studies have found that hand rotation responses of children with DCD do not conform to physiological or biomechanical constraints (medial rotations faster than lateral rotations/smaller response time and angle trade off) (Williams et al., 2004), suggesting that children with DCD may employ alternate strategies to perform the rotation tasks. While Noten et al. (2014) found the responses of children with DCD to conform to these constraints, the effect of orientation was not as strong in the children with DCD compared to controls, suggesting a decreased engagement in a motor imagery strategy. Similarly, while adults with pDCD were found to engage in a motor imagery strategy, they were found to be less efficient at judging medial compared to lateral rotations, and palm compared to back orientations than controls (Hyde et al., 2014). Only six of nine hand laterality studies compare medial to lateral rotations (Deconinck et al., 2009; Hyde et al., 2014; Lust et al., 2006; Noten et al., 2014; Williams et al., 2011, 2013). Similarly, when the hands are facing down, it is biomechanically more challenging to respond to palm view, compared to back view orientations. Only two (Deconinck et al., 2009; Hyde et al., 2014) of four studies (Noten et al., 2014; Wilson et al., 2004) with back and palm view compare response times between orientations. Both of these studies found that responses were faster when hand position was congruent with the image displayed on screen, suggesting that responses of both groups conformed to biomechanical constraints (Deconinck et al., 2009; Hyde et al., 2014). It is important that analysis is undertaken to determine whether responses conform to biomechanical constraints, as other forms of imagery (e.g. visual imagery) cannot be ruled out when these types of comparisons are not made.

Wilson et al. (2004) suggest that hand rotation paradigm response patterns of children with DCD reflect both a motor imagery deficit and the use of an alternative object-based approach rather than an egocentric motor imagery strategy. The ability to perform egocentric transformations enables observers to imagine movements from both their own and other’s perspectives relative to the surrounding environment (Zacks, Mires, Tversky, & Hazeltine, 2002; Zacks, Gilliam, & Ojemann, 2003), which is important during the mental rehearsal of movements, imitation, and observational learning (Vogt, Taylor, & Hopkins, 2003 Williams et al., 2008). Response patterns for whole body rotation assessments of motor imagery ability also suggest that children with DCD may, at least partially, rotate the images rather than imagine themselves in the position of the image (Williams et al., 2006, 2008). It is important to note that the whole body rotation task is more complex than hand rotation tasks; control children also displayed low accuracy levels on this task (approximately 65% in one study; Williams et al., 2006) when compared to adults in previous research (97% accuracy; Zacks et al., 2002). The increased complexity of the whole body rotation suggests that the observed response patterns of children with DCD may be task-specific and difficult to compare directly to the outcome of studies using the hand rotation task. In contrast, other hand rotation studies have found that children with DCD perform differently from their peers, with a greater number of participants scoring below the 70th percentile compared to controls (Lust et al., 2006; Williams et al., 2006, 2008). Williams et al. (2006, 2008) found the responses of children with DCD to conform to these constraints, the effect of orientation was not as strong in the children with DCD compared to controls, suggesting a decreased engagement in a motor imagery strategy. Similarly, while adults with pDCD were found to engage in a motor imagery strategy, they were found to be less efficient at judging medial compared to lateral rotations, and palm compared to back orientations than controls (Hyde et al., 2014). Only six of nine hand laterality studies compare medial to lateral rotations (Deconinck et al., 2009; Hyde et al., 2014; Lust et al., 2006; Noten et al., 2014; Williams et al., 2011, 2013). Similarly, when the hands are facing down, it is biomechanically more challenging to respond to palm view, compared to back view orientations. Only two (Deconinck et al., 2009; Hyde et al., 2014) of four studies (Noten et al., 2014; Wilson et al., 2004) with back and palm view compare response times between orientations. Both of these studies found that responses were faster when hand position was congruent with the image displayed on screen, suggesting that responses of both groups conformed to biomechanical constraints (Deconinck et al., 2009; Hyde et al., 2014). It is important that analysis is undertaken to determine whether responses conform to biomechanical constraints, as other forms of imagery (e.g. visual imagery) cannot be ruled out when these types of comparisons are not made.

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While current evidence at a motor behaviour level certainly indicates some deficits in imitation and motor imagery, further research is required. Future research to explore imitation proficiency based on standardised complex novel gestures and sequences of gestures would build on previous research to provide a greater understanding of imitation and MNS function in children with DCD. Despite a strong body of research across a range of tasks providing support for deficits in motor imagery processes, the application of tasks with a higher level of complexity in a paediatric DCD sample would extend the literature to explore the extent of motor imagery and potential MNS dysfunction and enable comparisons of results with pDCD adult samples.
4.3. Neuroimaging evidence for MNS dysfunction

Whilst no published studies have been undertaken to examine MNS functioning in children with DCD utilising neuroimaging techniques, Werner et al. (2012) proposed deficits in the MNS on the basis of neuroimaging evidence implicating MNS areas. They suggest that differences in brain activation patterns during motor tasks in MNS areas between individuals with and without DCD provides encouraging support for an MNS dysfunction hypothesis of DCD (Werner et al., 2012).

Differential activation of frontal MNS regions in children with DCD, in particular, the IFG, has been demonstrated in a number of fMRI studies (Debrabant et al., 2013; Licari et al., 2015; Zwicker et al., 2010, 2011). The strongest support for MNS dysfunction comes from a recent study exploring cortical activation contributing to motor overflow (Licari et al., 2015). Because participants were required to imitate the observed finger sequencing actions during scanning, it is highly likely that the MNS was active to complete these functional tasks. Children with DCD displayed decreased activation in the left IFG, a region involved in the observation and imitation of hand movements (Buccino et al., 2001, 2004; Caspers et al., 2010; Hari et al., 1998; Heiser, Iacoboni, Maeda, Marcus, & Mazziotta, 2003; Iacoboni et al., 1999; Rizzolatti et al., 1996). Differences in activation patterns were not identified in other mirror regions in this study (Licari et al., 2015).

Further evidence for differential IFG activation is provided by Debrabant et al. (2013) who identified a small area of decreased activation in the right IFG of children with DCD compared to controls during an increased timing uncertainty condition on a reaction time task. As imitation performance is impaired when IFG activation is disrupted by rTMS (Heiser et al., 2003), a possible deficit in this essential component of the MNS circuitry has the potential to contribute to imitation difficulties in children with DCD.

The pars opercularis of the IFG is another MNS area in which differential activation between children with and without DCD has been identified. Zwicker et al. (2010) used fMRI to measure brain activation patterns of children with DCD and controls during a single session while using a joy stick to complete a trail-tracing task which was modified from the trail-tracing task from the Movement Assessment Battery for Children (Henderson and Sugden, 1992). Despite a similar level of task performance, children with DCD were observed to have significantly decreased activation in the left IFG and left precuneus compared to controls, both areas involved in the putative human MNS, suggesting children with DCD employed different neural strategies to perform the task. Furthermore, in this study, children with DCD were found to activate almost twice as many neural regions in comparison to the typically developing controls, suggesting an increased level of effort for similar levels of task performance.

A follow-up study to assess brain activation changes following three motor skill practice sessions of the same tracing task was undertaken using the same participants (Zwicker et al., 2011). In contrast to controls, children with DCD experienced no change in number of errors recorded and had decreased activation in bilateral IPLs and other areas. Because the tracing task used for these two studies was not chosen to activate and explore mirror neuron function, relating the differences in activation between children with and without DCD to MNS functioning should be interpreted with caution.

Differential activation between children with and without DCD within parietal and temporal MNS regions has also been identified in several fMRI studies (Debrabant et al., 2013; Kashiwagi et al., 2005; Querne et al., 2008; Zwicker et al., 2010, 2011). In a visually guided tracking task, children with DCD displayed decreased activation of the left posterior parietal cortex (SPL and IPL) and left postcentral gyrus compared to controls (Kashiwagi et al., 2009). In addition, signal change in the left IPL was negatively correlated with the behavioral task performance, suggesting a putative involvement of this MNS area in the underpinnings of DCD (Kashiwagi et al., 2009). Lower levels of activation in the right temporoparietal junction (IPL and caudal STS) in children with DCD during an unpredictable vs. predictive block design reaction time task provides further evidence for involvement of MNS regions (Debrabant et al., 2013). No DCD greater than control activation was observed in these studies (Debrabant et al., 2013; Kashiwagi et al., 2009). In contrast to these results, children with DCD had greater IPL activation than controls during an initial attempt at a trail-tracing task (Zwicker et al., 2010), yet a reduced percentage signal activation change compared to controls in the left IPL, and other non-MNS regions following task practice (Zwicker et al., 2011).

Altered patterns of effective connectivity in MNS parietal regions during a go–no go task have been suggested, with between-group differences in strength and directions of multiple connections identified, including a greater strength of anterior cingulate cortex to inferior parietal cortex posterior network in the DCD group relative to controls (Querne et al., 2008).

Evidence for MNS dysfunction from fMRI studies is not entirely consistent. Inconsistencies in parietal activation and connectivity patterns across studies could be the result of different parietal involvement in the specific tasks used (Zwicker et al., 2010). A greater understanding of the underlying neurology associated with DCD, which will be gained with further neuroimaging work, is likely to increase our understanding of these inconsistencies. For example, in some studies, there has been a global increase in activation of brain regions which has been interpreted as the need for increased effort and cognitive resources, and possible deficits (e.g. Zwicker et al., 2010), whereas others have interpreted reduced activation as reflecting deficits (e.g. Debrabant et al., 2013; Licari et al., 2015). While both interpretations are valid and match the results of the respective studies, these inconsistencies in activation patterns, and our limited understanding of neural activation patterns in DCD, in conjunction with the fact that these studies were not set up to explore MNS function, mean that it is difficult to interpret these inconsistencies in an MNS context beyond children with DCD displaying differential activation patterns in these regions.
While none of these studies specifically explore MNS activation, they do suggest some involvement of frontal, parietal, and temporal MNS regions. Differences in parietal lobe function have the potential to result in deficits in the internal representation of movements (Williams et al., 2006; Wilson et al., 2001, Wilson et al., 2004), as well as in kinaesthetic coding of actions, and general motor planning and motor learning. Furthermore, differential temporal lobe activation may have implications for the storage and retrieval of information required to program movements and make online comparisons during actions, as well as for learning of sequences of movements. Deficits in any one of these areas has the potential to contribute to the motor difficulties characteristic of DCD.

Only one neuroimaging has explored neural involvement during a motor imagery task. In their assessment of electrical activity over a number of areas of the parietal cortex, using EEG during a hand rotation task, Lust et al. (2006) identified no significant main group effect on the mean rotation-related negativity interval amplitude or peak latency at the parietal electrodes (P3, P4, and Pz). Although inconsistent with the majority of the fMRI research indicating decreased activation in parietal regions (Debrabant et al., 2013; Kashiwagi et al., 2009; Zwicker et al., 2011), this finding is not surprising given the lack of performance differences between the two groups on the motor imagery task, in which children with DCD were only slightly, yet not significantly less accurate and slower in their responses. The hand rotation task used displayed the back view of hands in 45° increments; it is possible that a more complex task, such as one also including palm view, may result in differences in response patterns between groups and accompanying neural activation differences. While EEG has a high temporal resolution, a limitation of the technique is the low spatial resolution; the use of EEG to explore MNS function (e.g. Virji-Babul et al., 2012) in children with DCD has the potential complement fMRI data.

Recent neuroimaging work has shifted from exploring isolated brain regions, towards exploring functional connectivity and interactions of neural areas (Rosazza and Minati, 2011). By exploring low-frequency (<0.1 Hz) fluctuations in BOLD signal which are correlated in time in the absence of a task, information about how anatomically distinct areas are functionally connected and influence one another can be gained (Rosazza and Minati, 2011). The direct link between functional connectivity of neural areas at rest and during and functional tasks enables a link between rest-state paradigms and behaviour. As rest state is free from the confounding effect of differences in level of task performance (Rosazza and Minati, 2011), this could be a useful strategy to explore neural activity in children DCD whose motor task performance is not as proficient as typically developing controls.

The one recently published study of resting state neural activity in children with DCD used resting state data to explore functional connectivity with the primary motor cortex (M1) (McLeod et al., 2014). In comparison to their typically developing peers, children with DCD were identified to display decreased functional connectivity between bilateral IFG/ precentral gyrus and M1, suggesting these regions may contribute to the motor difficulties characteristic of DCD. In addition, a combined DCD/ADHD sample displayed a decreased level of connectivity between the right motor cortex (BA6) and M1. While only seven children were included in the DCD sample, this study provides further evidence in support of neurological underpinnings of this disorder, suggesting that children with DCD display different functional connectivity to that of their typically developing peers. The exploration of functional connectivity has been suggested as a future research direction (Kashiwagi and Tamai, 2013) and warrants further research in this population.

The small collection of neuroimaging studies provide evidence for differential magnetic resonance (MR) signal activation patterns of MNS regions (Debrabant et al., 2013; Kashiwagi et al., 2009; Licari et al., 2015; Zwicker et al., 2010, 2011), as well as altered effective (Querne et al., 2008) and functional connectivity (McLeod et al., 2014). While these results present preliminary evidence of dysfunction in MNS regions; assessment of the involvement of the MNS itself is precluded due to the types of tasks that have been used. The evidence does, however, suggest that MNS regions represent targets for further study, and that future neuroimaging work to assess MNS function specifically should be undertaken.

4.4. Limitations of existing literature

While the literature regarding imitation suggests that children with DCD have deficits, these conclusions must be interpreted with some caution. At a behavioural level, representational gesture assessment batteries which have been used are not standardised, and there is a high degree of variation in both the numbers of gestures (which in cases has resulted in ceiling effects), and in the actual gestures used across studies. Although the papers using representational gestures to assess praxis ability are suitable for assessing praxis development, the imitation of learned skills may better reflect an individual’s skill set rather than their imitation proficiency alone. Given that reduced performance proficiency of learned skills is characteristic of DCD (APA, 2013), it may not come as a surprise that children with DCD tend to perform at a lower level than typically developing controls. While imitation of non-meaningful, novel gestures may better reflect mirror neuron function, limitations exist within this literature as well. Only one study of imitation proficiency within this review employed standardised measures of imitation with known psychometric properties (Goyen et al., 2011), with the others using small non-standardised batteries (Dewey and Kaplan, 1992; Hill, 1998). In addition, the remainder of papers exploring non-representational gestures unfortunately do not have an assessment of motor proficiency, and as a result, have not been included in this review (Ayres, 1965; Elbasan et al., 2012; Filipić and Ozbić, 2008; Ozbić and Filipić, 2010). Furthermore, only a small number of assessments have explored sequences of gestures, and those that do only use a limited number of sequences are often not well explained. Exploring imitation of sequence gestures is important in terms of both assessing MNS function and practical treatment and intervention applications. When learning new skills, most are comprised of sequences of movements, rather than discrete actions.
The majority of implicit and explicit motor imagery tasks provide support for differences in motor imagery proficiency between typically developing individuals and those with DCD. This supports both of these approaches for assessing motor imagery. A limitation of implicit and explicit motor imagery assessments is the lack of standardisation of assessment batteries. Differences in complexity of tasks within the same paradigm and the analysis techniques used have contributed to the inconsistent nature of the degree of motor imagery deficits proposed. Group differences were more apparent with increasingly complex tasks, particularly notable for hand laterality and whole body rotation paradigms. Increasingly complex paradigms are more likely to facilitate a motor imagery strategy (Ter Horst et al., 2010). Task complexity is highlighted as an important factor to consider in the development of study protocols. Given the variation that is observed in the performance of tasks by children with DCD, it is likely that the averaging of group data may mask the extent of variation. For example, the regression fits for VGPTs using group means for each index of difficulty mask the response variation observed when correlations of individual's real and imagined responses are calculated.

Several methodological limitations were observed including group selection procedures, lack of blinding, the use of small and non-standardised assessment batteries, limited assessment with respect to degree of motor impairment, and disproportionate gender ratios between groups and small female sample sizes. Indeed, group selection methods led to the exclusion of several reports, where, as mentioned above, no movement assessment was reported for either group. Furthermore, the studies by Dewey (1991, 1993) and Dewey and Kaplan (1992) only report examining movement proficiency in the motor difficulty group. As a result of the difficulties recruiting children with DCD, a common method of participant recruitment, employed by a large number of studies in this review, is screening children at schools following referral by teachers of children whom they believe to have coordination below that of their peers. Given the milder deficits observed by Sinani et al. (2011) in a school sample of children with DCD in comparison to the clinical sample, it is possible that using school samples rather than individuals who have been referred through a variety of clinical pathways may reduce the deficits observed.

A common limitation across studies is the male:female participant ratio, and the small female sample size meaning that only a limited number of studies have performed gender comparisons. While this likely reflects clinical prevalence (APA, 2013), the majority of studies also recruit an unequal ratios of males:females in DCD and control groups. Given the literature suggesting gender differences in both imitation performance (Chipman and Hampson, 2006, 2007) and MNS function (Cheng et al., 2006), the lack of gender matching has the potential to skew the results, as well as prohibit accurate gender comparisons.

At a methodological level, blinding is important in minimising bias in terms of group assignment for movement assessments, as well as during imitation and motor imagery assessments, given the subjective nature of components of these assessments. Only three studies in this review reported any form of blinding (Hill et al., 1998; Sinani et al., 2011; Zoia et al., 2002).

There are a number of limitations within the neuroimaging literature in this population, many of which are characteristic of fMRI studies in general. Sample sizes have typically been small, most likely the result of the high cost associated with fMRI scanning and subsequent data analysis, as well as difficulties of imaging in a paediatric population, with factors such as movement and scan time length to consider. At a subject level, participant samples have often not been clearly defined in terms of comorbidity status. At a data level, limited information is included regarding how much movement has been allowed before participants are excluded for excessive movement during scanning, which has the potential to seriously compromise data sets. At an analysis level, several papers compare trends in activation profiles of children with and without DCD rather than statistically comparing neural activation between groups, which results in a more descriptive form of analysis. For region of interest (ROI) and structural equation modelling analysis, it is important to redefine ROIs based on previous research. This is particularly the case in paediatric populations, where predefined functional ROI atlases do not exist. While not all fMRI studies used ROI analysis, no justification for ROI selection is explicitly stated in the fMRI research which has utilised this approach in a DCD sample. With regard to this review, a limitation of the neuroimaging literature is that the studies do not set out to explore MNS function. While not a limitation of the studies themselves, it does mean that the results must be treated with caution when being interpreted in the context of MNS function.

4.5. Limitations of the review

This review presents evidence for MNS dysfunction at a behavioural level through imitation and motor imagery, and at a neurological level exploring activation and connectivity of MNS areas. It does not include psychosocial aspects such as empathy or theory of mind. A limitation of this review is the absence of a meta-analysis of results in favour of a narrative summary. While a meta-analysis to determine the relative importance of outcomes would have strengthened the review, the nature of the results prohibited a meta-analysis approach. Furthermore, the types of outcome measures presented in the original papers, with multiple variables important in the assessment of performance on a particular task also meant that effect sizes could not be calculated for all outcomes and tasks. A further limitation of the review is that there was only one title and abstract reviewer, meaning that there was a potential for some studies to be missed. Despite this, the whole review process was conducted twice, reducing the potential for the omission of relevant articles.
5. Summary of evidence and future directions

The evidence presented in this review provides preliminary support for deficits in MNS function in children with DCD. At a behavioural level, deficits in imitation observed in children with DCD during representational learned gestures are established, with consistently large effect sizes. Preliminary evidence also suggests difficulties imitating non-representational, novel gestures, which possibly reflects MNS dysfunction. Further research to explore imitation of complex novel postures and sequences of movements is warranted as these have applications to motor skill learning and the development of intervention approaches.

The motor imagery literature is less consistent with the level of deficits and differences in response patterns between groups reported across studies varying, with some studies reporting no significant differences. Accompanying these results is a greater level of variation in terms of task complexity within the same paradigm, as well as in analysis techniques within the motor imagery assessments. Strong support for motor imagery deficits come from VGTI literature (Katschmarsky et al., 2001; Lewis et al., 2008; Maruff et al., 1999; Williams et al., 2013; Wilson et al., 2001) and imagined reaching tasks (Caçola et al., 2014). Moderate support can be drawn from hand laterality (Katschmarsky et al., 2001; Lewis et al., 2008; Lust et al., 2006; Noten et al., 2014; Williams et al., 2011, 2013, 2006, 2008; Wilson et al., 2004) and whole body rotation (Williams et al., 2006, 2008) paradigms. Whilst in most cases differences in response patterns between groups are observed, a large amount of variation in results may be able to be attributed to the differences in task complexity levels, with more complex tasks more likely to identify differences. Inconsistent results have been gained from Praxis Imagery Questionnaires (Sinani et al., 2011; Wilson et al., 2001), with potential ceiling effects being an issue, in addition to the use of questionnaires in this age group.

Further motor imagery research in this population would benefit from the use of complex paradigms, to ensure any differences in motor imagery proficiency are identified and to prevent ceiling effects. Given the stronger positive relationship between motor imagery proficiency and motor skill development with increasing age (Caeyenberghs et al., 2009), an exploration of the relationship between imitation proficiency and performance on motor imagery tasks also warrants investigation. In an intervention context, as most motor skills are complex, motor imagery interventions often require imagery of complex actions to assist in skill acquisition and development. An investigation of motor imagery performance using a complex hand rotation task would be beneficial, to explore whether children with DCD are still able to use a motor imagery strategy when task complexity increases.

Neuroimaging evidence indicates differences in brain activation patterns between children with and without DCD. The literature included in this review suggests that differences in MR signal and effective and functional connectivity exist within MNS regions, however to date no published fMRI studies have been undertaken to specifically examine MNS function. Consequently, the interpretation of these results in this context must be treated with caution. Functional MRI paradigms specifically designed to explore the activation patterns of MNS regions during MNS activation tasks (action observation, motor imagery, motor execution, imitation) are required. A recently completed doctoral thesis exploring MNS in adults (18–30 years) with dyspraxic characteristics is a promising start (Werner, 2013). In addition, rsfMRI to explore functional connectivity between and connectivity to MNS regions would provide a more holistic analysis of MNS function.

Based on the literature in this review, an exploration of MNS function in children with DCD appears to be a promising research direction. As these behavioural and neurological processes share a degree of overlap with other deficits children with DCD experience, such as motor learning and adaptation, sensori-perceptual function, and executive functioning, these areas also warrant further exploration, particularly at a neurological level. A greater understanding of MNS function in both boys and girls with DCD has significant clinical implications; a greater understanding of deficits at a neurological level has potential to inform and tailor intervention programs for this population. Although many intervention approaches have been trialled for DCD, with greatest success from task-oriented and motor-based programs (Smits-Engelsman et al., 2013), because the neural mechanisms of DCD are not fully understood, targeted intervention programs are often not evidence based, with the long-term impact of intervention programs unknown (Smits-Engelsman et al., 2014). Moderate support can be drawn from hand laterality (Katschmarsky et al., 2001; Lewis et al., 2008; Lust et al., 2006; Noten et al., 2014; Williams et al., 2011, 2013, 2006, 2008; Wilson et al., 2004) and whole body rotation (Williams et al., 2006, 2008) paradigms. Whilst in most cases differences in response patterns between groups are observed, a large amount of variation in results may be able to be attributed to the differences in task complexity levels, with more complex tasks more likely to identify differences. Inconsistent results have been gained from Praxis Imagery Questionnaires (Sinani et al., 2011; Wilson et al., 2001), with potential ceiling effects being an issue, in addition to the use of questionnaires in this age group.

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Further motor imagery research in this population would benefit from the use of complex paradigms, to ensure any differences in motor imagery proficiency are identified and to prevent ceiling effects. Given the stronger positive relationship between motor imagery proficiency and motor skill development with increasing age (Caeyenberghs et al., 2009), an exploration of the relationship between imitation proficiency and performance on motor imagery tasks also warrants investigation. In an intervention context, as most motor skills are complex, motor imagery interventions often require imagery of complex actions to assist in skill acquisition and development. An investigation of motor imagery performance using a complex hand rotation task would be beneficial, to explore whether children with DCD are still able to use a motor imagery strategy when task complexity increases.

Neuroimaging evidence indicates differences in brain activation patterns between children with and without DCD. The literature included in this review suggests that differences in MR signal and effective and functional connectivity exist within MNS regions, however to date no published fMRI studies have been undertaken to specifically examine MNS function. Consequently, the interpretation of these results in this context must be treated with caution. Functional MRI paradigms specifically designed to explore the activation patterns of MNS regions during MNS activation tasks (action observation, motor imagery, motor execution, imitation) are required. A recently completed doctoral thesis exploring MNS in adults (18–30 years) with dyspraxic characteristics is a promising start (Werner, 2013). In addition, rsfMRI to explore functional connectivity between and connectivity to MNS regions would provide a more holistic analysis of MNS function.

Based on the literature in this review, an exploration of MNS function in children with DCD appears to be a promising research direction. As these behavioural and neurological processes share a degree of overlap with other deficits children with DCD experience, such as motor learning and adaptation, sensori-perceptual function, and executive functioning, these areas also warrant further exploration, particularly at a neurological level. A greater understanding of MNS function in both boys and girls with DCD has significant clinical implications; a greater understanding of deficits at a neurological level has potential to inform and tailor intervention programs for this population. Although many intervention approaches have been trialled for DCD, with greatest success from task-oriented and motor-based programs (Smits-Engelsman et al., 2013), because the neural mechanisms of DCD are not fully understood, targeted intervention programs are often not evidence based, with the long-term impact of intervention programs unknown (Smits-Engelsman et al., 2013). Motor skill rehabilitation programs based on MNS activation have been successfully applied in stroke, cerebral palsy, orthopaedic, and Parkinson’s disease populations (Buccino et al., 2012). In addition to improving motor performance, fMRI assessment of action observation and imagery rehabilitation programs demonstrates these interventions induce neuroplastic changes with increased post-intervention MNS activation (Ertelt et al., 2007). It is possible that these types of interventions may be successful for children with DCD. A pilot motor imagery training intervention demonstrated promising results (Wilson et al., 2002). Functional changes in the MNS likely have the potential to result in improved imitation and motor imagery performance, accompanying improvements in motor proficiency, with hope for resultant secondary benefits in increased participation levels, and emotional and social development.

To date, no studies on MNS functioning in children with DCD have been published. While preliminary evidence contained in this review certainly indicates some deficit in the functioning of the MNS, further research to extend the existing literature regarding imitation and motor imagery ability, and MNS functioning in this population is worthy of investigation. An assessment of a sample of children with DCD on novel non-representational single gestures and sequences of gestures imitated is needed to confirm imitation deficits in this population and to examine whether there are consistent characteristic errors on certain tasks, and error types displayed. Future research to explore motor imagery deficits in DCD
would benefit from complex paradigms. Standardising hand rotation motor imagery assessments for future research will allow for comparison between children and adults with DCD as well as other neurodevelopmental disorders. Research to explore the MNS hypothesis in greater detail, particularly from a neuroimaging perspective, has the potential to provide information on the underlying mechanisms of DCD, inform future research into the aetiology of this disorder, and inform intervention approaches.

Future neuroimaging research could explore MNS activation and excitability patterns, and connectivity of MNS regions, using a range of techniques including fMRI, EEG, and rsfMRI. The information gained from neuroimaging studies could be used to assist the interpretation of existing behavioural studies that have only been able to hypothesise the neurological underpinnings of their results and to confirm speculations of neurological underpinnings of DCD, or suggest alternative neurological explanations. As existing interventions have been informed primarily by behavioural studies and therefore designed to address the behavioural deficits displayed by children with DCD, potential differences in MNS function opens up the possibility of designing interventions to address potential neurological underpinnings of the behavioural deficits. Training specific to the MNS might involve less performance of the actual movement and more time mentally rehearsing and modelling the action of others. This could open up a range of additional motor training interventions for children with DCD, such as action observation or motor imagery treatments, or could be implemented into existing beneficial therapy approaches like CO-OP by incorporating additional stages. Further neuroimaging research to explore whether motor behaviour changes are paired with neurological changes may also provide greater understanding of intervention approaches in DCD.

**Funding**

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**Acknowledgements**

The authors thank Karen Jones and Jacqui Mooney (UWA librarians) for their assistance in developing the search strategy and also thank Caroline Davis for reviewing an article.

**Appendix A. Appendix 1**

**Table A1**

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Appendix B. Appendix 2

Tables B1–B3 present Kmet, Lee, & Cook checklist scores for assessing the quality of quantitative studies for the imitation, motor imagery, and neuroimaging articles, respectively. Each article is assigned a value for each question reflecting: Yes = 2, Partial = 1, No = 0, or N/A.

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INTRODUCTION TO SERIES TWO: BEHAVIOURAL ASSESSMENTS OF MIRROR NEURON SYSTEM FUNCTION

As identified in the systematic review (Study 1), at a behavioural level, support for the MNS dysfunction hypothesis of DCD can be drawn from evidence that children with DCD display imitation and motor imagery deficits. However, the current literature examining imitation and motor imagery performance has a number of limitations. Although there are a number of studies that have compared imitative performance of children with DCD to controls, they have primarily used gestures that children will have been exposed to throughout their childhood, gestures that have meaning (representational gestures, e.g., waving goodbye; Dewey, 1991, 1993; Dewey & Kaplan, 1992; Dewey, Cantell, & Crawford, 2007; Hill 1998; Hill et al., 1998; Sinani et al., 2011; Zoia, Pelamatti, Cuttini, Casotto, & Scabar, 2002). DCD is not a condition in which children are completely incapable of learning motor skills and, with practice, skill acquisition is achievable. The use of representational gestures may not be sensitive enough to examine differences in imitative ability during the early acquisition phase, the period in which the greatest difficulty is experienced. Therefore, novel gestures and sequences of novel gestures are likely to be more sensitive. Despite this, limited research has been conducted to explore imitation of these types of gestures.

Several studies have explored motor imagery performance of both children and adults with DCD using a range of task paradigms (Adams, Lust, Wilson, & Steenbergen, 2014; Reynolds, Thornton et al., 2015). Although most literature has identified a generalised motor imagery deficit, not all individuals with DCD have been found to perform poorly on motor imagery tasks (Wilson, Maruff, Ives, & Currie, 2001; Wilson et al., 2013); some studies report no difficulties in adopting a motor imagery strategy but that individuals with DCD are less efficient than controls (Deconinck, Spitaels, Fias, & Lenoir, 2009; Lust et al., 2006), whereas another study reported difficulties in only some individuals with DCD (Katschmarsky, Cairney, Maruff, Wilson, & Currie, 2001). It is likely that these differences are the result of different paradigms employed as well as the differing levels of task complexity, differences in analysis techniques employed within paradigms (e.g., for hand rotation analysing all or analysing only correct responses), and individual differences in severity of DCD and motor impairments. Although preliminary evidence suggests that motor imagery deficits appear to be more pronounced in children with DCD.
with increasing task complexity (Caçola, Gabbard, Ibaña, & Romero, 2014; Noten, Wilson, Ruddock, & Steenbergen, 2014), most studies that have used hand rotation tasks have used only one axis of rotation within a trial or only a small number of rotation steps (angles presented). More complex task paradigms, such as the use of both back and palm view across a number of angles, increase the likelihood of individuals adopting a motor imagery strategy (ter Horst et al., 2010). In addition, by analysing back and palm view responses separately, these task paradigms allow for an exploration of whether the motor imagery difficulties experienced by most children with DCD are more pronounced as task complexity increases.

This series includes two studies that explore MNS function at a behavioural level. The first study, accepted for publication in *Journal of Motor Behavior*, compares the imitation of complex novel whole body gestures and sequences of hand and finger gestures in children with probable DCD and group aged-matched controls (Reynolds et al., 2016). The relationship between imitation and movement proficiency is also investigated within this study, as is the relationship between imitation and age. The second study, published in *Human Movement Science*, explores motor imagery performance on a complex hand rotation task (Reynolds, Licari, Elliott et al., 2015). Furthermore, it explores group differences in the context of task complexity and the extent of benefits gained from receiving explicit motor imagery instructions.


The aim of this study is to:

- Explore imitation of complex novel gestures and sequences of gestures in children with and without DCD.

It is hypothesised that compared to typically developing controls, children with DCD will:

- Demonstrate imitation deficits for both posture and sequence imitation.
- Demonstrate slower responses.
- Experience increased deficits with increasing task complexity.
The aims of this study are to:

- Explore motor imagery proficiency in children with and without DCD using a complex hand rotation task.
- Identify whether children with DCD benefit from motor imagery instructions.

It is hypothesised that:

- Children with DCD will be able to utilise a motor imagery strategy, however, will have slower and less accurate response patterns when compared to typically developing controls.
- Motor imagery deficits in children with DCD will become more pronounced as task complexity increases.
- Children with DCD will gain less benefit from explicit motor imagery instructions compared to typically developing controls.

**Limitations and delimitations**

There are a number of limitations and delimitations of the two behavioural experimental studies:

- The Sensory Integration and Praxis Tests (SIPT) imitation battery is only age standardised until 8 years 11 months, so raw scores were utilised. Despite this, it was considered the best assessment to explore novel gestures.
- The complex hand rotation task is an implicit motor imagery task. Although participants verbally reported motor imagery strategies, it is difficult to determine the actual imagery engagement level, with inferences being made based on behavioural data.
- These studies are delimited by the inclusion of boys aged between 6 and 13 years. Only male children were included to eliminate potential gender differences in imitation and motor imagery (Chipman & Hampson, 2006, 2007), and to reflect the higher prevalence of males with DCD.
Children in the DCD group were not required to have a diagnosis. Diagnosis is not always pursued in Australia, even when children are actively participating in a range of therapies. Furthermore, this disorder is not well recognised in the medical community. As a result, the DCD groups have been classified as probable DCD.

The majority of the participants with probable DCD were recruited from The University of Western Australia’s Paediatric Exercise Programs. Most participants were receiving a movement therapy service, and/or have proactive parents seeking a service.

Participants over seven years of age participated in both of the behavioural studies.
CHAPTER 3: POOR IMITATIVE PERFORMANCE OF UNLEARNED GESTURES IN CHILDREN WITH PROBABLE DEVELOPMENTAL COORDINATION DISORDER


This is an Author's Accepted Manuscript of the article: Reynolds, J. E., Kerrigan, S., Elliott, C., Lay, B. S., & Licari, M. K. (2016). Poor imitative performance of unlearned gestures in children with probable developmental coordination disorder. Journal of Motor Behavior, Online ahead of print October 11 2016. DOI: 10.1080/00222895.2016.1219305, which has been published in final form in http://dx.doi.org/10.1080/00222895.2016.1219305. Copyright © Taylor & Francis Group, LLC
Abstract
It has been hypothesised that deficits in imitation, linked to abnormal functioning of the mirror neuron system (MNS), may contribute to the motor impairments associated with developmental coordination disorder (DCD). This study aimed to examine imitation of complex novel postures and sequences of gestures in children with and without probable DCD (pDCD), using the Postural Praxis and Sequencing Praxis subtests of the Sensory Integration and Praxis Tests (Ayres, 1989). Twenty nine boys with pDCD aged 6.08–13.33 years, and 29 group age matched typically developing boys aged 6.08–13.83 years participated. Responses of children with pDCD on both imitation tasks were less accurate than controls, with group differences more apparent with increasing task complexity. Furthermore, as a group, children with pDCD were slower and had a higher number of non-mirror imitated responses. There was considerable variability within the pDCD group, with some children displaying imitation scores within the normative range. Given the importance of imitation and visual learning for motor development, the difficulties in imitation displayed by some children with pDCD have the potential to impact on movement acquisition. Interventions to target imitation may be beneficial for these children.

Highlights
- Children with pDCD had difficulty imitating complex novel postures
- Children with pDCD had difficulty imitating gesture sequences
- Children with pDCD had slower responses than controls
- Group differences in imitation performance increased with task complexity
- Not all children with pDCD displayed imitation deficits

Key words: Developmental coordination disorder; DCD; Mirror neuron system; Imitation; Praxis; Sensory Integration and Praxis Tests; SIPT
3.1 Introduction

Developmental coordination disorder (DCD) is a condition characterised by impaired motor coordination and an inability to perform motor skills at an age appropriate level. It impacts approximately 6% of children (American Psychiatric Association, 2013; World Health Organisation, 2010). Although there is a relatively good understanding of the fine and gross motor impairments in children with DCD, very little is known about the underlying mechanisms and aetiology. A cortical network that has recently been hypothesised to be associated with DCD is the mirror neuron system (MNS; Reynolds, Licari, Billington et al., 2015, Reynolds, Thornton et al., 2015; Werner, Cermak, & Aziz-Zadeh, 2012), a cluster of multimodal neurons in the central nervous system that fire when a person observes and replicates an action performed by another (Iacoboni & Dapretto, 2006; Buccino et al., 2006). Deficits in MNS function are thought to interfere with a child’s ability to learn or imitate movements they observe.

Imitation provides a foundation for skill learning via observation and involves the recognition and understanding of an action, and the subsequent transformation and integration of observed visual patterns and sensory stimuli into motor commands to reproduce actions and acquire skills (Arbib, Billard, Iacoboni & Oztop, 2000). Imitation is an important learning mechanism from a young age (Bergès & Lézine, 1965), with this behaviour demonstrated in neonates and young infants (Lloyd-Fox, Wu, Richards, Elwell, & Johnson, 2015; Meltzoff & Moore, 1977). During the course of typical development imitation proficiency and the ability to learn via imitation, improves steadily (Meltzoff, Williamson, & Marshall, 2013; Tomasello & Carpenter, 2005) as children are exposed to more complex actions and mature mentally and physically.

Imitation ability of children with DCD has typically been explored in a praxis context to assess representational gestural ability. The term praxis traditionally refers to learned motor skills and movements related to tool use (Steinman, Mostofsky, & Denckla, 2010). Praxis assessments of gestures have predominantly been developed to assess a sudden loss of function (e.g. apraxia resulting from stroke – the loss of learned purposeful actions not able to be accounted for by sensori-motor, or comprehension deficits). To evaluate changes in function, these batteries use simple well known tasks such as using ‘a vegetable peeler to shred a carrot’, ‘wave goodbye’, or ‘hitchhike’ (Power, Code, Croot, Sheard, & Gonzalez Rothi, 2010). These tasks have not been developed to explore imitation in the context of motor learning and the acquisition of new skills.
Most studies evaluating imitation performance of children with DCD have adapted these adult apraxia assessments batteries, as no standardised paediatric assessments existed at the time (Zoia, Pelamatti, Cuttini, Casotto, & Scabar, 2002). Paediatric praxis examinations usually assess low complexity learned or skilled (as opposed to novel) transitive (object/tool related) actions which children are likely exposed to in everyday situations and occasionally incorporate symbolic intransitive (non-object related) gestures (Steinman et al., 2010). These assessments incorporate gestures such as ‘show me how to brush your teeth’ or ‘wave goodbye’ (Sinani, Sugden & Hill, 2011). The majority of assessments of representational gestures indicate that children with DCD have poorer performance when compared to controls (Dewey, 1991, 1993; Dewey & Kaplan, 1992; Hill, 1998; Hill et al., 1998; Sinani et al., 2011; Zoia et al., 2002), with only one study, comprised of an older age group (8.6 to 16.0 years), finding no group differences (Dewey, Cantell, & Crawford, 2007). Given that children with DCD also display praxis deficits to verbal command (Dewey, 1991; Dewey & Kaplan, 1992; Hill, 1998; Sinani et al., 2011; Zoia et al., 2002), it is possible that praxis assessments also reflect deficits in learned skill performance, rather than imitation deficits alone.

Apraxia batteries are simple and are effective in identifying acute injury to the brain, however they are probably too simple to detect motor skill acquisition difficulties in conditions like DCD. In developmental disorders, the underlying mechanisms of imitation deficits are different, with these children still capable of learning skills through practice, albeit less efficiently (Reynolds, Thornton et al., 2015). The acquisition of new gestures is equally as important in examining imitation deficits in populations who are in the early phases of acquiring skills, such as those with developmental disorders, who may have difficulty processing observed information and integrating it into movement based contexts. In these populations, assessing imitation from a motor learning perspective using novel complex gestures may provide a more accurate reflection of imitation proficiency.

The small number of studies that have explored imitation of novel gestures in DCD provide preliminary evidence to support suspected imitation deficits extending into novel and sequential gestures (Ayres, 1989; Elbasan, Kayihan, & Duzgun, 2012; Filipčič & Ozbič, 2008; Goyen, Lui, & Hummell 2011; Ozbič & Filipčič, 2010). One further study demonstrated that imitation performance of children with DCD is similar, although slightly better than children with Asperger’s Syndrome (Green et al. 2002), a
neurodevelopmental disorder which has been consistently associated with deficits in imitation. Although supportive of imitation deficits, the majority of the early (Ayres, 1965) and more recent work (Elbasan et al., 2012; Filipčič & Ozbič, 2008; Ozbič & Filipčič, 2010) using established novel imitation assessments have not used standardised assessments of movement proficiency to confirm group selection, or excluded individuals with additional developmental disorders, such as attention deficit hyperactivity disorder (ADHD) or autism spectrum disorders (ASD), which may have influenced their findings. Non-standardised novel imitation batteries have also been used to explore imitation in DCD (Dewey & Kaplan 1992; Hill, 1998). An acknowledged limitation of these assessments (Dewey & Kaplan 1992; Hill, 1998) is the small number of gestures (n ≤ 10) and low complexity level, which may have prevented group differences or resulted in only minimal differences being observed (Dewey & Kaplan 1992; Hill, 1998).

Given the importance of imitation for motor learning, deficits in imitation and observational learning have the potential to hamper the acquisition of movement skills in children with DCD. Whilst there has been some research exploring praxis and imitation of learned skills in this population, to date there has been limited research to explore imitation of complex novel, non-meaningful gestures. Further research to explore complex novel, and sequences of gestures using larger, more complex batteries would extend the current body of literature. Of particular importance is a greater understanding of sequence imitation because many of the novel tasks we learn and perform on a daily basis are comprised of sequences of movements. An increased understanding of imitation performance of children with DCD has the potential to assist in the development of targeted interventions to aid in improving motor skill development in this population.

The present study aimed to examine imitation proficiency of children with and without probable DCD (pDCD) using the postural praxis (complex novel) and sequencing praxis (sequence gestures) subtests of the Sensory Integration and Praxis Tests (SIPT). The SIPT subtests were selected because of their use in other paediatric research, the standardised nature, and validity and reliability (Ayres, 1989). Based on previous research, it was hypothesised that children with pDCD would demonstrate deficits in imitation, reflected in slower and less accurate response patterns than controls. Further, it was hypothesised that compared to controls, children with pDCD would have a greater difficulty mirror imitating responses, and greater difficulty on the more complex bimanual postural tasks.
3.2 Methods

Seventy boys were initially recruited for this cross-sectional study, comprising 40 children with pDCD recruited from the University of Western Australia’s Paediatric Exercise Programs, and via referrals from Occupational Therapists and Paediatricians, and 30 age group matched controls recruited from the local community after responding to printed, email and word of mouth advertising. Movement proficiency was assessed using the Movement Assessment Battery for Children – 2 (MABC-2; Henderson, Sugden, & Barnett, 2007), which was chosen due to its reliability and validity. Children in the pDCD group were required to fall at or below the 16th percentile on the MABC-2, while children in the typically developing group were required to score at or above the 20th percentile. Due to the high levels of comorbidities associated with DCD, and the potential involvement of these disorders with imitation and MNS dysfunction, children with a diagnosis of ADHD or ASD were excluded. In addition, the Swanson Nolan and Pelham-IV ADHD questionnaire (SNAP; Bussing et al., 2008) and the Childhood Autism Rating Scale (CARS; Schopler, Reichler, & Renner, 1988) were administered to measure symptoms of these disorders across both groups of participants; children scoring above cut-off scores were excluded. On completion of the screening assessments, 12 boys were excluded (11 with pDCD and one control): one based on the SNAP questionnaire (pDCD); one due to a subsequent diagnosis of ADHD (pDCD); six screened for scoring in normative range although previously ≤16th prior to their exit from UWA paediatric programs (pDCD); two for suspected other disorders (pDCD); one based on a subsequently discovered neurological condition (typically developing; TD); and one due to behaviour (pDCD). This left a final sample of 29 boys with pDCD aged 6.08–13.33 years, and 29 group age matched controls aged 6.08–13.83 years. Participant characteristics are presented in Table 3.1. Participants and their legal guardians provided informed consent for inclusion in the study, which was approved by the University of Western Australia Human Ethics Committee (RA/4/1/6492). Rolling recruitment and data collection ran from February 2014 to July 2015.

3.2.1 Test apparatus: Imitation batteries

Children undertook two imitation components from the SIPT (Ayres, 1989): the postural praxis, which requires imitation of body postures (e.g. one hand on side of head, other hand on hip, head and trunk leaning), and the sequencing praxis, which involves imitation
the imitation tasks were presented in a counterbalanced order.

The postural praxis is comprised of 17 postures in which children are instructed to mirror imitate the positions as quickly as possible. Children’s positions are then scored with a score of 2 given if the posture is correctly replicated (mirrored or non-mirrored) in up to 3 seconds, a score of 1 if the correct posture is assumed in 4-7 seconds, or has minor errors as specified in the scoring manual, and a score of 0 is given if the posture is incorrect or outside the time frame. Although children are instructed to mirror imitate, they are not penalised in the scoring system for non-mirrored responses. The sequencing praxis is comprised of six hand and arm sub-components, each of which contain five to six sequences of two to six movements, and three finger sub-components comprising six sequences each of three to eight movements. Children are instructed to mirror the sequences after the demonstration has finished, however, like the postural praxis component, mirroring is not accounted for in the scoring. A score of 2 is given when the sequence is correctly copied (mirrored or non-mirrored), a score of one is given when the participant acknowledges and corrects an error, and a score of 0 is given for an incorrect sequence. Each subcomponent is discontinued following two consecutive incorrect responses. The SIPT only has standardised scores until the age of 8 years, 11 months, so raw test scores were used.

As the administrator of the imitation assessments works within the UWA Paediatric Exercise Programs from where the majority of the participants with pDCD were sourced, blinding to group membership was not possible. All assessments were filmed, and all postural praxis and a random subsample of 10 (17.24%) sequencing praxis videos were subsequently assessed by a second assessor who was blind to group assignment. Scores were compared and, where differences arose, were discussed and the relevant gesture re-watched and a consensus made. Due to technical issues, the postural praxis video for one participant was missing.

3.2.2 Data analysis
All statistical analyses were run in Statistical Package for the Social Sciences (SPSS Inc., version 22). Data for each test battery were assessed for normality, following which group differences were explored; parametric data was assessed using independent samples t-tests, and non-parametric using Mann Whitney U. Although not incorporated in the
standardised scoring system, the ability to mirror imitate was also included in the analysis. The percentage of mirrored postures for responses in the two point (three second) category were calculated and compared between groups. Percentage of mirrored responses was also calculated and analysed for a subset of postures that involved both sides of body crossing over the midline or linking of hands/fingers (items 3, 5, 6, 8-11, 14-17). Because children with DCD typically respond slower during tasks (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013), the time taken to imitate postures was evaluated. The percentage of correct responses that were in the less than three second category were calculated and compared between groups. For the sequencing praxis, performance was also compared based on the number of movements per sequence. The number of correct performances for sequences of gestures with two through to eight movements were calculated for each individual. Additionally, correlations between each imitation assessment and age and MABC-2 total test scores (sum of the standard scores for the eight MABC-2 test items) were performed. Significance level was set at \( p < .05 \).

### 3.3 Results

#### 3.3.1 Participant characteristics

Group characteristics are presented in Table 3.1. Groups were well matched for age, with no differences found between pDCD and control groups. As expected, the pDCD group had significantly poorer performance on the MABC-2 \( (p < .001) \), with all members in the pDCD group falling at or below the 16\(^{th}\) percentile, and all controls scoring between the 25\(^{th}\) to 98\(^{th}\) percentiles. Interestingly, children with pDCD displayed significantly greater ADHD and autistic symptoms on the SNAP and CARS questionnaires \( (p < .05) \), even though none of the children with pDCD had a formal diagnosis of either disorder, or fitted into the clinical range based on the questionnaires. No differences were found in the screening assessments for handedness.

<table>
<thead>
<tr>
<th></th>
<th>pDCD (n=29)</th>
<th>TD (n=29)</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Age (years)</td>
<td>9.29</td>
<td>1.85</td>
<td>9.27</td>
<td>1.83</td>
</tr>
<tr>
<td>MABC-2 (percentile)</td>
<td>5.69</td>
<td>5.28</td>
<td>68.97</td>
<td>20.67</td>
</tr>
<tr>
<td>CARS</td>
<td>18.42</td>
<td>3.11</td>
<td>15.41</td>
<td>0.69</td>
</tr>
<tr>
<td>SNAP-IV</td>
<td>0.93</td>
<td>0.53</td>
<td>0.53</td>
<td>0.40</td>
</tr>
</tbody>
</table>

* \( p < .05 \); ** \( p < .001 \)
3.3.2 Postural Praxis

Children with pDCD were less proficient at imitating postures (pDCD mean (SD) = 19.86 (5.66), TD mean (SD) = 27.07 (3.38); t (45.740) = 5.891, p < .001, mean difference (95% CI) = 7.21 (4.74 – 9.67)), with a large effect size observed (d = 1.547). Although not significantly different, of the postures that were imitated correctly, controls had a slightly higher percentage of mirrored responses (75.76%) than the pDCD group (70.15%), particularly for postures that involved both sides of body crossing over the midline or linking of hands/fingers (TD = 60.93%, pDCD = 52.05%). Typically developing controls (81.41%) also had a significantly (p < .05) higher percentage of their correct responses in the less than 3 second category than the children with pDCD (73.65%). Furthermore, this variable displayed a weak positive correlation with the total MABC-2 test score ($r_s = .318$, $p = .016$), indicating that children had a greater percentage of their correct responses in the faster time category as their level of motor proficiency increased.

3.3.3 Sequencing Praxis

Children with pDCD had lower scores for the hand and arm, and the finger sequence sections of the sequencing praxis, with moderate to large effect sizes observed (Table 3.2). For the sequencing praxis, there was a trend towards increased effect sizes as the task complexity, measured by number of movements within sequences, increased (Table 3.3). This trend continued until a point where controls (often the younger controls) also began to experience some difficulties with the length of the sequences.

**Table 3.2.** Imitation performance on sequencing praxis subtest.

<table>
<thead>
<tr>
<th></th>
<th>pDCD (n=29)</th>
<th>TD (n=29)</th>
<th>U</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sequencing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Praxis: Hand and arm</td>
<td>Mdn</td>
<td>IQR</td>
<td>Mdn</td>
<td>IQR</td>
<td></td>
</tr>
<tr>
<td></td>
<td>52.00</td>
<td>44.00-58.00</td>
<td>66.00</td>
<td>60.00-67.50</td>
<td>146.50</td>
</tr>
<tr>
<td></td>
<td>17.00</td>
<td>7.00-28.50</td>
<td>31.00</td>
<td>21.00-34.00</td>
<td>226.50</td>
</tr>
<tr>
<td>Praxis: Fingers</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>68.00</td>
<td>50.50-81.00</td>
<td>97.00</td>
<td>83.50-101.50</td>
<td>159.50</td>
</tr>
<tr>
<td><strong>Sequencing</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Praxis: Total</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* $p < .05$; ** $p < .001$; Mdn = median; IQR = interquartile range
Table 3.3. Sequencing Praxis: Summed scores by number of movements per item.

<table>
<thead>
<tr>
<th></th>
<th>pDCD (n=29)</th>
<th>TD (n=29)</th>
<th>U</th>
<th>p</th>
<th>r</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mdn</td>
<td>IQR</td>
<td>Mdn</td>
<td>IQR</td>
<td></td>
</tr>
<tr>
<td>Two</td>
<td>16.00</td>
<td>15.50-16.00</td>
<td>16.00</td>
<td>16.00-16.00</td>
<td>349.00</td>
</tr>
<tr>
<td>Three</td>
<td>24.00</td>
<td>17.50-26.00</td>
<td>26.00</td>
<td>24.00-28.00</td>
<td>237.00</td>
</tr>
<tr>
<td>Four</td>
<td>20.00</td>
<td>11.50-25.00</td>
<td>28.00</td>
<td>22.00-30.50</td>
<td>199.50</td>
</tr>
<tr>
<td>Five</td>
<td>8.00</td>
<td>2.00-10.50</td>
<td>14.00</td>
<td>12.00-17.00</td>
<td>158.50</td>
</tr>
<tr>
<td>Six</td>
<td>2.00</td>
<td>2.00-5.00</td>
<td>6.00</td>
<td>4.00-8.00</td>
<td>162.50</td>
</tr>
<tr>
<td>Eight</td>
<td>0.00</td>
<td>0.00-2.00</td>
<td>3.00</td>
<td>0.00-4.00</td>
<td>228.00</td>
</tr>
</tbody>
</table>

* p < .05; ** p < .001; Mdn = median; IQR = interquartile range

3.3.4 Impact of age and motor proficiency on imitation performance

Moderate positive correlations with age and MABC-2 total score were observed for all imitation assessment components (Table 3.4; Figure 3.1). Although both groups displayed age and movement proficiency related improvements in imitation performance, the control group approached a ceiling effect for the postural praxis, and reached a ceiling effect for the sequencing praxis task, both at around ten years of age (Figure 3.1). Although as a group children with pDCD continued to improve with age, a ceiling effect was not reached on either assessment.

A large degree of variability in imitation scores is present within each group (Figure 3.1), suggesting that some, but not all, children with pDCD have imitation impairments. In contrast, although there is still a degree of variability, the typically developing group are mostly clustered with higher scores, especially on the sequencing praxis, with the exception of a few younger participants in the group.

Table 3.4. Correlation between imitation performance on SIPT subtests and age and MABC-2.

<table>
<thead>
<tr>
<th></th>
<th>Age</th>
<th>MABC-2 total score</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>r</td>
<td>p</td>
</tr>
<tr>
<td>Postural Praxis</td>
<td>.398</td>
<td>.002*</td>
</tr>
<tr>
<td>Sequencing Praxis: Hand and arm</td>
<td>.549</td>
<td>.001*</td>
</tr>
<tr>
<td>Sequencing Praxis: Fingers</td>
<td>.560</td>
<td>.001*</td>
</tr>
<tr>
<td>Sequencing Praxis: Total</td>
<td>.585</td>
<td>.001*</td>
</tr>
</tbody>
</table>

a Pearson correlation; b Spearman’s rho; * p < .05; ** p < .001
Figure 3.1. Correlations between imitation performance and movement proficiency and age. A. Postural Praxis and MABC-2 total test score (sum of the standard scores for the eight MABC-2 test items), B. Sequencing Praxis and MABC-2 total test score, C. Postural Praxis and age, and D. Sequencing Praxis and age.
3.3.5 Inter-rater agreement

Exact agreement between the two imitation raters was 92.73% for the postural praxis (all videos, except for technical failures) and 88.49% for the sequencing praxis (n =10 videos subsample). Following discussion on discrepancies, agreement was 100%. This level of agreement was considered acceptable, with the inter-rater reliability for the two subtests reported as 0.96 and 0.90 respectively in the SIPT manual (Ayres, 1989).

3.4 Discussion

Children with pDCD displayed poorer imitation compared to controls for both components of the SIPT. The findings are consistent with preliminary research using the standardised Sensory Integration and Praxis Tests (Ayres, 1989) and its precursor, the Ayres Southern California Sensory Integration Test (Elbasan et al., 2012; Goyen et al., 2011), as well as the Bergès-Lézine Test of Imitation Gestures (Filipčič & Ozbič, 2008; Ozbič & Filipčič, 2010). Children with pDCD also displayed deficits imitating sequences of arm, hand, and finger positions, which is consistent with previous research using standardised assessments (Goyen et al., 2011). The medium to large effect sizes are also consistent with the imitation deficits observed using praxis tests exploring imitation of meaningful gestures (Dewey, 1993; Dewey & Kaplan, 1992; Sinani et al., 2011).

Given the importance of imitation and visual learning for motor development (Rizzolatti & Craighero, 2004), imitation difficulties are likely to impact on the movement acquisition of children with DCD (Reynolds, Thornton et al., 2015). It has been suggested that dysfunction of the MNS may be a neural mechanism associated with deficits in imitation, self-other mapping, and visuo-motor translation (Iacoboni, 2005; Williams, Whiten, Suddendorf, & Perrett, 2001). Based on the poor imitation performance observed behaviourally, at a neurological level, dysfunction of the MNS may be one factor which contributes to the movement difficulties characteristic of DCD (Reynolds, Licari, Billington et al., 2015, Reynolds, Thornton et al., 2015; Werner et al., 2012). Disruption of imitation performance, and self-other discrimination following repetitive transcranial magnetic stimulation (rTMS) over MNS regions including the inferior frontal gyrus (Heiser, Iacoboni, Maeda, Marcus, & Mazziotta, 2003), and the inferior parietal lobule (Kammers et al., 2009; Uddin, Molnar-Szakacs, Zaidel, & Iacoboni, 2006), implicates the MNS in imitation performance and perceptual body judgements; the processes supported also extend beyond the MNS, with these regions involved in additional processes such as
attentional processing which has the potential to impair imitation performance. As correct imitation performance requires the integration of multiple sensory systems, imitation deficits could also stem from dysfunction of processes that have also been associated with DCD such as, but not limited to, visual attention or processing (Wilmut, Brown, & Wann, 2007), working memory and executive function (Alloway, 2007; Piek, Dyck, Francis, & Conwell, 2007; Tsai, Chang, Hung, Tseng, & Chen, 2012), sensoriperceptual function (Sigmundsson, Whiting, & Ingvaldsen, 1999), or motor learning and adaptation (Kagerer, Bo, Contreras-Vidal, & Clark, 2004; Kagerer, Contreras-Vidal, Bo, & Clark, 2006), and are unlikely limited to one area. The underlying reasons as to why children with DCD may have difficulties with imitation has yet to be explored at a neurological level.

Despite the medium to large effect sizes observed, a high level of variability of imitation proficiency was observed, particularly in the DCD group. This is consistent with previous research (Elbasan et al., 2012), suggesting that other factors alongside visual learning difficulties may contribute to the movement deficits observed. Some researchers suggest that subtypes of DCD may exist, and can be used to explain the variation in deficits displayed between children; however, as highlighted by Gomez and Sirigu (2015), the current research exploring the concept of subtyping is inconclusive and inconsistent across studies, with subtypes based on different variables and divisions.

Interestingly, there were certain postures that both groups experienced difficulties with. Two of these three items (items 11 and 14) were: having arms crossed but both hands tucked under arms so that fingers are not visible; and creating a diamond by connecting each index finger with the opposite thumb. These postures are similar to known actions, and yet have notable differences to them (e.g. would normally cross arms in a classroom with one hand on top of arm, create a diamond with index fingers together) and may have been influenced by negative transfer from these learned actions. Excluding these gestures, there did not appear to be any notable theme tying the gestures together that the children with pDCD experienced difficulties with; there was in fact a broad range of postures performed incorrectly by each participant, without any clear items always being incorrect. This is supportive of a generalised imitation deficit, rather than a specific deficit for certain gesture types.

Although not having a set pattern of items that were incorrect, children with pDCD did tend to have slightly less mirrored responses (70.15% compared to 75.76%) and a greater
percentage of their correct responses in the slower time frame than controls (73.65% compared to 81.41%). Being able to mirror imitate is necessary in a learning context, to acquire new motor skills in the correct manner. Furthermore, the larger percentage of responses in the slower time category is consistent with what would be expected for children with DCD; slower responses can impact learning new skills in an everyday environment. In a practical sense, slower speed side-by-side (to remove mirroring component) motor skill demonstrations may be beneficial for children with DCD so that they are able to take in a greater amount of useful information. Consistent with previous DCD research across a range of assessment paradigms (Noten, Wilson, Ruddock, & Steenbergen, 2014; Caçola, Gabbard, Ibana, & Romero, 2014; Reynolds, Licari, Elliott, Lay, & Williams, 2015), the between group differences in performance were more noticeable as the task complexity increased. The larger effect sizes alongside increased numbers of movements in the sequences to be imitated suggest that other processes such as working memory may also be implicated in the imitation deficits observed.

Importantly, consistent with previous research (e.g. Zoia et al., 2002), an age related increase in imitation skills was observed in both groups. Although a ceiling effect plateau was reached in the control group, as a whole, the pDCD group did not appear to catch up to the control group. Only four children with pDCD over 10 years were included in the sample, which was likely not enough to characterise imitation performance at this age. It is possible that if there had been a larger sample of older participants, a ceiling effect may also have been reached in the pDCD group. The positive relationship between imitation performance and motor proficiency is most evident in the control group, with a larger degree of variability according to MABC-2 test scores present in the pDCD group. Consistent with previous research (Wilson et al., 2013), this highlights the heterogeneous nature of DCD, and suggests that although many individuals displayed poor imitation performance, not all individuals with pDCD have imitation impairments. It is possible that by increasing imitation performance of children with DCD at a young age, this may have a positive impact on their movement proficiency.

There are a number of implications for the imitation deficits identified, both in terms of the negative impact these deficits have on motor learning in some children with DCD, but more positively, the potential applications for observation and imitation based interventions in this population. Although children with DCD have been shown to display visuo-motor translation deficits and to process visual feedback slower than typically
developing controls (Wilson et al., 2004; Zoia, Castiello, Blason, & Scabar, 2005), they also demonstrate an over-reliance on visual feedback over other sensory feedback during task performance (Henderson, Rose, & Henderson, 1992; Laszlo, Bairstow, Bartrip, & Rolfe, 1989; Smyth, 1992). It is possible that developing and improving imitation skills represents an intervention approach that may provide benefits for children with DCD. Observational learning interventions, such as Action Observation Training protocols (Buccino et al., 2012), are based on mirror neuron activation properties and the principles of neuroplasticity, with research demonstrating that the MNS is a plastic system (Mehta et al., 2015). These types of interventions have been beneficial in other populations exhibiting motor dysfunction (Buccino et al., 2012). While specific gesture training does not appear to result in skill transfer (Barbarulo et al., 2012), broader training paradigms appear to develop general transferable motor representations (Hayes, Elliott, & Bennett, 2010). A challenge for the potential application of observation and imitation based intervention approaches in DCD is to ensure the transferability of skill development. It is also important that intervention studies are sufficiently powered to account for the heterogeneity of motor impairments displayed in children with DCD. It is probable that interventions focusing on the development of imitation skills themselves, may provide greater benefits than those concentrating on specific gestures and tasks alone.

While this research has provided valuable information surrounding the imitation of complex novel posture and sequence gestures in children with DCD, there are some limitations of our work. In addition to the visuo-motor translation skills involved in imitation, other factors which were not investigated, such as executive functioning skills, have the potential to be involved in delayed imitation performance. Working memory capabilities, an area which has been hypothesised to be deficient in DCD (Alloway, 2007; Piek et al., 2007; Tsai et al., 2012), may have impacted performance on the sequencing praxis, with increased cognitive demands present for the more complex longer sequences. Despite this, imitation deficits were also observed during the postural praxis, which involves online imitation (posture held by demonstrator for entire duration), demonstrating that these deficits persist beyond any working memory demands. Furthermore there are some limitations of the SIPT scoring procedures, with children not required to “mirror” what they see, with a score of 2 given when non-mirrored, but otherwise correct, postures or sequences are replicated. So any difficulties related to body posture orientation may be masked. We attempted to address this by performing additional analysis to look at exactly how many responses were correctly mirrored. An
additional limitation, is that one rater was not able to be blinded to group membership; we attempted to address this by having a second rater assess videos, with an acceptable agreement rate achieved.

Although no children had a formal diagnosis of ADHD or ASD, group differences were observed on the SNAP-IV and the CARS, with children in the pDCD group displaying more ADHD, and autistic-like symptoms based on parent responses. Despite being statistically significant, the differences on these scales are not likely to be clinically significant, with no children included who scored within the clinical symptom ranges. Additionally, it is important to note that both questionnaires include some movement-related questions, and questions surrounding engagement in movement activities, which may in part explain the slightly elevated scores seen within the pDCD group. One further limitation is that not all children in the pDCD group had a formal diagnosis of DCD, and inclusion was instead based on MABC-2 scores. Despite this, all participants in the pDCD group were recruited through the Paediatric Exercise Programs at the University of Western Australia (with their program attendance a result of the impact of their low motor skill proficiency on their daily living), the Western Australian Developmental Occupational Therapy group, and via referrals from Occupational Therapists and Paediatricians. We classified our sample as pDCD given the limitation that we did not utilise any measure of intelligence; despite this, all children from both groups were attending mainstream schooling. Furthermore, only males were included in this study. Given the gender differences in imitation performance (Chipman & Hampson, 2006, 2007), it was considered important to control for gender, however, further research to confirm these results in females may be beneficial.

There is now well documented evidence that a large number of children with DCD experience imitation deficits at a behavioural level. At a neurological level, however, we still have a limited understanding of the processes associated with these deficits. A greater understanding of which stage in the imitation process deficits are most pronounced, for example during the observation, planning, or performance components, would provide important information to be integrated in interventions. Exploration of action observation, imitation, and MNS activation at a neurological level, using neuroimaging studies may assist in providing information surrounding potential neurological underpinnings of the behavioural deficits observed in children with DCD and in formulating specific transferable/generalised targeted intervention approaches, and modifying existing
approaches (Brown-Lum & Zwicker, 2015; Reynolds, Thornton et al., 2015). The challenge will be to develop intervention approaches which demonstrate transfer to novel motor situations.

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CHAPTER 4: MOTOR IMAGERY ABILITY AND INTERNAL REPRESENTATION OF MOVEMENT IN CHILDREN WITH PROBABLE DEVELOPMENTAL COORDINATION DISORDER

Motor imagery ability and internal representation of movement in children with probable developmental coordination disorder

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Abstract
It has been hypothesised that deficits in the functioning of the mirror neuron system (MNS) and internal modelling may contribute to the motor impairments associated with DCD. These processes can be explored behaviourally through motor imagery paradigms. Motor imagery proficiency of children with and without probable DCD (pDCD) was examined using a complex hand rotation task to explore whether motor imagery strategies could be used during more complex tasks. Forty-four boys aged 7–13 years participated, 22 with pDCD (mean = 9.90 years ± 1.57) and 22 controls (mean = 9.68 years ± 1.53). Participants completed the task twice: with and without motor imagery instructions. Stimuli were presented in two rotational axes – palm/back, and eight 45° rotational steps. Both groups showed evidence of following the biomechanical and postural constraints of actual movements. Responses of children with pDCD were slower and less accurate than controls, with group differences increasing alongside task complexity. A greater impact of biomechanical constraints for accuracy was observed in the DCD group. The response characteristics of children with pDCD likely reflects a reduced capacity to mentally manipulate a body schema and reduced visuo-motor processing capabilities. Behaviourally, these processes are linked to MNS and internal modelling function, suggesting deficits in these systems may contribute to the movement difficulties characteristic of DCD.

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1. Introduction
Affecting up to 6% of school-aged children, developmental coordination disorder (DCD) is a condition characterised by impaired motor coordination and an inability to perform motor skills at an age appropriate level (American Psychiatric Association [APA], 2013; World Health Organisation [WHO], 2010). Although there is a relatively good understanding of the motor impairments impacting children with DCD, little is known about the underlying aetiology. While the definition states that the condition is not associated with any identifiable hard neurological signs, it has long been suspected that the motor difficulties experienced are neurologically based, with recent research exploring potential underlying neuro-cognitive mechanisms (Brown-Lum & Zwicker, 2015; Debrabant, Gheysen, Caeyenberghs, Van Waelvelde, & Vingerhoets, 2013; Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009; Langevin, MacMaster, Crawford, Lebel, & Dewey, 2014; Langevin,
The majority of motor imagery research supports the hypothesis that individuals with DCD are able to adopt a motor imagery strategy for simple tasks, however display different response patterns and accuracy levels compared to their typically developing counterparts (Deconinck et al., 2006). The internal rehearsal of movement, commonly referred to as motor imagery, is an important component of this system and studies have revealed activation of the same neural regions when imagining performance to that of the physical execution of a task (Decety, 1996; Page, Levine, & Leonard, 2007). Motor imagery has been demonstrated to be a valuable mechanism in both a clinical and sporting capacity to assist the acquisition and development of motor skills, likely as a result of these properties (Decety, 1996). In addition to assisting skill development, motor imagery is believed to represent one’s ability to plan movements and utilise internal forward models (Sirigu et al., 1996; Williams, Thomas, Maruff, Butson, & Wilson, 2006; Wilson et al., 2004) to predict movement outcomes prior to the availability of somatosensory feedback (Wolpert, 1997). As a cognition state which activates the MNS, poorer performance on motor imagery tasks by individuals with DCD may suggest some underlying dysfunction of this system (Lust, Geuze, Wijers, & Wilson, 2006; Reynolds et al., in press).

In hand laterality paradigms, differences in the use of one (back view) or two (back and palm views) rotational axes, number of rotational steps, the use or omission of motor imagery instructions, vision or occlusion of hands, and analysis methods, have the potential to have a large impact on the response patterns and whether a motor imagery strategy is used (ter Horst, van Lier, & Steenbergen, 2010). For example, because of the lower complexity level when only back view stimuli are presented, a motor imagery strategy might not be employed, and motor imagery deficits may have the potential to not be observed, (ter Horst et al., 2010). Inconsistent analysis of whether response patterns conform to biomechanical constraints (faster and more accurate responses for medial than lateral rotations, and back than palm view for palm down posture) makes it difficult to assess whether a motor imagery strategy has been used, and whether response deficits reflect motor imagery processes.

Motor imagery deficits appear to be more pronounced in individuals with DCD as task complexity increases (Caçola, Gabbard, Iiba, & Romero, 2014; Noten, Wilson, Ruddock, & Steenbergen, 2014) alongside an increased likelihood of engaging in a motor imagery strategy (ter Horst et al., 2010) this highlights the importance of using complex paradigms to explore motor imagery. Despite this, research has used tasks with only one axis of rotation within a trial. Only three hand rotation studies have explored back and palm responses in children with DCD (Deconinck et al., 2009; Noten et al., 2014; Wilson et al., 2004), with only two incorporating both rotational axes in the same trial (Deconinck et al., 2009; Wilson et al., 2004). One further study has comprehensively explored response patterns for back and palm in adults with pDCD (Hyde et al., 2014). The increased complexity associated with palm view stimuli is highlighted by the observation of Deconinck et al. (2009) that non-congruent hand posture resulted in a significant increase in response time for palm view stimuli but not for back view. These differences in complexity level and response patterns suggest that it may be of value to explore response time and accuracy measures for back and palm view responses separately.

Aside from this observation by Deconinck et al. (2009), no research in children with DCD has specifically analysed back and palm view comparisons in the context of biomechanical constraints and the ability to utilise a motor imagery strategy. Although back and palm response times were explored separately by Noten et al. (2014), no statistical comparisons of the two views were performed. As response accuracy is influenced by biomechanical constraints, and children with DCD been reported to have lower accuracy than controls, it is possible that the analysis of only correct responses may have understated the group differences observed. To date, there has been no assessment of palm view response accuracy during hand rotation tasks.
Motor imagery interventions in a clinical setting are currently receiving increased recognition as a mechanism to improve and restore motor function (Mulder, 2007; Page et al., 2007). As most motor skills are complex, motor imagery interventions often require imagery of complex actions to assist in skill acquisition and development. To improve our understanding of the potential use of motor imagery interventions in this population, it is important to establish whether biomechanical constraints are followed and motor imagery strategies are able to be adopted by children with DCD during more complex tasks.

It has been hypothesised that deficits in both the functioning of the mirror neuron system, and internal modelling, may contribute to the motor impairments associated with DCD (Adams et al., 2014; Reynolds et al., in press; Werner et al., 2012). These processes can be explored behaviourally through various methods, including motor imagery paradigms. The current body of hand laterality literature does suggest at least mild impairments in motor imagery for children with DCD. There has been no assessment of whether, similarly to back view tasks, palm view responses conform to biomechanical constraints to infer whether motor imagery strategies are able to be adopted for more complex tasks. The present study aimed to examine motor imagery proficiency of children with and without probable DCD (pDCD) using a complex hand rotation task. Specifically, it aimed to explore whether accuracy and response patterns conformed to biomechanical constraints for back and palm view stimuli. It was hypothesised that children with pDCD would demonstrate deficits in motor imagery, reflected in slower and less accurate response patterns than controls when judging lateral compared to medial rotations and palm view stimuli. It was further hypothesised that differences observed between the two groups would be greater for palm view responses, as task complexity increased.

2. Methods

2.1. Participants

Fifty children were recruited, comprising 25 children with pDCD and 25 age group matched controls. Three children in each group were excluded during analysis due to poor accuracy (see 2.3 Data analysis). Following analysis, participants included 22 males with pDCD aged between 7.92 and 13.33 years, and a convenience sample of 22 control males aged between 7.25 and 13.83 years. The lower age bound was selected based on previous research suggesting that children over the age of seven years are capable of using motor imagery to undertake hand rotation tasks (Butson, Hyde, Steenbergen, & Williams, 2014; Molina, Tijus, & Jouen, 2008; Sekiyama, Kinoshiba, & Soshi, 2014).

Movement proficiency was assessed using the Movement Assessment Battery for Children − 2 (MABC-2), which was chosen due to its reliability and validity (Henderson, Sugden, & Barnett, 2007). Children were considered to have pDCD if their movement performance fell at or below the 16th percentile and no known neurological or physical pathology was present. Children in the pDCD groups were recruited from the University of Western Australia’s Paediatric Exercise Programs, and via referrals from Occupational Therapists and Paediatricians. Due to the high levels of comorbidities associated with DCD, children with a diagnosis of ADHD or ASD were excluded to reduce confounding factors, and in addition the Swanson Nolan and Pelham-IV ADHD questionnaire ([SNAP]; Bussing et al., 2008) and the Childhood Autism Rating Scale ([CARS]; Schopler, Reichler, & Renner, 1988) were administered to measure symptoms of these disorders across both groups of participants.

Typically developing children were recruited from local community after responding to printed, email and word of mouth advertising. Children were considered to have typically developing movement proficiency if they scored at or above the 20th percentile on the MABC-2. Participants and their legal guardians provided informed consent for inclusion in the study, which was approved by the University of Western Australia Human Ethics Committee (RA/4/1/6492).

2.2. Test apparatus: hand rotation task

The ability to engage in motor imagery was assessed using a complex hand rotation task (Butson et al., 2014; Hyde et al., 2014). Single hand stimuli (12 cm × 10 cm) were presented on a laptop computer using E-Prime software (Psychology Software Tools, Pittsburgh, PA, USA), which allowed response time (to nearest 1 ms) and accuracy to be recorded. Participants were required to decide whether each stimulus presented was a left or a right hand as quickly and accurately as possible. The hands were high-resolution images displayed in the middle of the screen and presented in one of two rotational axes: palm view – the palm facing towards participant, or back view – the back of the hand facing the participant. An equal number of left and right hands were presented in a randomised order in 45° rotational steps between 0° (fingers pointing vertically) and 360°. Hand stimuli remained on screen until a response was recorded, or until 10 s had passed, in which case the stimulus disappeared and the next trial began (See Fig. 1).

Participants sat in front of the computer screen with their palms facing down and their hands covered following set up so that they could not use them as visual cues. Response keys (‘d’ for left hand, ‘k’ for right hand) were marked with blu-tack to ensure that they could be located under the hand cover. Participants were instructed to respond with their index finger. All participants first practiced with 10 back of hand stimuli at 0° of rotation baseline task, to ensure that they could distinguish their right from their left hand. Participants were required to score at least 7/10 on the baseline task. Prior to undertaking the experimental task, children were also shown a booklet with all the hand images that they would see to ensure that they understood the difference between the back and palm view images, and had a chance to see the rotated images. The task
consisted five practice trials followed by 80 test trials in a randomised order; each trial was followed by a random delay of between 2 s and 3 s.

Participants completed the hand rotation task twice: first with no imagery instructions (HR-NI) to obtain baseline measures not influenced by imagery instructions, and then with imagery instructions (HR-WI). Following Williams et al. (2006, 2008), for the HR-NI condition, participants were instructed to determine whether the stimulus was a left or a right hand as quickly and as accurately as possible, and to respond by pressing the appropriate key on the keyboard. They were not given any guidance on technique or strategy. In the HR-WI condition, participants were asked to imagine and feel their own hand in the position of the stimulus and to use this as a guide when deciding whether it was a left or right hand (see Appendix A). Again, they were asked to respond as quickly and accurately as possible. A series of movement tasks were undertaken between the two hand rotation tasks to eliminate practice effects.

2.3. Data analysis

All statistical analyses were run in Statistical Package for the Social Sciences (SPSS Inc., version 22). Participant characteristic distributions were assessed for normality, and parametric data was assessed using t-tests. Significance level for all comparisons was set at $p < .05$. For the experimental hand rotation task, each participant’s mean response time and accuracy (proportion correct) was calculated for each angle (for back view, palm view, combined back and palm view), as well as for overall palm and back view, and medial and lateral rotations. Following Butson et al. (2014), only children scoring at 50% (0.50) or above for accuracy for back view hands presented at 0° rotation (deemed the easiest stimulus presentation) were included in further analyses, rather than selecting an above chance accuracy cut-off level. Six children (three pDCD, three control) were excluded from the analysis on this basis, three of whom scored at less than 50% for the trial with no instructions, and a different three who performed at less than 50% for the with instruction trial.

2.3.1. Biomechanical constraints

It was considered important to undertake analyses to determine whether response patterns conformed to biomechanical constraints, as other forms of imagery (e.g. visual imagery) cannot be ruled out when these types of comparisons are not made. Because it is biomechanically more challenging to perform lateral (turning the hand outwards) compared to medial (inwards) rotations, if a motor imagery strategy is employed, lateral responses would be expected to be slower and/or less accurate. Similarly, when the hands are facing down, it is biomechanically more challenging to respond to palm view, compared to back view orientations (Adams et al., 2014). Response time and accuracy data were collapsed into medial (i.e. back left 45°, back right 315°), and lateral (i.e. back left 315°, back right 45°) stimuli, and two 2 (instructions: NI/WI) × 2 (View: Back/Palm) × 2 (Laterality: Medial/Lateral) × 2 (Group: pDCD/Control [TD]) mixed model ANOVA were performed, one for response time and the other for accuracy to explore whether response patterns conformed to biomechanical constraints. For all biomechanical constraints and response pattern analyses, multivariate tests were conducted to protect against violations to the assumption of sphericity.

2.3.2. Task accuracy

Task response accuracy was calculated for back, palm and combined views, for the WI and NI conditions. Between group differences were explored using a series of one way ANOVAs. Due to the high level of response accuracy variation observed within the pDCD group, the number of participants with accuracy below the lower bound of the 95th% confidence interval (CI) of control accuracy for each view was calculated, and analysed using chi square.
2.3.3. Response patterns
Following previous research (Butson et al., 2014; Noten et al., 2014), back and palm view responses were analysed separately. Hand rotation performance was analysed by collapsing medial and lateral rotations to provide mean values for responses from 0° to 180°. For example, data for the 90° and 270° trials were combined, as both stimuli were rotated 90° from upright. This resulted in eight trials at each angle (four left hand, four right hand) for both back and palm views. This is a common hand rotation analysis technique, used to increase the number of trials at each angle to increase the reliability of accuracy and response time estimates (Butson et al., 2014; Harris et al., 2000; Roelofs, van Galen, Keijsers, & Hoogduin, 2002). Collapsed response time and accuracy values were submitted to 2 (instructions: NI/WI) × 5 (angles: 0–180°) × 2 (group: pDCD/Control) mixed model ANOVAs.

Exploring the relationship between response time and accuracy can be undertaken by analysing mean inverse efficiency (IES) scores, calculated by dividing response time values by accuracy. IES analysis when accuracy levels are below 90% has been criticised (Bruyer & Brysbaert, 2011). IES values were not used as it was considered that they did not accurately represent/reflect the dataset, on the basis of the overall accuracy levels, and a small number of participants with a response accuracy level of 0% at certain angles.

3. Results
3.1. Participant characteristics
Group characteristics are presented in Table 1. Groups were matched for age, with no significant difference found between pDCD and control groups. As expected, the pDCD group had significantly poorer motor performance as compared to the control group on the MABC-2 (p < .001), with all members in the pDCD group falling below the 16th percentile, and all controls scoring between the 37th and 98th percentiles. Interestingly, there were significant differences in ADHD and autistic symptoms between groups (p < .05) even though none of the children with pDCD had a formal diagnosis of either disorder, or fitted into the clinical range based on the questionnaires. No significant differences were found in the screening assessments for handedness.

3.2. Biomechanical constraints
3.2.1. Response time
In line with the expected biomechanical constraints, significant main effects for view (Wilks’ Λ = .394, F(1,42) = 64.610, p < .001, n² = .066), and laterality (Wilks’ Λ = .633, F(1,42) = 24.353, p < .001, n² = .367) reflect faster responses to back compared to palm view stimuli and to medially, compared to laterally, rotated stimuli (Fig. 2). There were no significant interactions involving group, suggesting that both groups were utilising a motor imagery strategy and the group difference was not significant (F(1,43) = 3.387, p = .073, n² = .075). Furthermore, there were no significant interactions involving view, indicating that biomechanical constraints were followed for both back and palm view in both groups. There was a main effect for instructions (Wilks’ Λ = .548, F(1,42) = 34.666, p < .001, n² = .452), with responses faster after instructions were given; however there was no interaction between instructions and other variables, indicating that biomechanical constraints were evident both prior to, and after, motor imagery instructions were given.

3.2.2. Accuracy
Accuracy response patterns also followed biomechanical constraints (Fig. 3), with significant main effects for view (Wilks’ Λ = .588, F(1,42) = 29.416, p < .001, n² = .412), and laterality (Wilks’ Λ = .799, F(1,42) = 10.539, p < .002, n² = .201) reflecting more accurate responses to back compared to palm view stimuli, and to medially, compared to laterally, rotated stimuli (Fig. 3). There was a significant main effect for group (F(1,42) = 9.215, p = 0.004, n² = 0.180), with the typically developing group responding with higher accuracy levels than the pDCD group.

Table 1
Characteristics of participants (pDCD and typically developing peers).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>pDCD (n = 22)</th>
<th>TD (n = 22)</th>
<th>t</th>
<th>p</th>
</tr>
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<tr>
<td>Age (years)</td>
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<td>1.57</td>
<td>6.68</td>
<td>.53</td>
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<tr>
<td>MABC-2 (percentile)</td>
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<td>5.32</td>
<td>7.91</td>
<td>1.53</td>
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<td>CARS</td>
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<td>3.37</td>
<td>15.20</td>
<td>.37</td>
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<tr>
<td>SNAP-IV</td>
<td>.95</td>
<td>.55</td>
<td>.39</td>
<td>.34</td>
</tr>
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<td>Edinburgh handedness inventory</td>
<td>75.90</td>
<td>36.47</td>
<td>71.50</td>
<td>34.00</td>
</tr>
</tbody>
</table>

*p < .001.
The interaction between laterality and group approached significance (Wilks’ $\Lambda = .912$, $F(1, 42) = 4.073$, $p = .050$, $\eta^2_p = .088$), with pairwise comparisons demonstrating that only the DCD group responded less accurately to lateral compared to medial rotations ($p = .001$, $\eta^2_p = .248$). It is possible that the high accuracy levels displayed by the control group prevented an effect of laterality from being observed ($p = .390$, $\eta^2_p = .018$). In addition, pairwise comparisons indicated that children with DCD were less accurate than controls for lateral rotated stimuli ($p = .003$, $\eta^2_p = .193$). The interaction between view and group (Wilks’ $\Lambda = .912$, $F(1, 42) = 4.048$, $p = .051$, $\eta^2_p = .088$) fell just short of significance and was also followed up using pairwise comparisons. Although both groups followed biomechanical constraints, responding more accurately to back compared to palm stimuli (pDCD: $p < .001$, $\eta^2_p = .397$; controls: $p = .020$, $\eta^2_p = .122$), controls were more accurate than children with pDCD for both views (back view: $p = .029$, $\eta^2_p = .109$, palm view: $p = .006$, $\eta^2_p = .169$). As with response time, there was a significant main effect for instructions (Wilks’ $\Lambda = .608$, $F(1, 42) = 27.031$, $p < .001$, $\eta^2_p = .392$), but no interaction between instructions and any other variable.
3.3. Response patterns

3.3.1. Response time: back view

The control group were significantly faster than the pDCD group to respond to hands in the back view ($F(1,43) = 5.489$, $p = .024$, $g^2_p = .166$). Both groups were faster when provided with motor imagery instructions (Wilks’ $\Lambda = .545$, $F(1,43) = 35.095$, $p < .001$, $g^2_p = .455$) and slower to respond at larger angles of rotation (Wilks’ $\Lambda = .142$, $F(4,39) = 59.115$, $p < .001$, $g^2_p = .858$). No interactions were significant, though there was a trend towards significance in the interaction between group and angle (Wilks’ $\Lambda = .797$, $F(4,39) = 2.478$, $p = .060$, $g^2_p = .203$). Post-hoc analyses indicated that response time for both groups was slower as the angle of rotation away from $0^\circ$ increased; controls responded significantly faster than the DCD group for stimuli at $90^\circ$ ($p = .014$, $g^2_p = .135$) and $180^\circ$ ($p = .033$, $g^2_p = .103$), and response differences at $0^\circ$ approached significance ($p = .072$, $g^2_p = .075$). The effect of angle of rotation on mean response time is presented in Fig. 4.

3.3.2. Response time: palm view

The main effect for group did not reach significance ($F(1,43) = 3.337$, $p = .075$, $g^2_p = .074$) and there were no interactions involving group ($p > .05$). Both groups responded faster with instructions (Wilks’ $\Lambda = .601$, $F(1,43) = 26.746$, $p < .001$, $g^2_p = .389$) and were slower to respond at larger angles of rotation (Wilks’ $\Lambda = .370$, $F(4,39) = 16.601$, $p < .001$, $g^2_p = .325$).

3.3.3. Accuracy: back view

A significant interaction between angle and group was identified (Wilks’ $\Lambda = .706$, $F(4,39) = 4.052$, $p = .008$, $g^2_p = .294$) (Fig. 5). Pairwise comparisons indicated there was a significant decrease in accuracy paired with increased rotation away from zero in the pDCD group. In contrast, this pattern was not observed in the response patterns of the control group, for whom only responses for stimuli at $180^\circ$ were less accurate than other angles ($p < .05$). Furthermore, the control group were significantly more accurate than the pDCD group for responses at both $90^\circ$ and $135^\circ$. There was a main effect for instructions (Wilks’ $\Lambda = .715$, $F(1,42) = 16.760$, $p < .001$, $g^2_p = .285$), but no interaction involving group, suggesting that both groups were more accurate with instructions.

3.3.4. Accuracy: palm view

The control group were more accurate than the pDCD group when hands were presented in palm view ($F(1,43) = 9.623$, $p = .003$, $g^2_p = .186$), but there was no interaction between group and any other variable. Both groups were more accurate following instructions (Wilks’ $\Lambda = .735$, $F(1,42) = 15.132$, $p < .001$, $g^2_p = .265$), but there was no effect for angle on accuracy of performance (Wilks’ $\Lambda = .909$, $F(4,39) = .975$, $p = .432$, $g^2_p = .091$).

3.4. Task accuracy

Children with pDCD were found to be significantly less accurate than controls for the NI palm and combined views and all WI views. A significantly greater number of children with pDCD had accuracy levels below the lower bound of the 95th CI of the control group when compared to controls for NI and WI palm and combined views (Table 2). Seven participants with pDCD scored above the lower bound of the 95th CI of the control group for both back and palm view accuracy for each...
of the instruction conditions. Only four individuals in the pDCD group displayed an accuracy level above the lower bound of the 95th% CI of the control group for both back and palm view accuracy for both NI and WI trials; there were no features that distinguished individuals.

4. Discussion

4.1. Children with and without pDCD engage in motor imagery during the complex hand rotation task

Both groups showed evidence of following the biomechanical and postural constraints of actual movements, with and without motor imagery instructions. Consistent with the use of a motor imagery strategy, children with and without pDCD were faster when performing biomechanically less awkward medial compared to lateral rotations, and the posturally congruent back compared to palm view stimuli. Biomechanical constraints were also observed for accuracy in the pDCD group, however the absence of this effect in controls was likely the result of high accuracy levels. The ability of children with pDCD to employ a motor imagery strategy is consistent with previous research exploring back view and combined view hand laterality responses (Deconinck et al., 2009; Lust et al., 2006; Williams et al., 2006, 2008; Wilson et al., 2004). Extending the results of previous research, children with pDCD were also observed to be able to engage in a motor imagery strategy for the more complex palm view. The ability to use motor imagery during complex tasks is important in an intervention context, suggesting that children with pDCD have the potential to engage in motor imagery approaches to assist with movement acquisition.

A greater impact of biomechanical and postural constraints was observed for accuracy in the pDCD group, who also performed the task less accurately than controls. Although controls approached a ceiling effect for medial vs lateral responses (suggesting a greater capacity to proficiently undertake the task) which limits group comparisons of laterality responses, a biomechanical and postural effect was observed for hand view (back vs. palm responses), which is arguably more complex given the two axes of rotation component. Sekiyama et al. (2014) suggest an increased effect of biomechanical constraints is associated with a reduced capacity to mentally manipulate a body schema and a reduced visuo-motor processing capacity. They found the effects of biomechanical constraints on response time and accuracy to decrease with age, alongside a reduced reliance on a somatomotor action execution (influenced more by biomechanical constraints) strategy and a shift to the use body-related visuo-motor imagery to perform the hand rotation task (Sekiyama et al., 2014). Interestingly, using the same
task paradigm, adults with pDCD were also found to be less efficient at judging medial compared to lateral rotations, and palm compared to back orientations than controls (Hyde et al., 2014), suggesting these deficits persist into adulthood. In addition to impacting on hand laterality task performance, deficits in visuo-motor processing, possibly stemming from MNS and internal modelling dysfunction, have the potential to cause motor deficits and lead to delays in movement acquisition.

4.2. Slower and less accurate performance on the hand rotation task by children with DCD: increased difficulties with task complexity increases

Although children with pDCD were found to be able to engage in a motor imagery strategy for both back and palm view stimuli, as a group, their responses were less efficient than controls. This is consistent with other hand rotation research, which has found children with DCD to conform to the biomechanical constraints of the task but with slower response times and/or decreased accuracy, suggesting a less effective motor imagery strategy than controls (Deconinck et al., 2009; Lust et al., 2006; Williams et al., 2006, 2008). In conjunction with the observed increased impact of biomechanical constraints, these response patterns suggest that children with DCD may be less capable of performing egocentric perspective transformations and generating forward models, skills which are important in observational learning and motor skill production (Vogt, Taylor, & Hopkins, 2003; Williams et al., 2008).

As hypothesised, group differences became more apparent as the task complexity increased. As well as the greater drop off in accuracy as the degree of rotation away from zero increased observed in the pDCD group for back view responses, the pDCD group were significantly less accurate at the majority of angles for palm view stimuli. Similarly to the research by Noten et al. (2014), where deficits were observed for palm but not back view responses, the greater difficulties experienced as a group for the more complex palm view stimuli is reflected in the higher number of children with pDCD scoring outside the 95th percentile CI for accuracy of the control group. Although there were no group differences for response time for palm view stimuli, it is likely that inaccurate performance on the hand rotation task signifies a greater motor imagery deficit than slow but accurate responses (Williams et al., 2011). We argue this is likely because inaccurate performance is more likely to reflect an inability to successfully perform the task and to utilise motor imagery, whereas a slowing in performance suggests that motor imagery can be utilised but with reduced speed.

4.3. Extent of motor imagery deficits and response pattern variability within DCD group

Consistent with previous research, not all individuals with pDCD displayed motor imagery deficits (Katschmarsky et al., 2001; Lust et al., 2006; Wilson et al., 2001). A number of children with pDCD performed the hand rotation task with accuracy levels within the 95th percentile CI of the control group, however, this number decreased with increased task complexity. Only four individuals in the pDCD group performed at an accuracy level above the lower bound of the 95th percentile CI of the controls for both trials for all views, highlighting both the response variation, and the extent of motor imagery deficits in this population. This suggests that deficits in processes associated with motor imagery are likely contributing to the movement difficulties in the individuals with motor imagery deficits, rather than reduced movement proficiency translating to reduced imagery performance, in which case we would expect motor imagery deficits to be global. Further research to explore what characterises individuals with DCD who perform similarly to their typically developing peers on motor imagery tasks would be of interest.

4.4. Children with and without pDCD benefit from motor imagery instructions

Both groups appeared to benefit from the provision of motor imagery instructions, responding both faster and more accurately the second time they performed the task when provided with instructions. In contrast to interpretations provided in previous research, both groups appeared to benefit from instructions. Williams et al. (2006, 2008) examined changes in response patterns following the provision of motor imagery instructions, and suggest that children with DCD, in particular, those with more severe DCD, are less able to benefit from explicit imagery instructions. Although this interpretation was suggested, within group accuracy and response time changes were not explored in the initial paper (Williams et al., 2006), with the two instruction conditions analysed separately. It was inferred that a benefit was gained by the control group only based on between group accuracy differences only being evident following instructions (Williams et al., 2006). In the follow-up paper (Williams et al., 2008), paired sample t-tests indicated that while there were no improvements for the <5th percentile DCD group, the 6th–15th percentile DCD group were significantly more accurate following instructions, supporting the capability of some children with DCD to benefit from motor imagery instructions. Although it is possible that this effect within the pDCD group may also have been observed in this study had the sample size been larger, preliminary exploration of the dataset did not display differences between these group divisions. The benefit gained from motor imagery instructions by the pDCD group has important clinical implications; given that children with pDCD were able to motor imagery instructions to improve their performance, it is likely that targeted motor imagery intervention approaches can be developed to assist motor development in this population (Wilson, Thomas, & Maruff, 2002).
4.5. Limitations

Similarly to other motor imagery studies, this study was limited by an implicit assessment of an internal cognitive process. Although it is not possible to conclusively state that all children used motor imagery during the task, response patterns and verbal descriptions of strategies indicate that motor imagery was likely used by most individuals. A limitation shared with previous research to explore responses to motor imagery instructions, is that it is possible that performance improvements may have resulted from a practice effect rather than the provision of motor imagery instructions. This is particularly the case in this study given the high proportion of children from both groups reporting an imagery based strategy after their first attempt at the task. Although small practice effects have been observed for hand laterality paradigms across study sessions in adults (Boonstra et al., 2012), the extent of practice effects has not been explored in children, or within a single study session. Given that the accuracy improvements following instructions were greater than the 3% increases observed by Boonstra et al. (2012) following a 2 week inter-trial period, it is probable that the improvements reflect combination of improvements and practice. It is also likely however that the practice benefits would be greater during the same testing session. The addition of another group to undertake the task twice, but without extra motor imagery instructions would provide the relevant data to explore within-session practice effects.

In addition to the instructions, there are some other minor limitations. Although no children had a formal diagnosis of ASD or ADHD, group differences were observed on the SNAP-IV and the CARS, with children in the pDCD group displaying more autistic- and ADHD-like symptoms based on parent responses. Although this has the potential to introduce confounding comorbidity factors, it is important to note that both questionnaires include questions related to movement and engagement in movement activities. For example, the CARS includes questions about whether the child can perform age-appropriate movements (Schopler et al., 1988), and the SNAP-IV about engagement in leisure activities (Bussing et al., 2008). Despite being statistically significant, the between group differences were minimal and unlikely to be clinically relevant. Furthermore, only males were included in this study. Given the gender differences in MNS activation properties (Cheng, Tzeng, Decety, Imada, & Hsieh, 2006) it was considered important to control for gender, however, further research to confirm these results in females would be beneficial.

5. Conclusion

Children with pDCD were found to be able to engage in a motor imagery strategy during the complex hand laterality paradigm. Despite this, their responses were less efficient compared to controls, particularly as complexity increased. The strong effect of biomechanical constraints in the DCD group likely reflects a reduced capacity to mentally manipulate a body schema and reduced visuo-motor processing capabilities. Behaviourally, these processes are likely to be linked to MNS and internal modelling function, suggesting deficits in these systems may be causative mechanisms of the movement difficulties characteristic of DCD. The ability to of children with pDCD to improve their performance on the hand rotation task, either through instructions or through practice effect mechanisms, suggests the potential for clinical applications of motor imagery interventions in this population. Further research to explore the neural mechanisms of motor imagery deficits in DCD would provide a greater understanding of the neural mechanisms underlying the performance deficits characteristic of DCD.

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Appendix A. MI instructions

On the screen, a hand is going to come up and we want you to decide whether it’s a left hand or a right hand. If it is a left hand (point to their left hand), you will need to push the button with your left finger (‘k’ key), and if it is a right hand, you will need to push the button with your right finger (‘k’ key). The blu tack is on the keys, because your hands are going to be covered so you won’t be able to see them.

Remember that you will see the backs of hands, as well as the palms of hands, and that they will be rotated in all different positions (show familiarisation book).

A good trick to help you decide if it’s a left or right hand, that I’d like you to try, is to try to imagine and feel your own hands in the position that the hand comes up on the screen. So if the hand comes up upside down, imagine your own hand upside down and then compare it in your head to help you decide whether the hand on the screen is a left or right (demstrate with hand). Or if the hand on the screen is sideways, think about your hand sideways and compare it in your head. That way you can imagine your hands and rotate them around in your head if you need to (show your hand in front of the screen rotating to an upright position), so that you can work out which hand it is.

Just like last time, it is important that you decide quickly, but also important that you try to get the answer right.


INTRODUCTION TO SERIES THREE: NEUROIMAGING

The brain is a highly organised, adaptive, and complex structure which influences behaviour and functional capacity (Graham & Fair, 2015; Lenroot & Giedd, 2006). Disruptions to typical development of grey and white matter micro- and macrostructure, which have the potential to impact on functional activation patterns, have been identified to be characteristic of a range of neurodevelopmental disorders (Brambilla et al., 2003; Bush, 2011; Nickl-Jockschat et al., 2012; Richlan, Kronbichler & Wimmer, 2013; Valera, Faraone, Murray, & Seidman, 2007). Limited neuroimaging research has been undertaken to explore the neural origins of DCD, however, it is an expanding area of research (Brown-Lum & Zwicker 2015).

To date, hypotheses regarding the neural correlates of DCD have typically been drawn from behavioural studies. Given that the deficits displayed behaviourally are extensive, the motor deficits characteristic of DCD are unlikely to be isolated to one brain area (Zwicker et al., 2009). With advancements in technology, recent research has utilised a variety of different neuroimaging techniques, including electroencephalography (EEG), single-photon emission computed tomography (SPECT), and functional and resting state MRI neuroimaging techniques to examine areas of potential neurological dysfunction and investigate cortical activation patterns that may contribute to the motor deficits characteristic of DCD (Brown-Lum & Zwicker, 2015; Zwicker et al., 2009).

One technique to explore brain structure that has helped in the understanding of other neurodevelopmental disorders is voxel-based morphometry (VBM). VBM involves voxel-wise comparisons of grey matter volumes (modulated VBM data) or density/concentration (unmodulated VBM data), and tests for differences anywhere in the brain, rather than having a focus on differences in specific anatomical structures (Mechelli, Price, Friston, & Ashburner, 2005). Because grey matter volumes have been linked to performance (Draganski et al., 2004; Maguire, Woollett, & Spiers, 2006), and have been identified to be plastic (Draganski et al., 2004; Driemeyer, Boyke, Gaser, Büchel, & May, 2008), differences in grey matter volumes, in MNS or other regions, have the potential to contribute to the mechanisms of DCD. If differences in brain volumes exist, these may be able to help inform directions and processes to target for intervention approaches in this population. Although no lesions or hard neurological signs identifiable using standard clinical neurological examination are associated with DCD, two recent
studies, both utilising cortical surface area calculations (Caeyenberghs et al., 2016; Langevin et al., 2015), have identified differences in grey matter characteristics in this population. In other neurodevelopmental disorders, differences in brain structure have also been used to partially explain differences in functional neural activation patterns (Boddaert et al., 2004; Cortese & Castellanos, 2012; Kobel et al., 2010; Mueller et al., 2013; Silani et al., 2005).

One technique that has provided information on brain activation patterns of children with DCD is fMRI. Functional MRI is an indirect measure of brain activity by looking at changes in blood flow and oxygenation levels (blood-oxygen-level dependent (BOLD) response) in response to neural activity. The signal in fMRI is based on hydrogen atoms (protons) in water molecules within the brain that absorb energy in the presence of a magnetic field, and then the radiofrequency energy they emit to return to an equilibrium state and changes in the inhomogeneity of the magnetic field, are measured by the MRI scanner (Heeger & Ress, 2002; Poldrack, Mumford, & Nichols, 2011). BOLD fMRI exploits the fact that when a brain region becomes active, there is an associated increase in blood flow to the region to support neuronal activity, known as the haemodynamic response. As greater amount of oxygenated blood is directed to the active region than is required, there is an increase in the relative proportion of oxygenated blood (diamagnetic oxyhaemoglobin) to deoxygenated blood (paramagnetic deoxyhaemoglobin) (Heeger & Ress, 2002; Poldrack et al., 2011). Decreased levels of paramagnetic deoxyhaemoglobin induces inhomogeneity and results in a slower dephasing of the magnetic resonance signal, and a subsequent increased T2 signal, reflecting neural activity in the region (Heeger & Ress, 2002; Poldrack et al., 2011). Although this technique is useful for knowing which areas of the brain are active during certain tasks with a high spatial resolution, there are a number of limitations. These include the low temporal resolution of acquired data, restrictions of movement tasks that are able to be performed within the scanner, and activations are unable to be defined as excitatory or inhibitory in nature. That said, the technique has enormous potential to reveal brain regions that may contribute to the movement difficulties characteristic of DCD.

A small number of papers have used fMRI to explore possible neural correlates of DCD (Debrabant et al., 2013; Kashiwagi et al., 2009; Licari et al., 2015; Querne et al., 2008, Reynolds, Licari, Billington et al., 2015; Zwicker et al., 2010, 2011). Differences in results have characterised these studies, however, all report between group differences in
activation patterns. It is likely that these differences are the result of different methodological approaches, including differences in recruitment procedures (e.g. MABC-2 cut off, gender, handedness, and comorbidities), tasks utilised in scanner, analysis techniques, and statistical correction levels used. Although minimal differences in activation patterns have been identified in a large number of studies, differential brain activation patterns have been found in children with DCD compared to controls, who:

- In some studies have been identified to recruit a higher number of brain regions, suggesting they may use greater cognitive efforts to achieve similar levels of performance (Licari et al., 2015; Zwicker et al., 2010).
- In other studies demonstrate decreased activation of a number of brain areas including the parietal cortex, precuneus and the pars opercularis of the inferior frontal gyrus (Kashiwagi et al., 2009; Licari et al., 2015; Querne et al., 2008; Zwicker et al., 2010, 2011).
- Demonstrate different functional connectivity patterns with the left primary motor area (M1) during resting state (McLeod et al., 2014), as well as atypical within-and between-hemisphere functional connectivity strengths between the left and right primary and sensory motor (SM1) cortices, and a range of regions (McLeod et al., 2016).

Differences in activation patterns in MNS regions have been identified in a number of fMRI studies (Debrabant et al., 2013; Kashiwagi et al., 2009; Licari et al., 2015; McLeod et al., 2014, 2016; Querne et al., 2008; Zwicker et al., 2010, 2011). Only one fMRI study, however, performed by the researchers involved in this thesis, has been undertaken with a specific aim to explore MNS function in children with DCD (Reynolds, Licari, Billington et al., 2015). In this study, brain activation patterns were examined during the observation, execution and imitation of a finger sequencing task (Reynolds, Licari, Billington et al., 2015). Children with DCD were found to have significantly reduced activation compared to controls during the observation condition in the pars opercularis of the inferior frontal gyrus, the precentral gyrus, middle temporal gyrus, posterior cingulate, and precuneus. In the region of interest analyses, an interaction effect between group and task condition was revealed in the pars opercularis, a key MNS region, with the control group displaying greater activation during imitation compared to the DCD group, who showed a large deactivation in this region during imitation. Although suggested to provide preliminary evidence for MNS dysfunction, and the adoption of different neural strategies by children with DCD to perform the different task conditions,
the lack of expected MNS signal increase from execution to imitation at a whole brain level was interpreted as a potential learning effect which may have prevented group differences during execution and imitation from being identified. To address this, the authors (Reynolds, Licari, Billington et al., 2015) suggested further research be undertaken to explore hypothesised MNS dysfunction on a simpler task, one that does not require practice prior to scanning (to circumvent the possible effect of motor learning), but still achievable for the target population. To further explore the MNS across a range of activation states, Reynolds, Licari, Billington et al., (2015) also suggested incorporating motor imagery into the fMRI task paradigm.

Series 3 explores possible neural correlates of DCD and MNS function at a neurological level. The first study in the series, published in *International Journal of Developmental Neuroscience*, explores brain morphology utilising VBM to characterise relative grey matter volumes. The second study explores the functioning of the MNS and brain activation patterns during the observation, imagery and performance of an unpractised finger abduction/adduction task.


The aims of this study are to:

- Explore grey matter volumes in children with and without DCD using voxel based morphometry.
- Gain a better understanding of the brain structure-function relationship in children with DCD.
- Explore the relationship between grey matter volumes, and motor proficiency in children with and without DCD.

It is hypothesised that:

- Differences in grey matter volumes will exist in children with DCD compared to typically developing controls, specifically in motor regions and areas identified to have activation differences in fMRI studies.

The aims of this study are to:

- Explore MNS function in children with and without DCD at a neurological level using fMRI.
- Explore neurological correlates of imitation and motor imagery in children with and without DCD.
- Explore MNS activation at whole brain and region of interest levels.

It is hypothesised that:

- Children with DCD will have different activation patterns compared to children without DCD in one or a combination of MNS areas.
- Group differences will be greatest during the imitation condition.

Limitations and delimitations

There are a number of limitations and delimitations specific to the neuroimaging studies:

- The sample size for the fMRI study, although comparable with others, is still relatively small.
- Children with co-occurring conditions were excluded from this research, to prevent a confounding nature of imitation deficits in other neurodevelopmental disorders. The addition of co-morbid groups would be beneficial for future research to explore the overlap in neural presentations across disorders.
- This study is delimited by the inclusion of boys aged between 8 and 13 years of age. Only right handed boys were scanned, to avoid any activation differences related to lateralisation and/or gender.
- Because no behavioural measures were recorded for the task performed in scanner, there are no behavioural measures to confirm that children imagined the task correctly during the motor imagery condition. Despite this, children reported that they were imagining performing the task, and extensive activation was identified during this condition. In addition, although a simple task was used due to scanning constraints, the imagery of simple tasks has been shown to activate
cortical networks comparable to those activated during complex imagined tasks (Szameitat et al., 2007).

- The cerebellum was not scanned in the fMRI study. Although this region may be implicated in DCD (Zwicker et al., 2010, 2011), as the focus of this research project was on the MNS, a trade-off was made to scan a smaller volume, and increase the number of task presentations in the fMRI protocol whilst maintaining a scan length appropriate for the paediatric sample.

- Children in the DCD group were not required to have a diagnosis. Diagnosis is not always pursued in Australia, even when children are actively participating in a range of therapies. Furthermore, this disorder is not well recognised in the medical community. As a result, the DCD groups have been classified as probable DCD.

- The majority of the participants with probable DCD were recruited from The University of Western Australia’s Paediatric Exercise Programs. Most participants were receiving a movement therapy service, and/or have proactive parents seeking a service.

- Although there were between group differences in imitation and motor imagery measures, participants with DCD in the neuroimaging studies were not required to have a set level of motor imagery or imitation deficits. Because VBM had not been performed in DCD we undertook an exploratory approach and did not use this behavioural measure as a selection criterion. For the fMRI study, we wished to explore areas of brain activation differences linked to DCD, rather than potentially areas linked to imitation and motor imagery deficits alone. Either recruitment approach is valid, however, examining brain activation patterns of a subgroup of children with deficits in these areas would be of value in the future.

- Children who participated in the fMRI study were also included in the two behavioural studies.
**CHAPTER 5: REDUCED RELATIVE VOLUME IN MOTOR AND ATTENTION REGIONS IN DEVELOPMENTAL COORDINATION DISORDER: A VOXEL BASED MORPHOMETRY STUDY**

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Reduced relative volume in motor and attention regions in developmental coordination disorder: A voxel-based morphometry study

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A B S T R A C T

Background and objectives: Developmental coordination disorder (DCD) is a prevalent childhood movement disorder, impacting the ability to perform movement skills at an age appropriate level. Although differences in grey matter (GM) volumes have been found in related developmental disorders, no such evidence has been linked with DCD to date. This cross-sectional study assessed structural brain differences in children with and without DCD.

Methods: High-resolution structural images were acquired from 44 children aged 7.8–12 years, including 22 children with DCD (≤ 16th percentile on MABC-2; no ADHD/ASD), and 22 typically developing controls (≥ 20th percentile on MABC-2). Structural voxel-based morphology analysis was performed to determine group differences in focal GM volumes.

Results: Children with DCD were found to have significant, large, right lateralised reductions in grey matter volume in the medial and middle frontal, and superior frontal gyri compared to controls. The addition of motor proficiency as a covariate explained the between-group GM volume differences, suggesting that GM volumes in motor regions are reflective of the level of motor proficiency. A positive correlation between motor proficiency and relative GM volume was also identified in the left posterior cingulate and precuneus.

Conclusions: GM volume reductions in premotor frontal regions may underlie the motor difficulties characteristic of DCD. It is possible that intervention approaches targeting motor planning, attention, and executive functioning processes associated with the regions of reduced GM volume may result in functional improvements in children with DCD.

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1. Introduction

Developmental coordination disorder (DCD) is a condition characterised by an inability to perform fine (hand writing and shoelace tying) and gross motor skills [playing sport and getting dressed] at an age appropriate level [American Psychiatric Association, 2013]. DCD affects approximately 6% of school-aged children, making it the most common childhood movement disorder [American Psychiatric Association, 2013]. Such a broad range of deficits not only impacts performance of daily tasks, but also contributes to secondary long-term health consequences, including reduced engagement in physical activity and social activities [Poulsen and Ziviani, 2004; Zwicker et al., 2013], and increased risk of low self-esteem, anxiety, and depression [Jarus et al., 2011; Zwicker et al., 2013]. The coordination difficulties seen in 50–70% of children with DCD persist into adolescence and adulthood [American Psychiatric Association, 2013]. In young adults,
DCD creates new challenges at a stage of life when they are gaining a higher level of independence; DCD continues to impact on motor tasks, such as learning to drive a car, activities requiring high levels of executive functioning, and reduced perceptions of physical, social, and academic competence (Cantell et al., 2003; Kirby et al., 2011). Despite the relatively good understanding of the behavioral motor impairments experienced by children with DCD, the aetiology, and neurological origins long suspected to contribute to such deficits remain unclear (Brown-Lum and Zwicker, 2012).

Disruptions to development of grey (GM) and white matter (WM) structure have been linked to a range of neurodevelopmental disorders which often co-occur with DCD, and also include a motor deficit component, including autism spectrum disorder (ASD; Boddart et al., 2004; Brambilla et al., 2003; Mengotti et al., 2011; Mostofsky et al., 2007; Nickl-Jockschat et al., 2012), attention deficit hyperactivity disorder (ADHD; Carmona et al., 2005; Kobel et al., 2010; Langevin et al., 2015; Valera et al., 2007), and developmental dyslexia (Eckert et al., 2005; Richlan et al., 2013; Silani et al., 2005). Furthermore, differences in GM volumes in these populations have also been used to partially explain differences in functional neural activation patterns (Roddaart et al., 2004; Cortese and Castellanos, 2012; Kobel et al., 2010; Mueller et al., 2013; Silani et al., 2005).

To date, there have been a limited number of studies that have examined the potential of brain macrostructural differences that contribute to DCD. A recent cortical thickness study found that children with DCD exhibited localised structural differences in the temporal pole, a region typically associated with attentional functions (Langevin et al., 2015). One other recent study explored the structural connectome in DCD based on cortical thickness patterns, and identified clustering coefficient alterations compared to controls in the right lateral orbitofrontal cortex (Caytenberghs et al., 2016). While measures of cortical thickness provide some insight into GM morphometric structure, analysis of volume, which takes into account cortical surface area and folding, has the potential to provide a more detailed understanding. The aim of the present study was to examine global and regional GM volume in children with DCD compared to a group of typically developing age-matched controls using voxel-based morphometry (VBM) and to assess whether GM volumes correlate with motor proficiency, independent of diagnosis. We hypothesize that GM structural differences may be found in regions in which different activation patterns have been identified in previous functional studies, including the primary motor cortex (McLeod et al., 2014), precentral gyrus (Reynolds et al., 2015a), medial frontal gyrus (Debrabant et al., 2013; Zwicker et al., 2011), superior frontal gyrus (Licari et al., 2015; Zwicker et al., 2016), and inferior parietal lobule (Kashiwagi et al., 2005; Zwicker et al., 2012). A score ≥20th percentile was used as a cut-off for the control group, indicating a motor proficiency within the normative range. Due to the high level of comorbidity of DCD with other neurodevelopmental disorders, children with a diagnosis of either ASD, or ADHD, or any neurological conditions (Criterion D) were excluded.

Ethics approval was obtained from the Human Research Ethics Committee at UWA for both studies (RA/4/1/2572, Licari et al., 2015; RA/4/1/5275, Reynolds et al., 2015a), as well as from Princess Margaret Hospital for Children (RA: 1804) for the first study (Licari et al., 2015). Written consent was obtained from parents and ongoing verbal assent from participants throughout each phase of the study.

2.2. MRI image acquisition

All images were acquired at the Department of Radiology at Sir Charles Gairdner Hospital, Perth, Australia over a time period from October 2010 to July 2012. Study one images were acquired in 2010 using a 3T Philips Achieva TX scanner with an 8-channel head coil. Study two images were acquired in 2012 on a 3T Philips Magnetic Resonance scanner, with participants wearing an 8-channel head coil. In both data collection periods, high-resolution anatomical images were acquired using the same parameters (T1-weighted 3D FFE 160 slices 0.575 × 0.575 × 1 mm). Despite replicating the T1 scanning parameters, multi-scanner studies still run the risk of confounding results due to differences in scanner site (Pardoe et al., 2008; Stormington et al., 2008). Therefore, a 2 × 2 group × scanner factorial model was performed (cluster level correction P(FWE) < 0.05) to determine if scanner site would influence findings (Pardoe et al., 2008; Stormington et al., 2008). Although the main effect of scanner model resulted in increased GM volume (cluster level correction P(FWE) < 0.05, k = 1151) in the bilateral culmen (x,2, y = −33, z = −13; x,0, y = −35, z = −6; x,2, y = −38, z = −18, k = 2657), no group × scanner interactions for GM volume were identified, indicating that the scanner site was unlikely to influence group differences in activation (see results section).

Visual inspection of the structural images for inclusion, and conversion to Analyze files was done using MRicro (version 1.40; Rorden and Brett, 2000). At this stage, six participants (four DCD, two control) were excluded due to excessive head movement to leave a final sample of 44 boys (22 DCD, 22 controls).

2.3. Image processing

All pre-processing and VBM data analysis was carried out using Statistical Parametric Mapping 12 software (SPM12, Wellcome...
Department of Cognitive Neurology, London) in MATLAB 2014a (MathWorks, Natick, MA). Structural image pre-processing was performed using the VBM protocol (Ashburner 2010; Ashburner and Friston, 2000) in which structural T1 images were first approximately aligned with AC-PC space and segmented into GM, WM and cerebro-spinal fluid (CSF) based on SPM12 tissue probability maps. A Diffeomorphic Anatomical Registration Through Exponentiated Lie Algebra (DARTEL) algorithm (Ashburner, 2007) was implemented in order to iteratively warp GM and WM images from both data sets to a study-specific average template (Stonnington et al., 2008). The warped tissue maps were then modulated using DARTEL Jacobian determinants maps, which represent volume changes due to non-linear spatial normalisation, in order to ensure that the total amount of each tissue remained the same as it was in the pre-warped images. Following modulation, GM maps were affine transformed to Montreal Neurological Institute (MNI) space and smoothed with a full-width half-maximum Gaussian kernel of 10 mm (Ashburner 2010), with a final isotropic resolution of 1.5 mm.

2.4. Statistical analysis

All statistical models were set up using SPM12 (Wellcome Department of Cognitive Neurology, London). Global normalisation was applied using proportional scaling to correct for total intracranial volume (TIV) differences between individual participants (TIV: GM+WM+CSF; Pell et al., 2008). This corrects for volume differences that are a result of brain size differences between participants, such that the final data reflects the relative volume of each region, after correcting for TIV. Age was included as a covariate in all models. Unless otherwise stated, when estimating 2nd level contrasts uncorrected voxel height thresholds were set at \( p < 0.001 \) and a family-wise error (FWE) corrected threshold of \( p < 0.05 \) (family-wise error (FWE) corrected; Friston et al., 1996; Nichols and Wille, 2012). For all models, explicit masking was applied with inclusive GM masks created using the SPM Masking Toolbox (Ridgway et al., 2009), to obtain only GM areas (based on study specific average GM images) that were included in the analysis. All significant clusters extracted in MNI coordinates were converted to Talairach coordinates, and the nearest GM structure and Brodmann area identified using the Co-Planar Stereotaxic Atlas of the Human Brain (Talairach and Tournoux, 1988).

### 3. Results

#### 3.1. Participant characteristics

Participant brain volume characteristics are presented in Table 1. Groups were matched for age, with no significant difference identified between DCD and control groups (t = 0.611, \( p = 0.545 \); group age-matching was performed in both individual studies). The DCD group (mean MABC-2 percentile (SD) = 3.7 ± 4.0) displayed significantly poorer motor proficiency compared to the control group (mean MABC-2 percentile (SD) = 48.6 ± 21.1) on the MABC-2 \( (t = 9.821, p < 0.001) \). The DCD group MABC-2 percentiles ranged between the 0.1–16th and the controls from the 25th–98th percentiles. No significant differences were identified for global GM, WM, or total intracranial volume between groups \( (p > 0.05) \).

#### 3.2. Between-group grey matter voxel-based morphometry results

A \( 2 \times 2 \) (group \( \times \) scanner) factorial model \( (p_{\text{FWE}} < 0.05, \text{cluster level } k = 1151) \) was used to estimate group differences in regional GM volume. Controls were found to have one large area of increased GM volume compared to the DCD group in the frontal (middle, medial and superior frontal gyrus) lobe of right hemisphere (Table 2, Fig. 1). There were no regional GM volume differences for the DCD > TD contrast \( (FWE \text{ cluster corrected}) \), even when re-run at a less stringent level of \( p < 0.001 \), uncorrected. The GM group contrast analysis was re-run with motor proficiency (log normalised MABC-2 percentile scores; Henderson et al., 2007) specified as a mean-centered covariate within the \( 2 \times 2 \) (group \( \times \) scanner) factorial model; the addition of motor proficiency as a covariate explained the between-group GM volume differences, with no between-group differences persisting at \( p_{\text{FWE}} < 0.05, \text{cluster level } k = 1154 \).

#### 3.3. Grey matter volume correlations with movement proficiency

In order to determine if regional GM volume correlated with movement proficiency \( (\text{measured using the MABC-2}; \text{Henderson et al., 2007}) \), the two groups were collapsed and a full factorial model was run (scanner model as a factor) with log\(_{10}\) transformed MABC-2 percentile scores specified as a mean-centered covariate \( (p_{\text{FWE}} < 0.05, \text{cluster level } k = 1177) \). One cluster in the left pre-cuneus and posterior cingulate \( (k = 1298, x = −15, y = −49, z = 16) \) was identified to be positively correlated with movement profi-

### Table 1: Participant brain volume characteristics.

<table>
<thead>
<tr>
<th>Group</th>
<th>Mean (SD)</th>
<th>t</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCD (N = 22)</td>
<td>0.88 (0.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Controls (N = 22)</td>
<td>0.89 (0.06)</td>
<td>0.414</td>
<td>0.667</td>
</tr>
</tbody>
</table>

### Table 2: Grey matter relative volume differences for Controls > DCD (cluster level correction, \( p_{\text{FWE}} < 0.05 \)).

<table>
<thead>
<tr>
<th>Anatomical Region</th>
<th>Cluster (k)</th>
<th>Talairach Coordinates</th>
<th>Brodmann Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control &gt; DCD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Superior Frontal Gyrus (R)</td>
<td>1587</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>Middle Frontal Gyrus (R)</td>
<td>30</td>
<td>20</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td>29</td>
<td>7</td>
<td>40</td>
</tr>
</tbody>
</table>
considerable overlap with the TD > DCD contrast was identified in run at a less stringent significance level (p < 0.001, uncorrected), considerable overlap with the TD > DCD contrast was identified in the right medial and middle frontal, and superior frontal gyri. The use of uncorrected statistics may overstate this overlap, and should be interpreted with caution. No GM regions were negatively correlated with motor proficiency.

4. Discussion

The present study used VBM in order to examine whether there are focal differences in GM volume in children with DCD compared to controls. Typically developing controls were identified to have significantly increased right lateralised relative GM volume compared to children with DCD in frontal motor and attention regions. The addition of motor proficiency as a covariate explained the between-group GM volume differences, suggesting that GM volumes in motor regions are likely to reflect level of motor proficiency. Furthermore, GM volume in the left precuneus, extending into the posterior cingulate, was positively correlated with motor proficiency scores. Our findings were not consistent with the previous study of structural abnormalities in DCD (Langevin et al., 2015), which identified thinner cortex in the right temporal pole compared to controls. This disparity is probably due to methodological differences, with VBM providing a differing profile of structural morphology. These results are the first to suggest that focal differences in underlying brain structure, which are not identifiable through standard clinical neurological examination, may contribute to DCD and motor proficiency in general.

The reductions in GM volume in DCD in the right prefrontal and frontal lobe regions support the motor planning and execution, attentional (Tsai et al., 2009), working memory (Alloway, 2007; Tsai et al., 2012), and executive functioning deficits associated with DCD (Piek et al., 2007; Piek et al., 2004; Wilson et al., 2013). The medial frontal gyrus incorporates pre-motor regions, and in addition to the role played in motor planning and control (Hanakawa et al., 2008), this region has been implicated in executive control, decision making, inhibitory control (Garavan et al., 1999; Talati and Hirsch, 2005), and reorienting attention, particularly from exogenous to endogenous control (Japere et al., 2015). Deficits in motor planning have been observed behaviorally in children with DCD using assessments of Japere, end-state comfort, and dynamic planning, where children with DCD have been identified to perform less accurately or efficiently as controls (Adams et al., 2014; Reynolds et al., 2015a; Wilson et al., 2013). At a neurological level, differences in both cerebral blood flow and event related potentials during motor control (Zwicker et al., 2010, 2011), and visuomotor tasks (Kashigawa et al., 2009; Pangelinan et al., 2013) have been identified in fMRI and EEG studies of children with DCD.

The superior frontal gyrus has also been reported to be involved in working memory (Draganski et al., 2004; Driemeyer et al., 2008), and electrophysiological event related potential measures during spatial working memory (Tsai et al., 2012) and visuospatial attention (Tsai et al., 2009) EEG tasks have also been identified in children with DCD. The identified reductions in GM volume are consistent with behavioral research demonstrating motor planning and execution, attentional, and executive functioning deficits associated with DCD. Given the links between increased brain volume and better performance (Draganski et al., 2004; Maguire et al., 2006), this finding suggests that underlying structural differences in motor and attention regions may be one factor contributing to the motor impairments that are characteristic of DCD.

The positive correlation between the left precuneus/posterior cingulate volumes and motor proficiency suggests that the processes associated with these regions may, in part, underlie some of the deficits seen in children with DCD. The precuneus is thought to influence a wide range of highly integrated tasks that have the potential to impact on motor control, including visuo-spatial imagery (e.g., coordination of motor behaviour, attention-orientation, shifting, and tracking, and mental and motor imagery), as well as in self-processing (e.g., adopting a first person perspective), and episodic memory retrieval (Cavanna and Trimble, 2006). The cingulate cortex is an integrative centre (Pearson et al., 2011), with the posterior cingulate involved in both motor and attention networks/processes.

The results of this VBM study suggest that focal differences in underlying brain structure, and particularly GM volume, may contribute to the movement difficulties associated with DCD. In healthy populations, larger GM volumes in relevant brain regions have been associated with an increased level of performance and skill (Draganski et al., 2004; Maguire et al., 2006). Furthermore, increases in GM volumes have been identified following changes in function resulting from targeted practice and learning of skills (Draganski et al., 2004; Driemeyer et al., 2008). Given the plasticity of GM volume, it is possible that neurorehabilitation intervention approaches targeting the processes associated with regions of reduced GM volume, such as motor planning, attention, and executive functioning based interventions, may result in functional improvements in children with DCD. Future research to extend our understanding of GM volumes using VBM, quantitative multi-parameter mapping (Weiskopf et al., 2013) and Voxel-Based...
Quantification (VRQ; Callaghan et al., 2014) have the potential to enhance our understanding of DCD. Given the high level of comorbidity with other neurodevelopmental disorders, VBM studies to explore the possible overlap or distinct patterns of GM volumes differences in DCD and other neurodevelopmental disorders with associated movement difficulties would help inform our understanding of the possible shared neural origins of these disorders, and the impact of brain volumes on movement proficiency. A limitation of VBM is that it does not provide information relating to WM microstructure or tract integrity. Given the limited research that has been undertaken to examine WM morphology in children with DCD (Langvin et al., 2014; Werner, 2013; Zwicker et al., 2012), the use of diffusion tensor imaging with a large number of diffusion directions and advanced fibre tractography methods (e.g., constrained spherical deconvolution; Farquharson et al., 2013) also represents a promising research direction.

5. Conclusions

Although no hard neurological signs are currently associated with DCD, it is possible that differences in GM volume in premotor and frontal regions may correlate with the motor deficits associated with this disorder. These regions are involved in motor planning and execution, attention, and executive functioning, deficits of which are all characteristic of DCD. A more comprehensive understanding of grey and white matter structural morphology in DCD will increase our understanding of the neural contributions to this disorder, the brain structure-function relationship, and may optimize intervention approaches.

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Conflict of interest

All authors have indicated they have no potential conflicts of interest to disclose.

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References


CHAPTER 6: MIRROR NEURON SYSTEM ACTIVATION IN CHILDREN WITH DEVELOPMENTAL COORDINATION DISORDER: A REPLICATION FUNCTIONAL MRI STUDY

Abstract

It has been hypothesised that abnormal functioning of the mirror neuron system (MNS) may lead to deficits in imitation and the internal representation of movement (motor imagery), contributing to the motor impairments associated with developmental coordination disorder (DCD). Using functional magnetic resonance imaging (fMRI), this study aimed to examine brain activation patterns in children with and without probable DCD (pDCD) on a finger adduction/abduction task during four MNS activation states: observation, motor imagery, execution, and imitation. Nineteen boys aged 8.25 – 12.75 years participated, including 10 children with pDCD (≤16th percentile on MABC-2; no ADHD/ASD), and nine typically developing controls (≥20th percentile on MABC-2). Even though children with pDCD displayed deficits behaviourally on imitation (Sensory Integration & Praxis Test Subtests; Ayres, 1989) and motor imagery (Reynolds, Licari, Elliott et al., 2015) assessments, no differences in MNS activation were seen between the pDCD and control groups at a neurological level, with both groups activating mirror regions effectively across conditions. Small clusters of decreased activation during imitation were identified in non-mirror regions in the pDCD group, including the thalamus, caudate, and posterior cingulate - regions involved in motor planning and attentional processes. The results of this study do not support the MNS dysfunction theory as a causal mechanism of the motor deficits seen in this disorder. Further research is required to explore attentional and motor planning processes and how they may interact at a network level.
6.1 Introduction

Learning via imitation and through the internal representation of movement is thought to be one of our primary modalities of learning and consolidating new motor skills. The mirror neuron system (MNS) is a fronto-parietal network of multimodal neurons in the central nervous system that has an integrative role in these processes, firing when a person observes, imagines, executes, and imitates actions (Decety, 1996; Iacoboni & Dapretto, 2006). This network has recently been hypothesised to contribute to the motor impairments that are characteristic of developmental coordination disorder (DCD; Licari et al., 2015; Reynolds, Licari, Billington, et al., 2015; Reynolds, Thornton, et al., 2015; Werner, Cermak, & Aziz-Zadeh, 2012). Evidence for MNS deficits in DCD at the behavioural level can be drawn from deficits in imitation (Elbasan, Kayihan, & Duzgun, 2012; Reynolds, Kerrigan, Elliott, Lay, & Licari, 2016; Sinani, Sugden, & Hill, 2011; Zoia, Pelamatti, Cuttini, Casotto, & Scabar, 2002) and motor imagery performance (Adams, Lust, Wilson, & Steenbergen, 2014; Reynolds, Licari, Elliott, Lay, & Williams, 2015). To extend our knowledge of this system, further research is required to increase our understanding of the functioning of this system at a neurological level (Reynolds, Licari, Billington, et al., 2015; Reynolds, Thornton, et al., 2015). Functional activation differences in mirror neuron regions may underlie the motor, imitation, and motor imagery impairments, and contribute to the movement difficulties characteristic of children with DCD.

The MNS circuit in humans is believed to incorporate the pars opercularis (BA44) of the inferior frontal gyrus (IFG; Kilner, Friston, & Frith, 2007), the adjacent ventral premotor cortex (PMv; BA6; Buccino et al., 2001; Grafton, Arbib, Fadiga, & Rizzolatti, 1996; Rizzolatti et al., 1996) and the rostral inferior parietal lobule (IPL; BA 39 and 40; Arbib, Billard, Iacoboni, & Oztop, 2000; Caspers, Zilles, Laird, & Eickhoff, 2010; Rizzolatti & Craighero, 2004; Figure 6.1). These mirror regions fire when one actively observes, imagines, executes, or imitates a movement, with a progressive increase in functional MRI (fMRI) blood-oxygen-level dependent (BOLD) signal from observation through to imitation (Aziz-Zadeh, Koski, Zaidel, Mazziotta, & Iacoboni, 2006). Another important area involved in the MNS is the superior temporal sulcus (STS). Although STS neurons are not activated during motor execution (Aziz-Zadeh, Koski, et al., 2006; Buccino, Solodkin, & Small, 2006), this area is thought to be connected with mirror regions via the arcuate fasciculus and parallel tracts (Catani, Jones, & ffytche, 2005; Iacoboni et al., 1999; Rizzolatti, Fogassi, & Gallese, 2001) and is believed to play an important role in
visual input during observation by coding for goal-directed and meaningful actions (Jellema, Baker, Wicker, & Perrett, 2000; Perrett et al., 1989). The human MNS has been proposed to represent a ‘dynamic feedback control system’ (Schippers & Keysers, 2011, p. 40) that supports both forward and inverse internal modelling processes, with a primary predictive control function (Figure 6.1).

Figure 6.1. Information flow in the mirror neuron system (STS: superior temporal sulcus, IPL: inferior parietal lobule, PMv: ventral premotor cortex, IFG: inferior frontal gyrus; (created using images from BrainVoyager Brain Tutor: http://www.brainvoyager.com/products/braintutor.html; Goebel, Esposito, & Formisano, 2006).

At a behavioural level, research exploring deficits in imitation and motor imagery performance has been used as evidence to support the MNS dysfunction hypothesis of DCD (Reynolds, Thornton, et al., 2015; Werner et al., 2012). Imitation provides a foundation for skill learning via observation and is an important mechanism from a young age (Arbib et al., 2000; Billard & Arbib, 2002). The use of motor imagery, on its own, and in conjunction with traditional motor execution training, has repeatedly been shown to improve motor skill performance (Buccino et al., 2006) and assist motor skill development and acquisition (Decety, 1996). Imitation of learned, meaningful skills (Dewey, 1993; Sinani et al., 2011; Zoia et al., 2002) and non-meaningful simple and
complex gestures (Elbasan et al., 2012; Goyen, Lui, & Hummel, 2011; Reynolds et al., 2016) have been shown to be performed poorly by children with DCD, who make more errors and respond slower to visual cues. In addition to imitation deficits, children with DCD have difficulty with motor imagery. Results on mental rotation and other motor imagery tasks suggest that children with DCD are able to adopt the use of a motor imagery strategy; however, make slower, less accurate responses to stimuli (Adams et al., 2014; Reynolds, Thornton, et al., 2015).

In addition to the behavioural evidence, support for MNS dysfunction is evident in the small body of fMRI research in this population (Debrabant, Gheysen, Caeyenberghs, Van Waelvelde, & Vingerhoets, 2013; Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009; Licari et al., 2015; Zwicker, Missiuna, Harris, & Boyd, 2010, 2011). Although not directly exploring MNS function, these studies have identified differences in activation patterns, and effective (Querne et al., 2008) and functional connectivity (McLeod, Langevin, Goodyear, & Dewey, 2014, 2016) of cortical areas linked to the MNS, using a range of tasks and resting state paradigms. The strongest initial evidence for possible MNS dysfunction comes from a recent fMRI study conducted by Licari et al. (2015), who found that during the imitation of a finger sequence task, children with DCD had decreased activation in the left IFG compared to controls. Hypothesised to possibly reflect MNS dysfunction, a follow up study was undertaken to specifically explore MNS functioning during observation, execution, and imitation of the same finger sequencing task (Reynolds, Licari, Billington, et al., 2015). The control group was found to have significantly greater activation than the DCD group during observation in the pars opercularis of the IFG, the precentral gyrus, middle temporal gyrus, posterior cingulate, and precuneus (Reynolds, Licari, Billington, et al., 2015). In addition, an interaction effect between group and task condition was seen in the pars opercularis, a key MNS region, with the DCD group showing significantly greater deactivation in this region during imitation compared to the other conditions (Reynolds, Licari, Billington, et al., 2015). Although suggested to provide preliminary evidence for MNS dysfunction, and children with DCD possibly adopting different neural strategies while performing the different task conditions, the lack of expected MNS signal increase from execution to imitation at a whole brain level was interpreted as a potential learning effect which may have prevented group differences during execution and imitation from being identified.
Reynolds, Licari, Billington, et al. (2015) suggested further research to explore hypothesised MNS dysfunction using simple target-directed finger movements without practice prior to scanning to circumvent the possible effect of motor learning, and to incorporate motor imagery into the fMRI task paradigm. Therefore, the present study aimed to use fMRI to investigate whether a deficit in the MNS exists in children with probable DCD (pDCD) by examining brain activations during the performance of a target-directed adduction/abduction finger tapping task (modified from: Aziz-Zadeh, Koski, et al., 2006; Aziz-Zadeh, Maeda, Zaidel, Mazziotta, & Iacoboni, 2002) under four conditions: (1) action observation; (2) motor imagery; (3) action execution; and (4) imitation. (Aziz-Zadeh, Koski, et al., 2006; Decety, 1996; Iacoboni et al., 1999). It was hypothesized that there would be decreased activation in the MNS of children with pDCD compared to controls, specifically in the pars opercularis of the IFG, the PMv, IPL and STS, most prominent during the imitation condition. In addition, this study also aimed to explore other cortical areas that may contribute to the movement difficulties seen in children with DCD.

6.2 Methods

6.2.1 Participants

Thirty one right-handed males, aged 8 to 13 years participated in this cross-sectional research study. Of these participants, 12 (6 pDCD, 6 control) were subsequently excluded: three were withdrawn prior to the completion of scanning due to movement (3 pDCD), six during the analysis stage due to excessive movement (1 pDCD; 3 control) and signal dropout (1 pDCD; 1 control), and three due to neurological abnormalities (1 pDCD; 2 control; confirmed by a neuroradiologist). This left a final sample of 19 males (10 pDCD; 9 control). Group 1 consisted of 10 males with pDCD (≤16th percentile Movement Assessment Battery for Children – 2nd edition; MABC-2; Criterion A), recruited from the University of Western Australia (UWA) Paediatric Exercise Programmes, and clinical referrals (Criterion B and C). Group 2 consisted of 9 group age-matched typically developing controls (≥25th percentile MABC-2) recruited from the local community. Only right-handed males were recruited to eliminate any potential lateralisation or gender differences that may exist in brain activation patterns (Cheng, Tzeng, Decety, Imada, & Hsieh, 2006), imitation (Chipman & Hampson, 2007) or motor imagery ability. Ethics approval was obtained from the Human Research Ethics Committee (RA/4/1/6492) at UWA. Written consent was obtained from parents and participants prior to the commencement of the study and ongoing verbal assent was
sought from participants throughout each phase of the study. Rolling recruitment and data collection ran from August 2014 to June 2016.

6.2.2 Experimental design and screening assessments

Participants were required to attend two testing sessions. During the first session, participants completed motor and diagnostic screening assessments to ensure that they met the diagnostic criteria for inclusion. Motor proficiency was assessed using the MABC-2 (Henderson, Sugden, & Barnett, 2007). Due to the high level of comorbidity of DCD with other neurodevelopmental disorders (Dapretto et al., 2006), children with a diagnosis of either autism spectrum disorder (ASD), or attention deficit hyperactivity disorder (ADHD), or any neurological conditions (Criterion D) were excluded from the study. In addition, the Childhood Autism Rating Scale (CARS; Saemundsen, Magnusson, Smari, & Sigurdardottir, 2003; Schopler, Reichler, & Renner, 1988) and the Swanson, Nolan and Pelham-IV (SNAP-IV) ADHD questionnaire (Bussing et al., 2008) were used to assess symptoms of ASD and ADHD. Handedness was screened using a child modified version of the Edinburgh Handedness Inventory (Oldfield, 1971), and only right-handers (score ≥ 40) were included to eliminate any potential brain lateralisation differences related to handedness.

Once it was established that children met the inclusion criteria, imitation and motor imagery assessments were undertaken to explore MNS function at the behavioural level. The Postural Praxis (whole body imitation) and Sequencing Praxis (hand and finger sequencing imitation) sub-tests from the Sensory Integration and Praxis Tests (SIPT) developed by Ayres and colleagues (Ayres, 1989) were used to assess participants’ imitative ability. Motor imagery proficiency was assessed using a complex hand rotation task (Butson, Hyde, Steenbergen, & Williams, 2014; Hyde et al., 2014; Reynolds, Licari, Elliott, et al., 2015), with response time and accuracy measures recorded. During this session, participants also completed fMRI familiarisation during which they were introduced to the scanning environment (noise, confined space, head coil and restraints), and were provided with skills to enable them to lie still for a readable scan (Appendix D). This familiarization protocol has been used successfully in previous research by researchers involved in this study (Licari et al., 2015; Reynolds, Licari, Billington, et al., 2015). Participants were also familiarized with the task conditions. Due to previous research indicating that a learning effect may have occurred as a result of practicing the task prior to scanning (Reynolds, Licari, Billington, et al., 2015), an alternate hand
clenching task was used to practice the different conditions and cues involved in this study. The second session involved the use of fMRI to examine differential brain activations as children performed an adduction/abduction finger tapping task. Participants were shown the task immediately prior to their scan to avoid a learning effect. This session was conducted at the Department of Radiology at Sir Charles Gairdner Hospital, Western Australia.

6.2.3 Imaging parameters

Imaging was conducted using a Philips Ingenia 3T Multi Transmit Wide Bore Scanner, with participants wearing a 12-channel head coil. The participants’ head was restrained with soft pads to prevent small, unwanted movements from causing artefacts. A strap was used to help immobilize both wrists and forearms to limit the movement of the active hand in order to minimize participant head movement during scanning. A thermo-plastic splint was worn by participants on the active dominant hand during scanning to isolate movement in the digits. High-resolution anatomical images were acquired first (T1-weighted 3D FFE 175 slices 1 × 1 × 1 mm), followed by two eight minute functional studies (T2-weighted gradient echo, TR/TE = 3000/35 ms, flip angle 90°, 25 axial slices with a thickness of 4 mm, interslice gap = 0 mm, in-plane resolution 1.8mm×1.8 mm). Total scan time was 22.5 min.

6.2.4 Scanning task

Participants performed a target-directed adduction/abduction (side to side) index finger tapping task (modified from previous mirror neuron research: Aziz-Zadeh, Koski, et al., 2006; Aziz-Zadeh et al., 2002; Figure 6.2) using their right hand under four separate conditions: (1) action observation; (2) motor imagery; (3) action execution; and (4) action imitation. During action observation, participants viewed the finger tapping task and were prompted with a red coloured circle to observe the task but not imagine or execute it. In the motor imagery condition, participants were prompted by a yellow coloured circle to imagine themselves perform the finger tapping task with a still shot of the first hand stimulus image on the screen. In the action execution condition, participants were prompted by a green coloured circle to perform the finger tapping task with a still shot of the first hand stimulus image on the screen. Lastly, in the action imitation condition, participants viewed the sequencing task and were prompted with a green coloured circle to imitate the finger actions as they observed them. All images were displayed from a first
person point of view, with a metronome tick (1 Hz) used as an auditory cue to coordinate the timing of movements performed in each condition.

Participants completed a total of eight repetitions of each condition in a randomized order across two functional block design scans (four presentations per scan). Each condition lasted for approximately 18 seconds with 12 seconds of rest (rest condition) between each to allow for the BOLD response to return to baseline. The rest condition was a non-mirror neuron observation task to isolate changes in brain responses to those evoked by the task; participants viewed two scrambled hand images with a red cross, which were designed to have a similar contrast and luminance in the center of the screen to the active condition images (modified version of: Aziz-Zadeh, Iacoboni, & Zaidel, 2006). A smoothing function was applied to the edges of the scrambled blocks to remove the sharp edges. Rest images also changed at a frequency of 1Hz along with a metronome tick. An assessor in the scan room observed the performance of tasks within the scanner to ensure tasks were completed correctly, however, no quantitative measures were recorded. In addition, participants were asked whether they were imagining performing the task for the imagery condition.

![Figure 6.2](image.png)

**Figure 6.2.** A: Adduction/abduction finger tapping task condition images (observation example), B: Rest condition images.

### 6.2.5 Imaging analysis: Functional

All fMRI data processing and whole brain analysis was carried out using SPM12 software (Wellcome Department of Cognitive Neurology, London). Prior to analysis, all images
were corrected for slice timing using the middle slice as a reference slice. Structural anatomical scans were placed into AC-PC space, and all structural and functional images reoriented accordingly. A stringent fourth degree b-spline interpolation realignment procedure was applied to the images to realign to a mean functional image. In-scanner motion was checked for each participant, four participants (1 pDCD; 3 control) were removed at this stage for displaying motion > 3 mm. All other participants displayed minimal motion and there was no apparent difference of head movement during scanning between the pDCD and control groups. The mean functional image created during realignment (source image), and all realigned functional images (other images) were co-registered to the structural image (reference image). Segmentation using SPM12 tissue probability maps was performed to segment the anatomical images into grey matter, white matter and cerebrospinal fluid. All structural and functional images were normalized using affine and smooth non-linear transformations to an EPI template in Montreal Neurological Institute (MNI) space. Finally, all images were smoothed with a full width half maximum Gaussian kernel of 8 mm to optimise functional registration of activations.

Each run was split into blocks to reflect the observation, motor imagery, execution, and imitation task conditions outlined above. Individual statistical contrasts were set up by using the general linear model to fit each voxel with a combination of functions derived by convolving the standard hemodynamic response with the time series of the events and removing low-frequency noise with a high-pass filter with a frequency cut off of 128 s (Friston et al., 2000). The six nuisance regressors capturing head motion from each session that were created for each participant during the realignment stage were built into the first level models as covariates. In order to examine the signal activation patterns of the MNS, the main effect of each individual condition (e.g., observation, motor imagery, execution, and imitation) was contrasted against the rest condition (to identify brain regions activated by each task condition) using exploratory whole brain analysis. Contrasts were run at a cluster corrected level, with voxel height thresholds set at $p < 0.001$ (uncorrected), with an additional extent threshold set for each contrast to correct for multiple comparisons, thus activations passed a cluster-level extent threshold of $p < 0.05$ (FWE corrected; Friston, Holmes, Poline, Price, & Frith, 1996; Nichols & Wilke, 2012). Second level between-group contrasts were performed for each condition, first at a cluster corrected level of $p_{FWE} < 0.05$. Where no activation differences were identified at a corrected level, contrasts were re-run at an uncorrected level of $p < 0.001$, with a cluster of at least 10 contiguous voxels. All significant clusters extracted in MNI
coordinates were converted to Talairach coordinates; the nearest grey matter structure, and Brodmann area were identified using Talairach Client (http://www.talairach.org/; Lancaster et al., 1997; Lancaster et al., 2000) and the Co-Planar Stereotaxic Atlas of the Human Brain (Talairach & Tournoux, 1988).

Region of interest (ROI) analysis was also conducted in pre-selected locations to explore signal patterns in MNS regions. Percent signal change values were extracted from 15 ROIs created in MarsBaR region of interest toolbox for SPM (MarsBaR: http://marsbar.sourceforge.net/; Brett, Anton, Valabregue, & Poline, 2002) in SPM8 (Figure 6.3). Following Reynolds and colleagues (Reynolds, Licari, Billington, et al., 2015), each ROI consisted of a 10mm diameter sphere, centered on the coordinates reported in the study by Aziz-Zadeh et al. (Aziz-Zadeh, Koski, et al., 2006). This included mirror regions in the pars opercularis of the IFG, supplementary and premotor areas, posterior parietal lobe, and STS. A series of 2×4 mixed ANOVAs were run for each ROI on the percent signal change values extracted from individual participants (see Table 6.5). As a result of the lack of anatomical maps in children and similar functional data, the ROI analysis was based on established coordinates from adult MNS data (Aziz-Zadeh, Koski, et al., 2006). Although adults do not map on to children perfectly, it was felt that this approach was more accurate and objective than the use of anatomical ROIs.

![Figure 6.3. Regions of interest: Pars opercularis (magenta); Superior temporal sulcus (green); Parietal (red); Premotor area (blues); Supplementary motor area (yellow) (from: Reynolds, Licari, Billington, et al., 2015).](image)
6.3 Results

The final sample consisted of 19 participants (10 pDCD; 9 controls). The characteristics of this group are presented in Table 6.1. Groups were well matched for age, with no significant difference identified between the pDCD (8.25 – 12.75 years) and control groups (8.33 – 12.25 years). By inclusion criteria of the groups, children with pDCD had significantly poorer motor proficiency compared to the controls on the MABC-2 ($p < 0.001$), with the DCD group ranging from the 1st – 16th percentiles, and controls from the 37th – 98th percentiles. Consistent with previous research (Reynolds, Licari, Billington, et al., 2015), children with pDCD displayed significantly more ADHD and autistic symptoms ($p < 0.05$), however, none of the children with pDCD had a formal diagnosis of either disorder. Both questionnaires include questions about engagement in movement related activities, which is likely, in part, to explain these group differences. Children with pDCD were found to have significantly decreased imitative ability as compared to the control group on both the postural and sequencing praxis, and reduced accuracy levels for the motor imagery task ($p < 0.05$).

**Table 6.1.** Participant characteristics for fMRI study (pDCD and typically developing peers).

<table>
<thead>
<tr>
<th></th>
<th>pDCD (N=10)</th>
<th>TD (N=10)</th>
<th>t/U</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean/ SD/ Mdn/ IQR</td>
<td>Mean/ SD/ Mdn/ IQR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years)$^a$</td>
<td>10.18/1.34/10.12</td>
<td>10.41/1.17/10.20</td>
<td>0.401</td>
<td>0.694</td>
</tr>
<tr>
<td>MABC-2 (percentile)</td>
<td>7.80/5.40/7.36</td>
<td>70.11/23.04/70.11</td>
<td>7.922</td>
<td>&lt;0.001**</td>
</tr>
<tr>
<td>CARS$^a$</td>
<td>17.90/2.18/17.00</td>
<td>15.22/0.36/15.00</td>
<td>2.964</td>
<td>0.009*</td>
</tr>
<tr>
<td>SNAP-IV$^a$</td>
<td>0.87/0.53/0.77</td>
<td>0.31/0.22/0.31</td>
<td>3.820</td>
<td>0.004*</td>
</tr>
<tr>
<td>Postural Praxis$^a$</td>
<td>23.30/4.14/23.00</td>
<td>28.11/2.80/27.88</td>
<td>2.931</td>
<td>0.009*</td>
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<tr>
<td>Sequencing Praxis$^a$</td>
<td>84.50/9.28/84.00</td>
<td>98.56/6.34/98.00</td>
<td>3.805</td>
<td>0.001*</td>
</tr>
<tr>
<td>MI back accuracy$^b$</td>
<td>92.50/83.46-95.00</td>
<td>97.50/93.73-100.00</td>
<td>16.00</td>
<td>0.017*</td>
</tr>
<tr>
<td>MI palm accuracy$^b$</td>
<td>84.78/68.58-91.25</td>
<td>95.00/88.75-98.75</td>
<td>18.50</td>
<td>0.029*</td>
</tr>
<tr>
<td>MI combined accuracy$^b$</td>
<td>87.76/74.91-93.12</td>
<td>95.00/93.12-98.12</td>
<td>15.00</td>
<td>0.014*</td>
</tr>
</tbody>
</table>

MT: Motor imagery; Mdn: Median; IQR: Interquartile range; $^a$ t; $^b$ U; * ($p<0.05$); ** ($p<0.001$)
To explore MNS activation patterns, and whether there was a characteristic progressive increase in BOLD signal across conditions from action observation, motor imagery, action execution, to imitation (Aziz-Zadeh, Koski, et al., 2006; Iacoboni et al., 1999) during the finger adduction/abduction task, the main effect of each individual condition was contrasted against rest. The groups were initially collapsed to identify whether cortical areas typically associated with the MNS were activated across conditions. During the observation condition, there were no significant activation clusters compared to the rest condition (visual non-mirror control task). When children imagined themselves performing the task in the action imagery condition (purple in Figure 6.4), small significant clusters of activation were found in the middle frontal gyrus, posterior cingulate, and precuneus. All children reported that they imagined performing the finger tapping task. Furthermore, when children performed the task in the action execution (dark blue in Figure 6.4) and imitation (green in Figure 6.4) conditions, significant activation clusters were identified in the precentral gyrus and medial frontal gyrus, pre- and postcentral gyrus, inferior parietal lobule, thalamus, caudate and lentiform nucleus, with a greater extent of activation during imitation. The coordinates of the specific regions where significant activation was seen across the conditions are presented in Table 6.2.

Figure 6.4. Main effect of observation>rest (N/A), motor imagery>rest (purple), execution>rest (dark blue), and imitation>rest (green). Cluster-level extent threshold of \( p_{\text{FWE}} < 0.05 \); (N.B. fading represents depth; sky blue/teal represents overlap of execution>rest and imitation>rest contrasts).
Table 6.2. Whole brain analysis: Condition comparison (cluster level correction, $p_{(FWE)} < 0.05$).

<table>
<thead>
<tr>
<th>Anatomical region</th>
<th>Observation &gt; Rest</th>
<th>Motor imagery &gt; Rest</th>
<th>Execution &gt; Rest</th>
<th>Imitation &gt; Rest</th>
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</thead>
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<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Anatomical region</td>
<td>Clustering (k)</td>
<td>Talairach coordinates</td>
<td>Brodmann area</td>
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<td>y</td>
<td>z</td>
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<tr>
<td>Observation &gt; Rest</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N/A</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Motor imagery &gt; Rest</td>
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<td></td>
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<td>6</td>
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<td>-49</td>
<td>49</td>
<td>40</td>
</tr>
<tr>
<td>Execution &gt; Rest</td>
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<td></td>
</tr>
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<td>-24</td>
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<td>Putamen</td>
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<tr>
<td>Imitation &gt; Rest</td>
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<td></td>
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<td>Precentral gyrus (L)</td>
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<td>-17</td>
<td>54</td>
</tr>
<tr>
<td>Medial frontal gyrus (L)</td>
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<td>Lateral globus pallidus</td>
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<td>54</td>
<td>-34</td>
<td>29</td>
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<tr>
<td>Superior frontal gyrus (R)</td>
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<td>59</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Supramarginal gyrus (L)</td>
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<td>17</td>
<td>45</td>
<td>8</td>
</tr>
<tr>
<td>Inferior parietal lobule (L)</td>
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<td>17</td>
<td>45</td>
<td>8</td>
</tr>
<tr>
<td>Angular gyrus (L)</td>
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<td>-58</td>
<td>38</td>
<td>39</td>
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</tbody>
</table>
6.3.2 fMRI whole brain analysis: Group contrasts

When group differences were compared individually within each condition > rest, no significant differences were seen between groups in the action observation, motor imagery, or action execution conditions when run at corrected or uncorrected levels. However, in the imitation condition, children with pDCD were found to have small clusters of decreased activation compared to controls in the right caudate, thalamus, posterior cingulate, middle frontal gyrus, and precuneus, and left thalamus (uncorrected \( p < 0.001 \); Table 6.3).

Table 6.3. Between group analysis of task conditions > rest condition (uncorrected, \( p < 0.001 \)).

<table>
<thead>
<tr>
<th>Anatomical region</th>
<th>Cluster (k)</th>
<th>Talairach coordinates</th>
<th>Brodmann area</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( x )</td>
<td>( y )</td>
</tr>
<tr>
<td><strong>Imitation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control &gt; pDCD</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Caudate (R)</td>
<td>45</td>
<td>20</td>
<td>-19</td>
</tr>
<tr>
<td>Thalamus (L)</td>
<td>18</td>
<td>-14</td>
<td>-33</td>
</tr>
<tr>
<td>Caudate (R)</td>
<td>10</td>
<td>13</td>
<td>24</td>
</tr>
<tr>
<td>Thalamus (R)</td>
<td>29</td>
<td>6</td>
<td>-33</td>
</tr>
<tr>
<td>Posterior cingulate (R)</td>
<td>15</td>
<td>-40</td>
<td>11</td>
</tr>
</tbody>
</table>

Group comparisons (control > pDCD; pDCD > control) were also run for the imitation > execution, imitation > motor imagery, and imitation > observation contrasts, to explore regions that were more active when participants had to attend to and move in time with the visual stimuli, as opposed to just executing the movement without prompting visual stimuli, imagining without moving visual stimuli, or just watching the stimuli respectively. A number of uncorrected (\( p < 0.001 \)) small clusters were identified in all three control > pDCD contrasts (Table 6.4). There were no significant clusters for any of the pDCD > control contrasts.

6.3.3 fMRI region of interest

Using ROI percentage signal change analysis, significant main effects for task condition were observed in mirror neuron regions with a trend for increasing signal activations across the conditions to imitation (Table 6.5). Post-Hoc analyses revealed significant within-subject differences with greater activation during the motor imagery, execution
and imitation conditions compared with the observation condition in the posterior parietal regions, premotor and supplementary motor areas, and greater activation for motor imagery compared to observation in the pars opercularis. A significant group difference was identified in the right posterior parietal/inferior parietal lobe \((x = 52, y = -30, z = 38, \text{BA40}, F = 4.570; p = 0.047)\), with controls having increased activation across conditions, compared to the pDCD group (mean difference = 0.085). No significant condition \(\times\) group interactions were found.

Table 6.4. Between group analysis of imitation \(>\) observation, imagery, and execution conditions (uncorrected, \(p < 0.001\)).

<table>
<thead>
<tr>
<th>Anatomical region</th>
<th>Cluster ((k))</th>
<th>Talairach coordinates</th>
<th>Brodmann area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Execution: Control (&gt;) pDCD</strong></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Insula (R)</td>
<td>16</td>
<td>31 -35 15 13</td>
<td></td>
</tr>
<tr>
<td>Caudate (R)</td>
<td>32</td>
<td>11 23 8</td>
<td>Caudate body</td>
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<tr>
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<td>10 -7 54 6</td>
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<td>30</td>
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<td><strong>Motor imagery: Control (&gt;) pDCD</strong></td>
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<td>24 -13 25</td>
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</tr>
<tr>
<td><strong>Observation: Control (&gt;) pDCD</strong></td>
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</tr>
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<td></td>
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<td>-35 -38 15 41</td>
<td></td>
</tr>
<tr>
<td>Region of interest</td>
<td>Talairach coordinates</td>
<td>Brodmann area</td>
<td>F (between-subjects)</td>
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</tr>
<tr>
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<td>Posterior parietal /</td>
<td>-56</td>
<td>-26</td>
<td>36</td>
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<tr>
<td>Inferior parietal lobule</td>
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<td>-30</td>
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<tr>
<td>Premotor area</td>
<td>-32</td>
<td>2</td>
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<tr>
<td>Supplementary motor area</td>
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<td>6</td>
<td>52</td>
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Obs: Action observation; MI: Motor imagery; Exe: Action execution; Imi: Imitation
* Greenhouse-Geisser correction applied
* p < 0.05; ** p < 0.001
6.4 Discussion

The present study examined brain areas that contribute to the movement difficulties experienced by children with pDCD, specifically, proposed deficits in MNS function (Reynolds, Thornton, et al., 2015; Werner et al., 2012). At a behavioural level, children with pDCD had reduced performance proficiency on both imitation and motor imagery tasks, demonstrating that the children with pDCD included in this study had deficits supportive of the MNS dysfunction hypothesis at a behavioural level. Interestingly, no differences in MNS activation were seen between groups at a neurological level, with both groups activating mirror regions similarly across conditions. At a whole brain level, group comparisons of neural activation for each task condition over rest condition revealed minimal between-group differences, with small clusters of decreased activation seen in the pDCD group in non-mirror regions including the thalamus, caudate, and posterior cingulate during the imitation condition. When the imitation condition was compared to the other conditions, the pDCD group displayed decreased activation compared to controls in the bilateral medial frontal gyrus, insula, caudate, and precuneus, the left postcentral, parahippocampal, superior temporal, and transverse temporal gyri, and right thalamus. No pDCD > control activation was identified for any contrast. The reduced activation in these regions suggest that the imitation and imagery deficits observed in children with DCD may in part stem from difficulties with the planning phase of movement production, and integration and updating of relevant visuospatial information rather than deficits in MNS function.

The design of this study was based on previous MNS research (Reynolds, Licari, Billington, et al., 2015), incorporating additional MNS activation states using a novel task without prior practice to examine MNS function. The activation profiles observed at a within-subject level revealed that both groups effectively activated MNS regions, including the inferior and medial frontal gyri, and inferior parietal lobule, as well as other expected motor regions. Furthermore, an examination of the percentage signal changes in the ROI analyses revealed the expected increase in signal activation trends across conditions. Although there were no significant activation clusters for the observation > rest contrast, which we would expect to see (Caspers et al., 2010), it is possible that the rest condition, which also incorporated moving images, activated some mirror regions, or that the participants were not actively engaging in the observation condition. Despite this, based on the consistent MNS activation patterns observed during the other task conditions, and across the conditions at a ROI level, any group differences at a
neurological level in this system impacting movement execution would still be expected to be identified. Furthermore an examination of the percentage signal changes in the ROI analysis revealed the expected increased signal activation trends across conditions from observation to imitation (Aziz-Zadeh, Koski, et al., 2006), suggestive of mirror region activation during the tasks. The increasing activation at whole brain and ROI levels across the conditions suggests that a practice effect was not encountered as it may have been in previous research (Reynolds, Licari, Billington, et al., 2015). The similar activation patterns observed by both the pDCD and control groups across most ROIs, suggests that both groups activated mirror neuron regions to perform the tasks, with no differences in MNS activation patterns to support a deficit in this system at a neurological level.

The absence of between-group differences in MNS activation at a whole brain level is consistent with the results from the previous fMRI research by our research group (Reynolds, Licari, Billington, et al., 2015). Given the evidence for MNS dysfunction in DCD at a behavioural level in conjunction with differences in MNS activation patterns during other functional tasks (Debrabant et al., 2013; Kashiwagi et al., 2009; Licari et al., 2015; Querne et al., 2008; Reynolds, Licari, Billington, et al., 2015; Zwicker et al., 2010, 2011), the minimal group differences in MNS activation had previously been hypothesized to be the result of a learning effect. Interestingly, to date, aside from work by Zwicker and colleagues (2010, 2011), minimal differences in brain activation patterns between children with and without DCD have been observed using fMRI across a range of tasks (Debrabant et al., 2013; Kashiwagi et al., 2009; Licari et al., 2015; Reynolds, Licari, Billington, et al., 2015).

Although no group differences were identified in regions associated with the MNS, during imitation, children with pDCD were found to have reduced activation in small clusters in the caudate body, thalamus (pulvinar), and posterior cingulate, compared to controls. Children with pDCD also had small clusters of reduced activation for all of the imitation > execution, imagery, and observations contrasts, where attention to a visual stimuli as well as attention to task performance was required, again in the thalamus and caudate, as well as in the cingulate gyrus, precuneus, insula, superior temporal gyrus and medial frontal gyrus. Differential activation patterns in these non-mirror regions are consistent with neural activation patterns that have been associated with impaired imitation. For example, lesions centered on the caudate nucleus and insular cortex, have been associated with disturbed finger position imitation (Goldenberg & Karnath, 2006).
The small differences in activation of these regions also suggest that reduced levels of motor planning, and visuospatial and motor attentional processes at a neural level may be involved in the motor deficits seen in children with DCD. The caudate has been identified to be involved in automated processes such as motor planning, execution of action schemas (Grahn, Parkinson, & Owen, 2008), attentional processes (Berger & Posner, 2000), and interestingly, has been implicated in other neurodevelopmental disorders which have a high incidence of associated movement difficulties (Schrimsher, Billingsley, Jackson, & Moore, 2002). The pulvinar (thalamus) has been implicated in selective visuospatial attention, as well as acting to relay attentional feedback to the visual cortex (Cola, Gray, Seltzer, & Cusick, 1999; Desimone & Duncan, 1995; Kowler, Anderson, Dosher, & Blaser, 1995; Saalmann, Pinsk, Wang, Li, & Kastner, 2012; Zhou, Schafer, & Desimone, 2016). Furthermore, increased levels of visual attention and motor control during imitation have been associated with hyperactivation in the posterior cingulate cortex (Hanawa et al., 2016; Zhang et al., 2016), an integrative centre (Pearson, Heilbronner, Barack, Hayden, & Platt, 2011) involved in both motor and attention processes, suggesting that children with DCD may have difficulty integrating relevant information at a neurological level. The precuneus is thought to influence a wide range of highly integrated tasks including visuo-spatial imagery, attention orientation, and self-processing adopting a first person perspective (Cavanna & Trimble, 2006); decreased activation in imitation > observation contrast in pDCD is consistent with proposed deficits mentally manipulating body schema (Reynolds, Licari, Elliott, et al., 2015). Reduced activation of these regions in children with pDCD may suggest that deficits attending to stimuli, learning of automated movements, and the processing and updating of relevant information may contribute to the motor deficits seen in DCD.

Deficits in motor planning, generating internal models and the use of feedforward information have previously been hypothesized to underlie the movement difficulties characteristic of DCD (Adams et al., 2014). In addition to reduced grey matter volumes in motor planning and attention regions identified in previous research (Reynolds et al., 2017), the small reduced activation clusters in planning and attention regions during imitation in children with pDCD provides preliminary support for dysfunction of motor planning and attentional processes neurologically. Reduced motor planning and predictive control capabilities of children with DCD have been demonstrated using a range of behavioural paradigms, such as control of overt and covert manual actions (Adams et al., 2014), visuo-motor adaptation and sequencing tasks (Gheysen, Van
Differential activation patterns in motor planning and attention regions have also been identified in children with DCD in other fMRI studies (Debrabant et al., 2013; Querne et al., 2008; Zwicker et al., 2010). Based on structural equation modelling of the middle frontal cortex, anterior cingulate, inferior parietal cortex and striatum during a go no-go task, Querne and colleagues (2008) proposed dysfunction of attention network effective connectivity in children with DCD. In addition, reduced activation of the insula in children with DCD was also observed during a trail tracing task (Zwicker et al., 2010). Consistent with these deficits, reduced functional connectivity between the caudate, insula, and anterior cingulate gyrus, and the left primary motor cortex (M1) was identified in children with DCD during a rsfMRI study (McLeod et al., 2014); however, the use of seed based functional connectivity does not allow for an exploration of moderating factors that may be influencing correlated activation. Interestingly, research on other neurodevelopmental disorders with movement difficulties, such as ADHD, also implicates these neural regions and processes (Hart, Radua, Nakao, Mataix-Cols, & Rubia, 2013; Schrimsher, et al., 2002). In conjunction with the high levels of comorbidity associated with DCD, the incorporation of combined comorbidity groups in neuroimaging research may be beneficial for future research.

While this study found no evidence to support the MNS theory of motor impairment, there are some minor limitations to our work to consider. Although the adduction/abduction finger tapping task has been shown to activate MNS regions in previous research, the task itself is relatively simple due to task constraints within a scanning environment. Imagery of simple tasks has, however, been shown to activate cortical networks comparable to those activated during complex imagined tasks (Szameitat, Shen, & Sterr, 2007). Despite this, it is possible that group differences may have become more apparent with a more complex task (Kuhtz-Buschbeck et al., 2003); however, performing a complex unlearned task during scanning is likely to present a challenge for children with DCD, as well as those without. As the sample size is small, although comparable with other studies in this population, uncorrected statistics have been reported for group comparisons and should be interpreted with caution. Given the small sample size, the study may have been under-powered to detect MNS differences between groups. To keep scan time to a minimum, the volume was reduced and did not
extend down to the cerebellum. This brain region has been implicated in DCD (Marien, Wackenier, De Surgeloose, De Deyn, & Verhoeven, 2010; Zwicker et al., 2010, 2011), however, as this study was specifically exploring MNS, a trade-off was made to instead increase the number of task presentations in the fMRI protocol.

6.5 Conclusions and future directions
At a behavioural level, children with pDCD displayed deficits in imitation and motor imagery performance. Given that children with pDCD and controls displayed similar activation profiles in MNS regions, it is likely that the performance deficits observed behaviourally stem from dysfunction of other neural networks also supporting these processes. This research provides new information about the underlying mechanisms of DCD, with the findings pointing to deficits in neural areas linked to motor planning and attention. Further fMRI research, in particular the use of motor attention tasks, to explore likely deficits in motor planning and internal forward modeling, and attentional processes, appears to be a promising research direction to increase our understanding of the causal mechanisms of the movement difficulties associated with DCD and potential targeted treatments. Resting state fMRI and dynamic causal modelling to explore effective connectivity between brain regions also has the potential to shed further light on the connectivity of other networks such as the default mode network, salience network and dorsal attention network at rest, as well as during imitation and other movement tasks.

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References


CHAPTER 7: DISCUSSION

7.1 Overview
The body of research presented in this thesis aimed to test the hypothesis that dysfunction of the MNS is an underlying mechanism of motor deficits that are characteristic of DCD. A systematic review of the literature was initially undertaken to identify the current level of evidence for MNS dysfunction, and to identify the gaps in the research that needed to be addressed in order to comprehensively evaluate the MNS hypothesis. The systematic review provided strong preliminary evidence to support possible MNS dysfunction in DCD at a behavioural level; however, there were a number of areas identified, particularly at a neuroimaging level, which required further exploration (Reynolds, Thornton et al., 2015). This thesis extends current and provides new behavioural and neuroscience knowledge that can inform future research for children with DCD. The plain language summaries for stakeholders (parents, children, clinicians, policy makers) optimise the knowledge translation of this research by allowing it to reach a wider readership. (Appendix C).

7.2 Systematic literature review and research aims
The systematic review identified support for children with DCD having deficits in imitation and motor imagery, both MNS activation states. Strong support was identified for deficits imitating representational/learned gestures; however, no research has conducted a comprehensive evaluation of the imitation of novel or sequencing gestures by children with DCD. Support for motor imagery deficits was identified across a range of task paradigms, where children with DCD had slower and less accurate responses, and showed less similarity between real and imagined movements compared to controls. The need for further work using more complex tasks was identified, to explore the extent of motor imagery deficits across different task complexity levels. Therefore, there is a need for behavioural studies to confirm imitation and imagery deficits using novel and complex assessments. Although preliminary support for differences in neural activation and functional connectivity patterns in MNS regions was identified at a neuroimaging level, there is still a limited understanding of both grey matter volumes and neural activation in general in this disorder, with no neuroimaging tasks having been used specifically to activate MNS regions.
7.3 Behavioural assessment of MNS series

The behavioural studies in this thesis extend previous research by utilising novel and complex imitation and motor imagery assessments to assess behavioural correlates of MNS function in children with DCD. Consistent with possible MNS dysfunction, children with DCD were found to have deficits in both novel and sequencing gesture imitation and motor imagery, displaying slower and less accurate responses than controls. Across both the imitation and motor imagery tasks, these deficits became more evident as task complexity increased. A high level of variability in task performance was identified in children with DCD in both tasks, with numerous children scoring within a typically developing range, despite demonstrating deficits in coordination. Deficits in these processes behaviourally are consistent with MNS dysfunction. It is important to note, however, that both imitation and motor imagery require the integration of multiple sensory systems and, at a neurological level, are also supported by systems and mechanisms beyond the MNS; these processes share a high degree of overlap with other deficits children with DCD are known to experience, such as visuo-spatial attention and integration (Wilmut, Brown, & Wann, 2007), sensoriperceptual function (Sigmundsson, Whiting, & Ingvaldsen, 1999), executive functioning (Alloway, 2007; Piek, Dyck, Francis, & Conwell, 2007; Tsai et al., 2012), and motor learning and adaptation (Kagerer, Bo, Contreras-Vidal, & Clark, 2004; Kagerer, Contreras-Vidal, Bo, & Clark, 2006). Therefore, research at a neuroimaging level was required to further evaluate the neural mechanisms related to imitation and motor imagery deficits in DCD.

7.4 Neuroimaging series

As a result of limited neuroimaging research having been undertaken in this population (Brown-Lum & Zwicker, 2015), hypotheses regarding the neural correlates of DCD have typically been drawn from behavioural studies. The neuroimaging series in this thesis aimed to extend this literature to increase our understanding of brain structure and function in DCD, both within and beyond the MNS. Because grey matter volumes have been linked to performance (Draganski et al., 2004; Maguire et al., 2006), and importantly for intervention approaches, have been identified to be plastic (Draganski et al., 2004; Driemeyer et al., 2008), identifying whether differences in brain macrostructure within and beyond MNS regions exist in DCD has the potential to increase our understanding of the neural mechanisms of this disorder.
To date, only two papers have been published that explore grey matter structure in DCD, with both utilising measures of cortical thickness (Caeyenberghs et al., 2016; Langevin et al., 2015). Disruptions to the development of grey matter volumes have been linked to a range of neurodevelopmental disorders that often co-occur with DCD (Brambilla et al., 2003; Bush, 2011; Nickl-Jockschat et al., 2012; Richlan et al., 2013; Valera et al., 2007). To examine whether differences in grey matter volumes may also contribute to DCD, a voxel-based morphometry study was performed to test for differences in grey matter volumes anywhere in the brain. Although no differences were identified in MNS regions, children with DCD were found to have reductions in grey matter volume in the right medial and middle frontal, and superior frontal gyri compared to controls. Reduced grey matter volumes in these regions may have a negative impact on motor planning (Hanakawa, Dimyan, & Hallett, 2008), attention (Hopfinger, Buonocore, & Mangun, 2000; Japee, Holiday, Satyshur, Mukai, & Ungerleider, 2015), and executive functioning (Du Boisgueheneuc et al., 2006; Garavan, Ross, & Stein, 1999; Talati & Hirsch, 2005) processes associated with these regions. Although it cannot be established whether these reductions in brain volume seen in DCD are a result of reduced motor capabilities, or the cause of them, based on the principles of neural plasticity and neurorehabilitation (Nudo, 2006), intervention approaches targeting the processes associated with the regions of grey matter reductions may result in functional improvements in children with DCD.

Investigation of neural mechanisms associated with MNS function was extended by examining the activation of cortical areas associated with the MNS. This was done by examining brain activation during the observation, imagery, and performance (execution and imitation) of an unlearned finger tapping task. At a behavioural level, children with DCD participating in this study displayed deficits in both imitation and motor imagery performance. At a neurological level, both groups activated MNS regions to perform the task, however, no differences in activation patterns in MNS regions were observed between the DCD and control groups across all task conditions (action observation, motor imagery, action execution and imitation). This suggests that dysfunction of the MNS is unlikely to be the underlying mechanism of the motor deficits characteristic of DCD. While at this point our findings do not support a deficit in MNS function, this is one series of neuroimaging studies. Repeated studies in the area with similar findings are required before abandoning the MNS hypothesis. The finding that children with DCD had decreased activation in the thalamus, caudate, and posterior cingulate during imitation suggests that it is possible that the imitation, motor imagery, and motor acquisition
deficits observed behaviourally stem from dysfunction of other neural networks that also underlie and support these processes, such as motor planning and attentional networks. Future neuroimaging research using paradigms that target these processes has the potential to increase our understanding of the underlying mechanisms of DCD.

7.5 Limitations
While the findings of this thesis provide important evidence to counter the hypothesis that dysfunction of the MNS may be a causal mechanism of the motor deficits characteristic of DCD, the following limitations should be taken into consideration when applying these results to a broader population.

- These series of studies included only boys aged between 6 and 13 years. While only male children were included to eliminate potential gender differences in imitation and motor imagery, and to reflect the higher prevalence of males with DCD, future research would benefit from the inclusion of females with and without DCD.
- Children in the DCD group were not required to have a diagnosis, as diagnosis is not always pursued in Australia even when children are actively participating in a range of therapies. Although children included in the DCD group met the criteria for DCD, the DCD groups have been classified as probable DCD as a result.
- Numbers in the fMRI study were restricted due to the specific sample that we were aiming to recruit. Additionally, numbers were limited by the exclusion of children who had neurological abnormalities or who moved during the scanning session. While the numbers in our study are comparable to other neuroimaging studies, scanning a larger sample would increase power and may be more sensitive to identifying group differences in activations.
- The scan volume in the fMRI study could not be extended to include the cerebellum. Although this region has been implicated in DCD (Mariën et al., 2010; Zwicker et al., 2010, 2011), the focus of this research project was on the MNS. As the scan time was already a long duration for a paediatric sample (22.5 minutes), a trade-off was made to scan a smaller volume, and increase the number of task presentations in the fMRI protocol.
- There was no consumer involvement in the research planning phase, however, clinicians were involved across all phases of the project.
7.6 Implications and knowledge translation

The translation and integration of basic science research findings to clinical practice is an important phase of any research project. The knowledge translation gap between research and practice (T2 ‘translation to patients’ and T3 ‘translation to clinical practice’ research phases; Szilagyi, 2009) is well documented in health-care (Imms et al., 2015; Russell et al., 2015); this is particularly the case in DCD, where the gap is exacerbated by the fact we are still unsure of aetiology and mechanisms of this disorder. Importantly, in this research, although children with DCD displayed imitation and motor imagery deficits, children were still found to be able to engage in these processes while completing the tasks. As a result, intervention approaches grounded in these processes, including Action Observation Therapy (Buccino, 2014), Motor Imagery Training protocols (e.g. Imaginaction™; Wilson et al., 2016), or CO-OP interventions (Missiuna, Mandich, Polatajko, & Malloy-Miller, 2001) modified to incorporate observation or imagery phases may be beneficial to improve motor skill acquisition in this disorder. Preliminary findings from motor imagery training in this population suggests that children with DCD benefit from this intervention in a comparable manner to traditional perceptual-motor training (Wilson et al., 2002; Wilson et al., 2016).

Translational medicine uses neuroscience research findings to develop clinical intervention programs that target neural circuits underlying a disorder to promote functional improvement through neuroplasticity. Based on the principles of neural plasticity and neurorehabilitation (Nudo, 2006), intervention approaches targeting the processes associated with regions of grey matter volume or activation pattern differences may result in functional improvements in children with DCD. Although imitation and motor imagery interventions have been demonstrated to be beneficial, given the variability in performance at a behavioural level, and the absence of differential activation patterns within the MNS at a neural level, these programs may not be beneficial for all children with DCD. Interventions that are able to address the core neural deficits of DCD to induce neuroplastic changes in the brain at the neuronal, as well as regional and network levels, are likely to have better outcomes. Based on the VBM and fMRI research presented in this thesis, intervention approaches targeting motor planning, attention, and executive functioning might be the most beneficial. For example, neurofeedback interventions (theta/beta band training) in children with ADHD have been demonstrated to improve inattention, impulsivity and hyperactivity symptoms (e.g. Gevensleben et al., 2009). However, further research is required to explore these processes at a basic research
level, to enable the development of more effective means of early diagnosis, and targeted and transferable intervention programs.

### 7.7 Future research

In order to move towards the goal of targeted intervention approaches in DCD, a greater understanding of the aetiology of DCD and the mechanisms by which it acts on behavioural outcomes is required. This is particularly the case given the heterogeneity of expression of this disorder. Further research that explores genetics and biomarkers (aetiology), and brain structure and function (mechanisms) using task paradigms based on evidence-based hypotheses will advance our understanding of, and ability to treat, this disorder. Increased knowledge surrounding biomarkers and risk factors for DCD is likely to facilitate earlier diagnosis through a combination of examination of risk factors, neuroimaging, and clinical examinations; early diagnosis is an important goal to enable early intervention (ideally less than two years of age), to capitalize on the opportunity to implement interventions during the maximal window of neuroplasticity.

#### 7.7.1 Genetics and biomarkers

Despite the reportedly high heritability of DCD, with estimates to be around 70% (Martin, Piek, & Hay, 2006), only one study specifically exploring the genetics of DCD has recently been published. This paper explores the contribution of copy number variations (CNVs) to the genetics of DCD and suggests the involvement of an increased number of rare CNVs, as well as of genes involved in frequently co-occurring neurodevelopmental disorders (Mosca et al., 2016). In addition, research exploring the phenotypic presentation of 16p11.2 deletion has identified that individuals with this deletion present with a high frequency of developmental disorders, including developmental coordination disorder (Hanson et al., 2015). Future research to identify genetic variants which are potentially causative or a risk factor, including both heritable forms and de novo cases of DCD, could help inform early screening for DCD and research directions for this disorder. Furthermore, given the phenotypic similarities and high levels of comorbidity of DCD with other neurodevelopmental disorders (e.g., ASD, ADHD, dyslexia, and speech disorders), research to determine if the genetic profile for DCD is also reminiscent of these has the potential to increase our understandings of the aetiology of DCD. Research beyond a DCD cohort to gain a greater understanding of the genetic variants contributing to the mechanisms of movement dysfunction across these neurodevelopmental disorders has the potential to further our understanding of movement dysfunction and the overlap
of these disorders. In addition, it may help to improve diagnosis, the applications of targeted interventions, and treatment outcomes. An exploration of the relationship between genetic variants and brain morphology and function has the potential to further our understanding of the mechanisms through which possible genetic variants associated with this disorder act, and enable earlier monitoring and diagnosis.

7.7.2 Brain morphology

Although no hard neurological signs are currently associated with DCD, it is possible that differences in micro- or macrostructure that are not identifiable through routine imaging may contribute to the motor deficits associated with this disorder. Disruptions to typical development of grey and white matter micro- and macrostructure, have the potential to impact on functional activation patterns and behavioural outcomes. Differences in brain structure have been identified to be characteristic of a range of neurodevelopmental disorders that have a high level of comorbidity with DCD (Brambilla et al., 2003; Bush, 2011; Nickl-Jockschat et al., 2012; Richlan et al., 2013; Valera et al., 2007). Despite these findings, still little is known about white (Langevin et al., 2014; Werner, 2013; Zwicker et al., 2012) or grey matter (Caeyenberghs et al., 2016; Langevin et al., 2015) structure in DCD, with only a small number of studies published. Future research to extend our understanding of brain microstructure could incorporate the use of diffusion tensor imaging with a large number of diffusion directions (e.g., 32-64 directions) and advanced fibre tractography methods (e.g., constrained spherical deconvolution) which addresses the crossing fibre problem of traditional DTI methods (Farquharson et al., 2013). The use of VBM, cortical thickness measures, quantitative multi-parameter mapping (Weiskopf et al., 2013), voxel-based quantification (VBQ; Callaghan et al., 2014), and structural connectomics (Fornito, Zalesky, & Breakspear, 2015; Griffa, Baumann, Thiran & Hagmann, 2013) techniques could be applied to further advance our understanding of brain macrostructure in this disorder, and how the integrity of structural connections influence function. It is also possible that these imaging techniques may, in the future, be able to assist in early diagnosis and be used as outcome measures for interventions.

7.7.3 Brain function

Functional neuroimaging research in DCD is steadily growing (Brown-Lum & Zwicker, 2015). The neuroimaging literature does not currently provide clear support for the involvement of any one specific network or brain regions that have been hypothesised to contribute to this disorder. This is the result of the very different paradigms utilised,
differences in acquisition strategies and data analysis procedures, and group inclusion criteria. The tasks performed during imaging have been highly variable, each designed to explore specific hypotheses surrounding the motor deficits of DCD. As similar tasks have not been used across research, nor replication studies performed, meta-analyses (e.g., activation likelihood estimation meta-analyses) of either structural or functional results are not able to be conducted, and it is difficult to interpret and apply these results to other task contexts. Interestingly, aside from work by Zwicker and colleagues (2010, 2011), only small differences in brain activation patterns (often at an uncorrected level) between children with and without DCD have been observed using fMRI during a range of tasks (Debrabant et al., 2013; Kashiwagi et al., 2009; Licari et al., 2015; Reynolds, Licari, Billington et al., 2015) In combination with the specificity of tasks utilized, this has resulted in limited overlap of regional activation difference results between studies. Current imaging research in DCD is moving towards including groups with single-, as well as co-morbid neurodevelopmental disorders, or comparing different neurodevelopmental disorders (e.g., Caeyenberghs et al., 2016; Langevin et al., 2014, 2015); this is a promising direction as it enables an exploration of the unique and shared pathways of these disorders.

The results of the structural and functional MRI studies in this thesis (Studies 4 & 5) provide support for hypothesised deficits in motor planning, generating internal models and the use of feedforward information (Adams et al., 2014) and attentional processes. Deficits in motor planning and attentional processes at a neurological level are consistent with the behavioural deficits observed in DCD (Wilson et al., 2013) and may underlie the motor deficits. To evaluate these hypotheses further, further neuroimaging research to explore these processes is necessary. Differences in neural connectivity and brain network integrity have been hypothesised to contribute to a range of neurodevelopmental disorders (Rudie et al., 2013; Uddin et al., 2008; Weng et al., 2010). Research to explore brain function at a network level also appears to be a research direction that can increase our understanding of DCD. For example, resting state fMRI and the use of dynamic causal modelling to explore effective connectivity (excitatory and inhibitory driven connections) between brain regions has the potential to shed further light on the connectivity of a range of networks which may have an involvement, such as the default mode network, salience network, and dorsal attention network. The combined use of different imaging techniques (e.g., paired EEG and fMRI) will be able to provide a more holistic view and understanding of this disorder across different temporal and spatial resolution scales.
There are a number of important considerations for any future fMRI research being undertaken in this population. These considerations span across all levels of research methodology, from study design, task selection, scanning paradigm to data analysis. The selection of appropriate tasks and rest/baseline conditions to explore hypothesis and data driven research questions is an important factor in the design of fMRI studies. This will ensure that there is a contribution to our understanding of the underlying mechanisms of DCD. Scanning paradigms (block design/event related), length of scanning sessions, and data acquisition sequences should also be considered during the study design phase. For comparison of results across studies, it is important that the statistical thresholds that are being utilised for comparisons are clearly stated. The most stringent statistical procedures should be favoured, such as family wise error (FWE) or false discovery rate (FDR) controls for the multiple testing problem (Nichols & Hayasaka, 2003) at a voxel peak level run at $p < 0.05$, followed by cluster corrections, such as a FWE correction for multiple comparisons at a cluster level of $p < 0.05$ (based on an uncorrected voxel height threshold of $p < 0.001$; Friston et al., 1996). In some cases, the corrections applied may be too stringent, and while it is acceptable to then present data at an uncorrected voxel peak level of $p < 0.001$, this should be clearly stated and results interpreted with caution. Furthermore, statistical comparisons of the activation patterns between conditions and groups (e.g., Group X > Group Y contrast) should be undertaken, rather than a comparison of the clusters that are found to be significant in each group individually (Group X activation and Group Y activation reported and differences in these interpreted). Clear procedures for ROI selection, for ROI analyses, or structural equation modelling/dynamic causal modelling need to be specified. Finally, analyses should avoid circularity or double dipping of data (the use of the same data set to select regions for analysis; Kriegeskorte, Simmons, Bellgowan, & Baker, 2009).

7.8 Significance of this research
A summary of findings and future research directions is presented in Figure 7.1. Children with DCD experience movement difficulties that lead to activity limitations at home, school and in the community. If left untreated, the motor difficulties can extend to impact children’s emotional and social development, which often continue through adulthood. Although there is a relatively good understanding of the behavioural motor impairments characteristic of DCD, limited research has been undertaken to explore the mechanisms of this disorder at a neurological level. The research undertaken for this thesis addressed
the question: are deficits in MNS function an underlying mechanism of DCD? Although children with DCD had deficits when performing behavioural tasks designed to assess MNS function, no deficits in this system were identified at neurological level. Instead this research suggests that reduced grey matter volume and activation in motor planning and attention regions may contribute to this disorder. Although deficits in MNS function were not identified, this thesis has identified other potential mechanisms contributing to DCD, and has identified important future research directions. Further research on the underlying aetiology of DCD through genetics, in combination with neuroimaging research to increase our understanding of the underlying mechanisms through which it acts, will improve our understanding of this disorder and enable earlier detection and treatment. A greater understanding will enable us to move closer towards the goal of translational intervention approaches that can improve the quality of life for children and adults living with DCD.
Figure 7.1. Summary of research findings and future research directions.

**PROBLEM?**

Aetiology and mechanisms of Developmental Coordination Disorder remain unknown

1. Understanding based on behavioural research
2. Limited neuroimaging studies
3. Targeted interventions have not been based on aetiology or underlying neural mechanisms

It has recently been hypothesised that a defect in the functioning of the mirror neuron system (MNS) may be an underlying mechanism of the movement difficulties associated with DCD

**Could it be the mirror neuron system?**

The MNS is thought to be a cluster of multimodal neurons in the central nervous system that fire when a person observes, acts, or imagines an action performed

Current behavioural and neuroimaging literature provides preliminary support for deficits in this system

**Does behavioural evidence support it?**

Consistent with possible MNS dysfunction, children with DCD had deficits imitating novel gestures and sequences of gestures

Children with DCD were slower and less accurate than controls during a complex motor imagery task

Deficits in these processes are more evident as task complexity increases

**Does neuroimaging evidence support it?**

Children with DCD had reduced relative grey matter volume in right pre-motor frontal lobe regions

fMRI findings did not support a deficit in the MNS

Structural and functional MRI findings suggest reduced motor planning capabilities and attentional processing may be involved in the motor deficits

**SOLUTION?**

Based on behavioural deficits in associated processes, action observation, modified CD-OP, and motor imagery training programs may be beneficial for improving motor skills in this population

Further research to shed light on possible aetiology and mechanisms of DCD could incorporate an analysis of:
- Genetics and links with other neurodevelopmental disorders
- Brain micro- and macrostructure
- Motor planning and attentional processes at a neurological level
- Neural networks
- Combined use of imaging techniques

Improved quality of life for children with DCD

1. What is the evidence for MNS dysfunction in DCD? A systematic review
2. Imitation of unlearned actions in children with probable DCD
3. Motor imagery performance in children with probable DCD
4. Reduced relative grey matter volume regions in DCD: A voxel based morphometry study
5. Mirror Neuron Activation in Children with DCD: A replication fMRI study
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Bruyer, R., & Brysbaert, M. (2011). Combining speed and accuracy in cognitive psychology: Is the inverse efficiency score (IES) a better dependent variable than
the mean reaction time (RT) and percentage of errors (PE)? *Psychologica Belgica, 51*, 5-13.


to-understand-the-working-brain/brain-mapping-of-developmental-coordination-disorder


APPENDICES
APPENDIX A: ARTICLES

This appendix includes one additional related paper on MNS function, published by the candidate (Reynolds, Licari, Billington et al., 2015). A summary infographic for stakeholders is also presented following the article.


- This is the first published paper to explore MNS function in children with DCD at a neurological level.

The aims of this paper are to explore:

- MNS function in children with DCD at a neurological level using fMRI.
- Neurological correlates of imitation in children with and without DCD.
- The relationship between behavioural measures of imitation and cortical activation patterns.

It is hypothesised that:

- Children with DCD will have different activation patterns compared to controls in one or a combination of MNS areas.
Mirror neuron activation in children with developmental coordination disorder: A functional MRI study

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Cortical function

The aim of this study was to reveal cortical areas that may contribute to the movement difficulties seen in children with Developmental Coordination Disorder (DCD). Specifically, we hypothesized that there may be a deficit in the mirror neuron system (MNS), a neural system that responds to both performed and observed actions. Using functional MRI, 14 boys with DCD ($\bar{x} = 10.08$ years $\pm 1.31$, range $= 7.83 – 11.58$ years) and 12 typically developing controls ($\bar{x} = 10.10$ years $\pm 1.15$, range $= 8.33 – 12.00$ years) were scanned observing, executing and imitating a finger sequencing task using their right hand. Cortical activations of mirror neuron regions, including posterior inferior frontal gyrus (IFG), ventral premotor cortex, anterior inferior parietal lobule and superior temporal sulcus were examined. Children with DCD had decreased cortical activation mirror neuron related regions, including the precentral gyrus and IFG, as well as in the posterior cingulate and precuneus complex when observing the sequencing task. Region of interest analysis revealed lower activation in the pars opercularis, a primary MNS region, during imitation in the DCD group compared to controls. These findings provide some preliminary evidence to support a possible MNS dysfunction in children with DCD.

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1. Introduction

Development Coordination Disorder (DCD) is a neurodevelopmental condition characterized by impaired motor coordination that significantly interferes with an individual’s academic achievement and performance of daily activities (American Psychiatric Association, 2013; Cermak et al., 2002). It is the most prevalent childhood movement disorder affecting about 6% of children (World Health Organisation, 2010; American Psychiatric Association, 2013). Individuals with DCD present with a wide spectrum of difficulties including poor fine and gross motor skills (such as dressing, tying shoeaces, handwriting and playing sports), (Zwicker et al., 2009, 2011) balance, and postural control (Geuze, 2005). More recently, deficits in imitation ability (Dewey, 1993; Elbasan et al., 2012; Goyen et al., 2011; Sinani et al., 2011; Zoia et al., 2002) have been highlighted. The etiology of DCD is currently unknown but it is generally thought to be related to a deficit in the functioning of the central nervous system (CNS) (American Psychiatric Association, 2013; Flouris et al., 2005; Steinman et al., 2010; Zwicker et al., 2009). A relatively new neural model to be implicated in DCD relates to a potential deficit in the functioning of the mirror neuron system (MNS) (Licari et al., 2015; Reynolds et al., 2015; Steinman et al., 2010; Werner et al., 2012), a fronto-parietal network of brain regions playing an integrative role in imitation of motor skills. Due to its essential role in mediating imitation (Heiser et al., 2003), and its role in visual motor learning (Cross et al., 2006, 2009), dysfunction of the MNS has the potential to impact on the formation of motor representations and learning of new skills.

Mirror neurons were first discovered using single cell recordings, in a sector (area F5) of a macaque monkey’s ventral premotor cortex (di Pellegrino et al., 1992; Fogassi and Gallese, 2002; Gallese et al., 1996) and subsequently within the prefrontal cortex (Gallese et al., 2002). Numerous neurophysiological and brain imaging stud-
MNS in humans is thought to be critical for imitation (Heiser et al., 2003). The MNS is generally considered to be a biologically primitive system that has been conserved across species and is thought to reflect the mirror properties of the mirror neuron system. The mirror neuron system encompasses areas in the human brain that are thought to constitute the pars opercularis of the inferior frontal gyrus (IFG; Brodmann area (BA) 44), the ventral premotor cortex (BA 6), the inferior parietal lobule (IPL), and the superior temporal sulcus (STS; Rizzolatti and Craighero, 2004; Rizzolatti and Matelli, 2003) (see Craighero, 2004), and inferior parietal lobule (Arbib et al., 2000; Grafton et al., 1996; Rizzolatti et al., 1996b; Rizzolatti and Craighero, 2004; Iacoboni and Dapretto, 2006; Iacoboni et al., 1999; Licari et al., 2015). It was hypothesized that there will be decreased activation in the MNS of children with DCD, specifically in the pars opercularis of the IFG, ventral premotor cortex, inferior parietal lobule, and superior temporal sulcus, most prominent during the action imitation condition. In addition, this study also explored other cortical areas that may contribute to the movement difficulties seen in children with DCD.

2. Methods

2.1. Participants

Twenty-seven right-handed male children, aged 8 – 12 years participated in this study. Participants were divided into two groups: Group 1 consisting of 15 males with DCD, one of whom was later excluded as a result of excessive head movement during scanning (n = 14, x = 10.58 years ± 1.31, range = 7.83 – 11.58 years), and Group 2 consisting of 12 group age-matched typically developing controls (x = 10.10 years ± 1.15, range = 8.33 – 12.00 years). Only males were recruited to eliminate potential gender differences that may exist in cortical activation patterns (Cheng et al., 2006), or imitation ability (Chipman and Hampson, 2007). Participants in Group I were recruited from the Paediatric Exercise Programs at The University of Western Australia (UWA). Children are referred by a range of clinicians to these programs based on their movement difficulties interfering with their daily living, which stem from a range of neurodevelopmental (including DCD), and other disorders, to undertake one-on-one, or group, movement-based intervention programs. The participants were currently attending these programs, with participation usually spanning multiple years. Although not all children had a formal diagnosis of DCD, inclusion was based on movement difficulties interfering with their daily living evidenced through referral to our programs, and MABC-2 scores ≤16th percentile. Group 2 participants con...
sisted of a convenience sample obtained from the community. All children from both groups attended regular schools. Ethics approval was obtained from the Human Research Ethics Committee (RA/4/1/5275) at UWA. Written consent was obtained from parents prior to the commencement of the study and ongoing verbal assent from participants throughout each phase of the study.

2.2. Experimental design

Participants were required to attend two testing sessions. During the first session, participants completed motor and diagnostic screening assessments to ensure that they met the diagnostic criteria for inclusion. Participants also completed a practice fMRI session to familiarize themselves with the scanning environment (noise, confined space, head coil and restraints), to practice the behavioral task to be performed, as well as develop skills to enable them to lie still for a readable scan. This familiarization protocol has been used successfully in previous investigations by researchers involved in this study (Licari et al., 2015). The second session involved the use of fMRI to examine differential brain activations as children performed a finger sequencing task. This session was conducted at the Department of Radiology at Sir Charles Gairdner Hospital.

2.3. Screening assessments

Motor proficiency was assessed using the Movement Assessment Battery for Children – 2nd edition (MABC-2; Henderson et al., 2007). The total score for each task was adjusted for age, summed and converted into a percentile where a score of ≤16th percentile indicated low motor proficiency and ≥20th percentile indicated normal motor proficiency. Due to the comorbidity of DCD with other neurodevelopmental conditions such as attention deficit hyperactivity disorder (ADHD) and autism spectrum disorder ( ASD), children with a diagnosis of these disorders were excluded to reduce potential confounding factors. In addition, the Swanson, Nolan and Pelham-IV (SNAP-IV) ADHD questionnaire (Bussing et al., 2008) and the Childhood Autism Rating Scale (CARS; Saemundsen et al., 2003; Schopler et al., 1988) were used to assess symptoms of ADHD and autism, and children scoring within a clinical symptom range were also excluded. Handedness was screened using the Edinburgh Handedness Inventory (EHI; Oldfield, 1971) and only right-handers (score ≥ 40) were included. Lastly, the Postural Praxis imitation test of the Sensory Integration and Praxis Tests (SIFT) developed by Ayres (1972) was used to assess participants’ imitative ability. The test involved participants imitating a series of novel meaningless postures accurately and quickly (e.g. ‘one hand on side of head, other hand on hip, head and trunk leaning’; Ayres, 1972). Results were computer generated by Western Psychological Services headquarters in California.

2.4. Behavioral task

Participants performed a finger sequencing task (Licari et al., 2015) (see Fig. 2) using their dominant (right) hand under three separate conditions: (i) action observation, (ii) action execution, and (iii) action imitation; a common protocol in previous MNS fMRI studies (Aziz-Zadeh et al., 2006; Iacoboni et al., 1999; Molenberghs et al., 2009). The finger sequencing task to be observed and executed remained the same across all conditions. During action observation, participants viewed the finger sequencing task and were prompted with a red colored circle to observe the sequence but not execute or imitate the task. In the action execution condition, participants were prompted by a green colored circle to perform the finger sequencing task with a still shot of the first hand stimulus image on the screen. Lastly, in the action imitation condition, participants viewed the sequencing task and were prompted with a green colored circle to imitate the actions as they observed them. Each condition lasted for approximately 18 s with 12 s of rest (baseline condition) between each to allow for the blood-oxygen-level dependent (BOLD) response to return to baseline. Participants completed a total of eight repetitions of each condition performed in a randomized ordered across the two 6-min functional scans. Along with the visual cues, a metronome tick (0.8 Hz) was used to coordinate the timing of movements performed in each condition. An assessor observed the performance of tasks within the scanner to ensure tasks were completed correctly. While no quantitative measures were obtained, both groups appeared to successfully perform the finger sequencing task, and to perform the correct movements required for the conditions presented.

2.5. Imaging parameters

Neuroimaging was conducted using a 3.0 T Philips Magnetic Resonance Scanner, with participants wearing an 8-channel head coil. High-resolution anatomical images were acquired first (254 s; T1-weighted 3D FFE 160 slices 0.575 mm × 0.575 mm × 1 mm), followed by two six minute functional studies. Total scan time was 18.5 min. The participants’ heads were restrained with soft pads to prevent small, unwanted movements from causing artifacts. A strap was used also to help immobilize the wrist and forearm of the active hand during the scan in order to minimize participant head movement during scanning. Functional images were collected using 25 slices covering the whole brain (slice thickness 4 mm, inter-slice distance 0 mm, in-plane resolution 1.8 mm × 1.8 mm) with an echo planar imaging sequence (TR = 3 s, TE = 35 ms, flip angle = 90◦). 120 scans (plus 2 dummy scans) per run were acquired. This study employed a block design and all fMRI data analysis was carried out using SPM8 software (Wellcome Department of Cognitive Neurology, London). Prior to analysis, all images were corrected for slice timing using the
middle slice as a reference slice. In-scanner motion was checked for each participant, one DCD participant was removed at this stage for displaying >9 mm of motion. All other participants displayed minimal motion (<1.5 mm) and there was no apparent difference between the DCD and control groups. This outcome advocates the benefits of having pre-scanning training sessions for children participating in experimental studies. A stringent fourth degree b-spline interpolation realignment procedure was applied to the images to realign to the first image in the sequence. Functional images were co-registered to the structural image. All images were smoothed with a full width half maximum Gaussian kernel of 8 mm.

Each run was split into blocks to reflect the observation, execution and imitation task conditions outlined above. Individual statistical contrasts were set up by using the general linear model to test the null hypothesis of no difference in the MNS, the present study contrasted the main effect of each individual condition (i.e. observation, execution and imitation) against rest/baseline using exploratory whole brain analysis. Second level between-group contrasts, the effect of multiple comparisons (FWE) rate to remove activations that may have occurred by chance at any predetermined threshold (Worsley et al., 1992). An extent threshold of k > 5 voxels was set. In order to examine the signal activation patterns of the MNS, the present study contrasted the main effect of each individual condition. Significant differences were identified at a corrected level. First level significance set at p < 0.001, followed with cluster significance set at p < 0.05.

Percent signal change values were extracted from 15 a priori regions of interest created in MarsBar region of interest toolbox for SPM (MarsBar; http://marsbar.sourceforge.net). Each region of interest consisted of a 10 mm diameter sphere, centered on the coordinates reported in the study by Aziz-Zadeh et al. (2006). This included regions in the pars opercularis of the IFG, supplementary and premotor areas, posterior parietal lobe, and superior temporal sulcus.

3. Results

3.1. Clinical characteristics of participants

The clinical data of participants are presented in Table 1. Group differences were observed in participants’ motor proficiency, imitation ability and autistic traits. As expected, the DCD group had significantly poorer motor performance as compared to the control group on the MABC-2 (p = 0.001; Henderson et al., 2007). From the Postural Praxis assessment, children with DCD had a formal diagnosis of the disorder. No significant differences were found in the age and screening assessments for ADHD and handedness.

3.2. Whole brain analysis

The first stage in the analysis was to ensure that MNS regions were activated during the task paradigm. Based on MNS theory, and activation patterns among healthy controls of varying skill levels (Calvo-Merino et al., 2005), it was hypothesized that both children with and without DCD would display varying extents of MNS activation. As a result, the DCD and control groups were collapsed and a series of whole brain analysis were carried out to identify if cortical areas typically associated with the MNS were activated during the tasks. To explore MNS activation patterns and identify whether there was a characteristic progressive increase in BOLD signal from action observation, to action execution and to imitation (Aziz-Zadeh et al. 2006; Iacoboni et al., 1999) during the sequencing task, the main effect of the observation condition was contrasted against baseline, and the execution and imitation conditions contrasted against observation. Importantly, activation in MNS regions was not identified. During the observation condition, there were significant activation clusters in the extrastriate cortex of the occipital lobe (BA 18 and BA 19) compared to baseline (see Fig. 3). Furthermore, when children performed the task in the action execution (dark green in Fig. 3) and action imitation (light green in Fig. 3) conditions, compared to the observation condition, additional clusters of activation were reported in the postcentral gyrus, medial frontal gyrus and insula. A small cluster in the IFG had a higher activation during the execution than observation condition. Interestingly, there were no differences in cortical activation when the execution and imitation conditions were compared. All of the specific regions with coordinates where differences were seen across the conditions are presented in both Table 2 and Fig. 3.

3.3. Whole brain analysis: group X condition comparison

When group differences were compared individually within each condition, the control group was found to have significantly more activation than the DCD group during observation compared to baseline in the right pars opercularis of the IFG, the precentral gyrus bilaterally, the left middle temporal gyrus, left posterior cingulate, and the right precentral gyrus. No significant differences were seen between groups in the action execution condition or action imitation conditions when run at uncorrected value of p < 0.001.

3.4. Regions of interest analysis

A series of 2 × 3 mixed ANOVAs were run in MATLAB (http://mathworks.com; code: Johnson, 2010) for each region of interest (Fig. 5) on the percent signal change values extracted from individual participants. Region of interest analysis yielded a significant (p < 0.05) main effect for task condition in mirror neuron regions including the pars opercularis, posterior parietal regions (inferior parietal lobule), supplementary and premotor areas as well as the superior temporal sulcus (see Table 4). Post-Hoc analysis (Bonferroni corrected within each ROI, p < 0.0083) revealed significantly greater activations during both the execution and imitation conditions compared with observation condition in the posterior
Table 2
Whole brain analysis for collapsed DCD and control groups – condition comparison (FWE, \( p < 0.05 \)).

<table>
<thead>
<tr>
<th>Anatomical region</th>
<th>Cluster (k)</th>
<th>Talairach coordinates x y z</th>
<th>Brodmann area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Observation &gt; baseline</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle occipital gyrus (R)</td>
<td>2279</td>
<td>47 -72 5 19</td>
<td></td>
</tr>
<tr>
<td>Precuneus (R)</td>
<td></td>
<td>22 -55 56 7</td>
<td></td>
</tr>
<tr>
<td>Middle occipital gyrus (L)</td>
<td>804</td>
<td>-47 -72 5 19</td>
<td>19</td>
</tr>
<tr>
<td>Cuneus (L)</td>
<td></td>
<td>-31 -88 6 18</td>
<td>18</td>
</tr>
<tr>
<td>Middle frontal gyrus (R)</td>
<td>9</td>
<td>33 2 57 6</td>
<td>6</td>
</tr>
<tr>
<td>Precuneus (L)</td>
<td>6</td>
<td>-22 -76 35 19</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td>417</td>
<td>-24 -52 52 7</td>
<td>7</td>
</tr>
<tr>
<td><strong>Execution &gt; observation</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Postcentral gyrus (L)</td>
<td>934</td>
<td>-38 -24 55 3</td>
<td>3</td>
</tr>
<tr>
<td>Medial frontal gyrus (L)</td>
<td>244</td>
<td>-4 -3 50 6</td>
<td>6</td>
</tr>
<tr>
<td>Insula (L)</td>
<td>382</td>
<td>-45 -4 6 13</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-40 -19 14 13</td>
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<tr>
<td>Postcentral gyrus (L)</td>
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<td></td>
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<tr>
<td>Cuneus (R)</td>
<td></td>
<td>6 -57 -6</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>51 -21 51 2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>37 -10 58 6</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>13</td>
<td>46 0 9 44</td>
<td>44</td>
</tr>
<tr>
<td>Inferior frontal gyrus (L)</td>
<td>22</td>
<td>-56 6 27 9</td>
<td>9</td>
</tr>
<tr>
<td>Thalamus (L)</td>
<td>52</td>
<td>-17 -24 10 13</td>
<td>Pulvinar</td>
</tr>
<tr>
<td><strong>Imitation &gt; observation</strong></td>
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<td></td>
<td></td>
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<td>Postcentral gyrus (L)</td>
<td>681</td>
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<td>3</td>
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<tr>
<td>Medial frontal gyrus (L)</td>
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<td>6</td>
</tr>
<tr>
<td>Insula (L)</td>
<td>89</td>
<td>-40 -19 14 13</td>
<td>13</td>
</tr>
<tr>
<td>Postcentral gyrus (L)</td>
<td>681</td>
<td>-38 -24 55 3</td>
<td>3</td>
</tr>
<tr>
<td>Thalamus (L)</td>
<td>40</td>
<td>-45 -4 6 13</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 3
Between group analysis of observation > baseline condition (uncorrected, \( p < 0.001 \)).

<table>
<thead>
<tr>
<th>Anatomical region</th>
<th>Cluster (k)</th>
<th>Talairach coordinates x y z</th>
<th>Brodmann area</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Control &gt; DCD</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferior frontal gyrus (R)</td>
<td>7</td>
<td>58 6 27 9</td>
<td>9</td>
</tr>
<tr>
<td>Precentral gyrus (L)</td>
<td>44</td>
<td>-45 -8 35 6</td>
<td>6</td>
</tr>
<tr>
<td>Precentral gyrus (R)</td>
<td>30</td>
<td>54 1 39 6</td>
<td>6</td>
</tr>
<tr>
<td>Middle temporal gyrus (L)</td>
<td>12</td>
<td>-35 -56 12 19</td>
<td>19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-36 -53 4 19</td>
<td>19</td>
</tr>
<tr>
<td>Precuneus (R)</td>
<td>9</td>
<td>14 -66 20 31</td>
<td></td>
</tr>
<tr>
<td>Posterior cingulate (L)</td>
<td>40</td>
<td>-24 -61 9 30</td>
<td></td>
</tr>
</tbody>
</table>

parietal regions, premotor and supplementary motor areas. There was also increased activation during the observation condition when compared to the imitation condition in a region of the premo-
tor cortex (BA 6). No significant between-group differences were observed. An interaction effect between group and task condi-
tion was revealed in the pars opercularis (BA 44; \( x = -36, y = 14, z = 24 \)), with the control group displaying greater activation during imitation compared to the DCD group; and vice versa for the obser-
vation condition (\( p = 0.05 \)). Interestingly, compared to the control
group (% signal change = 0.10, SE = 0.21), children with DCD (% sig-
nal change $=-0.40$, SE = 0.15) showed a large deactivation in the pars opercularis during the imitation condition.

3.5. Correlation with Postural Praxis imitation performance

Performance scores for imitation were entered as a covariate for the imitation > baseline contrast. Second level positive and negative correlations at a whole brain level were first run at an uncorrected level of $p<0.001$, followed with a cluster level significance set at $p<0.05$. A positive correlation between imitation performance and activation clusters in the left caudate, claustrum, and anterior cingulate was observed (cluster level $p<0.05$). An uncorrected negative correlation between activation in the right cingulate gyrus and posterior insula was also identified (uncorrected $p<0.001$, $k>75$; Table 5).

Given the established involvement of the pars opercularis in imitation (Caspers et al., 2010; Iacoboni et al., 1999), data were assessed for normality, following which Pearson correlations were run to explore the correlation between imitation performance on the Postural Praxis and activation values extracted from the three pars opercularis regions of interest during the imitation condition. Significant positive correlations were identified in two pars opercularis regions: TAL $=-47, 8, 6$, $r=0.402$, $p=0.042$; and TAL $=-36$, $14, 24$, $r=0.588$, $p=0.002$.

4. Discussion

The present study examined cortical areas that may contribute to the movement difficulties seen in children with DCD, specifically suspected deficits in the functioning of the MNS regions. The
DCD group was found to have reduced activation during the action observation condition in MNS related regions, including the pre-central gyrus and IFG using exploratory whole brain analysis. Using region of interest analysis, a significant interaction effect of group and condition in the pars opercularis (BA 44), precuneus (PCC/Pcu) complex during the action observation condition, with children with DCD displaying reduced activation compared to controls. Of importance to the current study is the significant interaction effect of group and condition in MNS related regions, including the pre-central gyrus, and the posterior cingulate gyrus (Rizzolatti et al., 1996a) and intention understanding (Fogassi et al., 2005). A further examination of the percentage BOLD signal change for the pars opercularis revealed that while there was a mean activation of this region in the control group, there was a large deactivation in the DCD group during the imitation condition. A deactivation in the BOLD signal has been reported to either reflect a local reduction in regional cerebral blood flow (rCBF) to less active brain regions or an inhibition of neural processes in brain regions that are not task relevant (Tomasi et al., 2006). It is unlikely that the deactivation of BOLD signal observed in the DCD group was a result of neural inhibition of task-irrelevant brain regions since the control group activated the pars opercularis during imitation, and numerous MNS studies have reported its involvement during imitation. Thus, the deactivation observed in the pars opercularis during imitation is likely to be the result of reduction in rCBF, and potentially reflects dysfunction in this area and differences in neural activation patterns of children with DCD. Interestingly, there was a moderate activation of the pars opercularis in the DCD group during the action observation condition, with children with DCD displaying reduced activation compared to controls.

Table 4
Region of interest analysis of mirror neuron regions.

<table>
<thead>
<tr>
<th>Anatomical region</th>
<th>Talairach coordinates</th>
<th>Brodmann area</th>
<th>F(between-subjects)</th>
<th>p</th>
<th>F(within-subjects)</th>
<th>p</th>
<th>F(interaction)</th>
<th>p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pars opercularis</td>
<td>−47 8 6 44</td>
<td>1 6 52 6</td>
<td>0.204</td>
<td>0.656 3.915</td>
<td>0.027 1.613</td>
<td>0.210 Exe&gt;Obs</td>
<td>0.177</td>
<td></td>
</tr>
<tr>
<td>Superior temporal sulcus</td>
<td>−36 14 24 44</td>
<td>1 6 52 6</td>
<td>0.648</td>
<td>0.429 1.086</td>
<td>0.346 3.171</td>
<td>0.050 ns</td>
<td>0.144</td>
<td></td>
</tr>
<tr>
<td>Posterior parietal/occipital lobe</td>
<td>−56 −58 6 21</td>
<td>0.072 0.420 4.179</td>
<td>0.018 0.614</td>
<td>0.054 Obs&gt;Imi</td>
<td>0.144</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inferior parietal lobe</td>
<td>−52 −30 38 40</td>
<td>2.103 0.160 5.201</td>
<td>0.009 0.322</td>
<td>0.727 Exe&gt;Obs</td>
<td>0.184</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Premotor area</td>
<td>−32 2 58 6</td>
<td>0.233 0.169 1.494</td>
<td>0.235 0.074</td>
<td>0.929 ns</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−42 0 48 6</td>
<td>1.281 0.259 2.062</td>
<td>0.138 0.040</td>
<td>0.305 ns</td>
<td>ns</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−36 −4 56 6</td>
<td>0.467 0.501 10.028</td>
<td>&lt;0.001 1.01</td>
<td>0.372 Exe&gt;Obs</td>
<td>0.273</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−38 −3.1 54 6</td>
<td>0.520 0.478 4.052</td>
<td>0.024 0.999</td>
<td>0.376 Exe&gt;Obs</td>
<td>0.154</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>−30 −5 60 6</td>
<td>0.825 0.373 26.407</td>
<td>&lt;0.001 0.286</td>
<td>0.752 Imi&gt;Obs</td>
<td>0.532</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Supplementary motor area</td>
<td>−16 0 64 6 4</td>
<td>1.339 0.259 4.052</td>
<td>0.023 0.188</td>
<td>0.829 Exe&gt;Obs</td>
<td>0.154</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5
Imitation + baseline activation correlated with imitation performance scores (uncorrected, p < 0.001, cluster extent corrections).

<table>
<thead>
<tr>
<th>Anatomical region</th>
<th>Cluster (k)</th>
<th>Talairach coordinates</th>
<th>Brodmann area</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Positive (uncorrected, p &lt; 0.001, cluster level p &lt; 0.05)</td>
<td>Caudate (L) 146</td>
<td>−8</td>
<td>12</td>
<td>16</td>
<td>Caudate body</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Claustrum (L)</td>
<td>−6</td>
<td>11</td>
<td>23</td>
<td>Claustrum</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Anterior cingulate (L)</td>
<td>−6</td>
<td>11</td>
<td>23</td>
<td>Claustrum</td>
<td></td>
</tr>
<tr>
<td>Negative (uncorrected, p &lt; 0.001, k = 75)</td>
<td>Cingulate gyrus (R) 88</td>
<td>22</td>
<td>−44</td>
<td>34</td>
<td>Cingulate gyrus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Posterior insula (R)</td>
<td>−31</td>
<td>47</td>
<td>23</td>
<td>Posterior insula</td>
<td></td>
</tr>
</tbody>
</table>
Consistent with other MNS research (Buccino et al., 2001, 2004; Hari et al., 1998; Iacoboni et al., 1999b; Rizzolatti et al., 1996b), this study found activation of the precentral gyrus and IFG during the action observation condition. The precentral gyrus is also part of the primary motor area (M1) that plays a role in voluntary hand movements (Rose et al., 2012; Sanes et al., 1995) and motor imagery (Porro et al., 1996; Roth et al., 1996). The degree of activation within these regions, however, was not consistent between groups; a reduced level of activation in these areas in children with DCD compared to controls provides further support for potential dysfunction of the MNS and motor regions in this population. Activation of the precentral gyrus and IFG has consistently been observed during action observation and imitation studies (Caspers et al., 2010). Frontal MNS regions are thought to be involved in the coding of the goals of actions and the motor representation of observed movements (Iacoboni, 2005; Iacoboni and Mazziotta, 2007; Rizzolatti and Craighero, 2004). Furthermore, the essential role of the IFG in the MNS circuitry is highlighted by the impaired imitation performance that results when the activation of this region is disrupted by rTMS (Heiser et al., 2003). Possible dysfunction, and differences in activation patterns of mirror neuron regions in children with DCD have important implications in terms of visual learning and movement acquisition strategies, possibly impacting the way children with DCD observe, plan, and execute actions.

Differential activation patterns observed in non-mirror regions also point to children with DCD experiencing difficulties with action observation and imitation. Despite not being a ‘mirror’ region, the middle temporal gyrus has been shown to activate during the observation of hand movements (Decety et al., 1997; Rizzolatti et al., 1996b), and interestingly, lesions centered on this region have been associated with disturbed imitation of hand postures (Goldenberg and Karath, 2006). The posterior cingulate and precuneus (PCC/Pcu) complex is a main area of the default-mode network, which activates during action observation and movement readiness (Astafiev et al., 2003; Tresemer et al., 2009). In line with the reduced activation levels displayed in the DCD group during the observation condition, a study of action observation in expert and novice dancers (Calvo-Merino et al., 2005), found the activation of the posterior cingulate to be influenced by expertise with higher levels of activation in the expert group.

Activation in a number of non-mirror regions were identified to be positively correlated with imitation performance outside of the scanner environment. These regions, including the anterior cingulate, claustrum and the caudate, are involved in attentional processes, prioritizing attention, and attention-demanding tasks (Berger and Posner, 2000; Davis et al., 2000; Goll et al., 2015; Mathur, 2014). The positive correlation between these regions and imitation performance possibly indicates that individuals who were more proficient at imitating gestures outside the scanner, used greater attentional resources while imitating the finger sequencing during scanning. In line with this, a negative correlation between imitation performance outside the scanner and the cingulate gyrus (BA31) and posterior insula, functionally connected regions (Taylor et al., 2009), was identified. The posterior portion of the cingulate gyrus, is a component of the default mode network (Di and Biswal, 2014; Shulman et al., 1997), the activation of which is anti-correlated with task performance (Rossazz and Miniati, 2011; Shulman et al., 1997; Uddin et al., 2009); this also suggests greater in-scanner task engagement for those who performed better on the behavioral task. Potential differences in attentional capabilities is consistent with research by Quenne et al. (2008), which identified differences in attentional network connectivity strength in children with DCD compared to controls.

In addition to the group differences during observation and the group × condition interaction observed in the pars opercularis, there were some interesting within-subject patterns of activity seen within MNS regions in general. Complementing the whole brain activation maps, the superior parietal lobule and supramarginal regions were best seen between conditions using the region of interest analysis, with significantly greater activation during the execution and imitation conditions compared with observation in the posterior parietal regions, premotor and supplementary motor areas. These findings are consistent with those of Aziz-Zadeh et al. (2005) who found significant within-subject differences with activation greater during execution and imitation than the observation in the pars opercularis, inferior parietal lobule, premotor and supplementary motor areas (BA 6) as well as the superior temporal sulcus.

Unlike previous MNS research, however, where mirror neuron regions were found to follow an increasing pattern of signal activity (active during action observation, slightly more active for action execution and highest during action imitation) (Aziz-Zadeh et al. 2006; Iacoboni, 1999), the present study did not find any significant activation differences between the execution and imitation conditions in the whole-brain or ROI analysis despite the imitation condition stimulus having a greater visual component. Furthermore, no group differences were observed for either the execution or imitation contrasts at a whole brain 2nd level analysis level, and no significant between group differences were identified for region of interest percentage signal change values. These findings may in part be due to a learning effect from extensive practice of the finger sequencing task prior to scanning. Although both groups appeared to be successfully performing the mirror, sequencing task for both of these conditions, a limitation of the research is that no quantitative performance measures were collected. In addition, although participants in this study were instructed to use the visual prompts during the imitation condition, given the previous practice of the task, there is a possibility that they might have performed the sequencing movement in much the same manner as they did in the execution condition, performing the task from memory and relying on proprioceptive feedback. There were consistencies in the activation profiles of the postcentral gyrus, medial frontal gyrus and insula in both the execution and imitation conditions, providing further evidence of similarities between the two tasks. These areas are suggested to play important roles in motor control (Cunnington et al., 2002), motor learning (Mutschler et al., 2007), and also error processing (Mars et al., 2005; Ullsperger and Von Cramon, 2004). To circumvent the possible effect of motor learning, further research into MNS function in this population would benefit from the use of simple finger movements based on previous MNS research (such as directing the finger toward a target) (Aziz-Zadeh et al. 2006) that have not been practiced extensively prior to scanning, as this might elicit a true imitation response.

In addition to the potential learning effect seen in the task, there are some other minor limitations in our work. Due to a lack of anatomical maps in children and similar functional data, the region of interest analysis was based on adult data (Aziz-Zadeh et al., 2006). Adults may not map on to children perfectly, but it was felt that basing the ROIs on established coordinates was more accurate and objective than using anatomical ROIs. In addition, differences were seen between groups on the CARS, with children in the DCD group displaying more autistic-like symptoms. Whilst MNS dysfunction and imitation deficits have been implicated in autism (Williams et al., 2006; Dapretto et al., 2006), some of the items within autism questionnaires typically include questions related to movement. For example, the CARS includes questions about whether the child can imitate sounds, words, and movements which are appropriate for his or her skill level and the child moves with the same ease, agility, and coordination of a normal child of the same age (Schopler et al., 1988). This may explain the slightly elevated scores seen within the DCD group on this questionnaire. Despite being
statistically significant, the differences on these scales are likely not clinically significant with no children included who had scored within a clinical symptom range on either questionnaire. One further limitation of the research is that not all children in the DCD group had a formal diagnosis of DCD, and inclusion was instead based on MABC-2 scores. Despite this, all participants in the DCD group were recruited through the Paediatric Exercise Programs at the University of Western Australia, with their program attendance a result of the impact of their low motor skill proficiency on their daily living. Finally, although the sample size is comparable with other studies in this population, the sample is small. As a result, uncorrected statistics have been reported for group comparisons, which may have overstated some of the results for the observation over baseline contrast relating to the hypothesized MNS regions.

5. Conclusion and future directions

This study is the first in providing a preliminary understanding of the MNS functioning in children with DCD and adds to the small number of imaging studies in this population. While the results should be interpreted with caution due to small sample size and uncorrected whole brain fMRI statistics, this study provides some evidence to suggest that MNS dysfunction may exist in children with DCD, and that they may have adopted a different neural strategy while observing, executing and imitating during the performance of the task. In addition to the different activation patterns within MNS regions, the current study also identified differences in brain activation patterns during the tasks in a number of regions outside of the MNS, which contribute to movement performance. Recent neuroimaging work has shifted from exploring isolated brain regions, toward exploring functional connectivity and interactions of neural areas (RonaZZa and Miniatt, 2011); future work to explore functional and effective connectivity of MNS regions, and interactions between the MNS and other neural systems would also be of benefit in this population. Further research should investigate whether a MNS dysfunction in DCD may be localized to a particular phase of movement. This would provide better insights for professionals working with this population as they develop novel intervention strategies to address the associated motor impairments. For example, a number of motor skill intervention approaches based on MNS theory have been successfully used in other populations, such as action observation treatment (Ertelt et al., 2007) and motor imagery training (Buccino et al., 2006). Further research into MNS function has the potential to inform how these paradigms could be modified for use, and applied in a DCD cohort. Taken together, the mirror neuron hypothesis in DCD has potential in providing insights into the associated neural mechanisms of the movement difficulties associated with this condition.

Conflict of interest

The authors declare they have no conflict of interest.

Ethical approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the Human Research Ethics Committees at the University of Western Australia (RA/4/1/5275) and with the 1964 Helsinki declaration and its later amendments or comparable ethical approval.

Consent

Informed consent was obtained from all parents/guardians and ongoing verbal assent from individual participants included in the study.

Acknowledgments

The authors would like to thank the radiology staff from Sir Charles Gairdner Hospital involved in this project, and the children and parents for their time and participation.

References


Mirror Neuron Activation in Children with Developmental Coordination Disorder
A functional MRI Study

The MNS is thought to be a cluster of multimodal neurons in the central nervous system that fire when a person observes, acts, or imagines an action performed.

**Who participated?**

26 8-12 year old right handed boys:
14 boys with probable DCD
12 typically developing controls

**What did they do?**

Participants performed a right handed finger sequencing task. Three conditions: watching, doing, and imitating the sequence.

**What brain regions were active?**

To identify if mirror neuron regions were active, a series of exploratory whole brain analyses were run to explore the regions that were active during each task condition. MNS regions were found to be active.

**What were the group differences?**

There was a decreased activation in mirror neuron regions in DCD during action observation, in the inferior frontal gyrus, precentral gyrus, middle temporal gyrus, posterior cingulate, and precuneus.

16 mirror neuron regions were explored in greater detail using a region of interest analysis. During imitation, the pars opercularis was found to be activated in the control group, however, there was a large deactivation in the DCD group. The pars opercularis is a key component of the MNS, and plays an essential role in imitation.

**What are the implications?**

This study provides some evidence to suggest that MNS dysfunction may exist in children with DCD and that they may have adopted a different neural strategy. Dysfunction and differences in activation patterns of mirror neuron regions in children with DCD have important implications in terms of visual learning and movement acquisition strategies, and likely impact the way children with DCD observe, plan, and execute actions.

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APPENDIX B: PUBLISHED CONFERENCE ABSTRACTS

This appendix includes published conference abstracts that resulted from the work presented in this thesis.
Perceptual and sensorimotor timing in children with Attention Deficit Hyperactivity Disorder with or without Developmental Coordination Disorder

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Aims: There is a considerable body of studies showing that subjects with Attention Deficit Hyperactivity Disorder (ADHD) have deficits in a range of timing functions (Noreika, Futter, & Kubia, 2013). Nevertheless, little is known whether comorbidities influence those timing disorders. Fifty percent of children suffering from ADHD show severe motor disabili-
ties leading to a diagnosis of Developmental Coordination Disorder or DCD (Martin, Perk, & Hay, 2006). Timing deficits may also occur in certain subtypes of DCD population. Yet, it is unclear whether deficits are associated or not with motor factors. The aim of the present work is to examine perceptual and sensorimotor timing abilities in children with ADHD with and without associated DCD. We expect to find more severe deficits in sensorimotor timing tasks in children with DCD; –ADHD as they involve motor performance. However, differences are not expected in purely perceptual timing tasks.

Method: 23 DCD+ADHD children, 20 ADHD children, and 14 healthy age-matched controls, all from 7 to 14 years of age, took part in the exper-
iment. They were submitted to the Battery for the Assessment of Auditory Sensorimotor and Timing Abilities (BAASTA, Benoit et al., 2014) which consists of both perceptual timing and sensorimotor timing tasks. Each measure was submitted to a one-way ANOVA, with a significance level set at p < .05. Then, post hoc analyses using Tukey tests were performed.

Results: Data analysis is currently in progress. Preliminary results sug-
gest a greater impairment in timing abilities in the DCD+ADHD group as compared to ADHD and control groups, even when the tasks do not require a motor response. However, this difference is not visible with all timing measures. The ADHD group also tends to show worse timing capacities as the controls.

Discussion: The goal of this study was to examine the potential effect of DCD+ADHD condition on timing abilities. Our results will pave the ground to remediation methods aimed to improve perceptual, motor and sensorimotor abilities among children with neurodevelopmental disorders.

References:

Keywords: Timing abilities; DCD; ADHD; Comorbidities.

Do they ‘look’ the same? Comparing gaze patterns in school-aged children with and without developmental coordination disorder during a visual-motor task

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Aims: To compare gaze patterns in children with developmental coordination disorder (DCD) and typically developing (TD) children using an eye tracker during a fine motor pouring task performed in a natural setting.

Method: Using a mobile eye-tracker and gaze analysis paradigm, we compared visual fixation patterns in children with DCD and their TD peers during a serial motor task. Wearing eye tracking glasses, children...
References:
Keywords: Psychomotor disorder; Motor abilities; Developmental coordi- nation disorder; Pediatriic psychiatric disorder.

Inter-language reliability of the European-French Developmental Coordination Disorder Questionnaire’07 (DCDQ’07)
S. Ray-Kaesser1, E. Thommen2, R. Marin1 & A.M. Bertrand2
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Aims: Developmental Coordination Disorder (DCD) is a condition whereby coordination difficulties significantly interfere with the performance and participation in daily activities. Guidelines for identi- fying DCD recommend the use of a culturally adapted, reliable and valid parent questionnaire, such as the DCDQ’07, to measure the child’s performance in daily activities (Blank et al., 2011). The DCDQ’07 is a Canadian-English parent-report questionnaire that assesses children’s motor performance with respect to the three factors that consider impairment in DCD: “general coordination”, “fine motor/handwriting”, and “control during movement”. The European-French DCDQ (DCDQ-EF) was produced following Beaton et al. (2000) guide- lines for cross-cultural adaptation (Ray-Kaesser et al., 2015). When modifications followed these standard procedures, the reliability of the DCDQ-EF should not be assumed without assessment of its psy- chometric properties. The aims of this study were to: (1) assess the inter-language reliability between the DCDQ-EF and the DCDQ’07 (2) assess the internal consistency of the DCDQ-EF and (3) estimate its predictive validity.

Method: The participants (n=30) were all living in the French-speaking part of Western Switzerland. They were French and English-speaking parents of children (non-clinically-referred: n=22; clinically-referred: n=8), ranging in age from 5 to 14 years (Mean age (SD)= 8.8 (2.8)). Par- ents completed both the DCDQ’07 and the DCDQ-EF (random order) at approximately 1-month interval.

Results: The inter-language reliability of the DCDQ-EF was moderate to excellent for each item and the two factors “general coordination” and “control during movement” (ICC=0.63–0.92). However, there was a systematic difference between the mean of the original ques- tionnaire and that of the translated version for the factor “fine motor/handwriting” (diff=0.80, p<0.03) and for the total (diff=2.3, p<0.03). Cronbach’s Alpha coefficient for the 15 items was high (0.93). All item- total correlations were moderate to high (0.46–0.88). Using the cut-off scores established by Wilson et al. (2009) for the DCDQ’07, the overall DCDQ-EF sensitivity was 100% and specificity was 95% with this sample.

Discussion: The DCDQ-EF showed fairly similar internal consistency to the original DCDQ’07 and Canadian-French DCDQ, attesting to the homogeneity of all items. Furthermore, no item seemed to be problem- atic. However, given the systematic difference between the total score of the DCDQ-EF and that of the DCDQ’07, the appropriateness of the original cut-off scores may need further examination for use in French-speaking Switzerland.

References:
Keywords: DCDQ’07; Psychometric assessment; Reliability.

Imitation of complex gestures in children with Developmental Coordination Disorder
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Aims: It has been hypothesized that children with DCD have deficits in the functioning of the mirror neuron system (MNS). Deficits in MNS function may impair imitation, which is our primary method of learning motor skills. Previous research provides support for difficulties while imitating meaningful learned gestures, however, only a small number of studies have explored imitation of unknown gestures in children with DCD. The present study examined the imitation ability of children with and without DCD using unlearned complex gestures.

Method: 53 boys aged 6–13 years participated in this study, 29 with DCD (mean age = 9.29yrs ± 1.85) and 24 typically developing controls (mean age = 9.49yrs ± 1.78). Children were tested on the MABC–2, with children in the DCD group (66th percentile (mean percentile ± 5.69 ± 5.28, range ± 0.5–36) and typically developing controls (20th percentile (mean percentile ± 68.13 ± 20.32, range ± 25–98). Measures of imitation were collected using the standardized Postural Praxis and Sequencing Praxis components of the Sensory Integration and Praxis Tests (Ayres, 1989). Assessments were scored by two assessors (one blinded to group).

Results: Consistent with previous research, children with DCD displayed imitation deficits. Children with DCD had significantly lower scores than typically developing controls on the postural praxis (DCD median ± 21, control median ± 27.5, U = 69.5, p < 0.001). Similarly, children with DCD scored lower on the sequencing praxis (DCD median = 68, control median = 96.5, U = 118.0, p < 0.001), and in particular displayed difficulty with finger sequencing gestures (DCD median = 17, control median = 34, U = 170.50, p < 0.001).
Discussion: Initial evidence suggests imitation deficits in children with DCD. This provides behavioural level support for a deficit in MNS functioning. Given that visual learning, and learning by imitation is our primary modality of learning skills through modelling behaviour and actions, deficits in praxis have the potential to contribute to the motor deficits associated with DCD. A greater understanding of imitation performance in children with DCD has the potential to inform intervention programs for this population.

References:

Keywords: Imitation; Gestures; Sensory Integration and Praxis Tests; Mirror neuron system (MNS).

Can a Little instrument make a big noise? A cross-cultural collaboration for identifying motor delay in young preschoolers


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Aims: Even though Developmental Coordination Disorder (DCD) is typically not diagnosed before 5 years, identification and monitoring of younger preschool children at risk of being diagnosed with DCD may mitigate secondary complications and participation difficulties, through the provision of early support. Screening tools to identify motor difficulties are needed, but instruments developed in one country may not be psychologically sound when shared between cultures. This study aimed to collaboratively develop the Little Developmental Coordination Disorder Questionnaire (LDCDQ) (a screening instrument to identify motor difficulties in young preschoolers) between several countries, while ensuring numerous psychometrically sound, comparable versions of the tool. This innovative project in the field of DCD will enable the analysis and comparison of different patterns of motor development and/or delay in different cultures.

Method: Based on a similar screening instrument for older children, the Little DCDQ was developed in Hebrew and psychometrically tested. After generating an English Little DCDQ (following recommended guidelines), 27 researchers from 17 sites adapted and psychometrically tested the instrument with their local cultures and languages. Thereafter, each collaborator used their local Little DCDQ to assess 40 children aged 3-4.11 (20 typically developing and 20 with suspected motor difficulties) following the same protocol, and the data was compared to assess motor development across cultures.

Results: The process of the first phase of this collaboration will be briefly described and initial cross-cultural comparative results will be reported based on data collected to date. Within most countries, significant differences in motor performance between referred and non-referred children were found; sub-scores in which differences have not been identified may be due to specific cultural characteristics. When comparing between countries, significant differences were more noticeable for non-referred than referred children; trends in high- and low-scoring means will be discussed.

Discussion: This study has important implications for DCD research and practice. This is the first attempt to develop an instrument with the aim of facilitating cross-cultural comparison of DCD in young preschoolers, which will enable a unified language for researchers investigating typical motor development and motor delay in this population.

Keywords: Developmental Coordination Disorder; Motor development; Young Preschoolers; Cross-cultural assessment.

Lessons learned using an eye-tracker in school-aged children with Developmental Coordination Disorder performing a real-world visual-motor task

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Aims: Eye tracking has become an innovative technique for measuring cognitive processes in children with neurodevelopmental disorders but this method has been employed infrequently with children with developmental coordination disorder (DCD). Eye tracking use may improve understanding of the cognitive processes that influence motor performance in DCD but it is not yet known whether this is feasible. Comorbid conditions may impact the reliable use of eye trackers with this population. The purpose of this study was to investigate the feasibility of using an eye tracker with children with DCD performing a real-world visual-motor task.

Method: As part of a larger study investigating selective visual attention, 12 children with DCD (11 M, 1 F; mean age (range): 10.5 yrs (6.71)) wore a mobile eye tracker while pouring water from 3 glass ‘pouring’ cups into 3 colour-matched plastic ‘filling’ cups sequentially (single trial). Children performed 12 trials of increasing difficulty (position of filling cups was altered on every 3rd trial). Each trial lasted 30-60 seconds; total testing time was 15-30 minutes. Parents completed the DCDFQ7 and the 45-stem Conners-3 Parent Rating Scales of attention. Children’s coordination was assessed using the Movement Assessment Battery for Children-2 (MABC-2). Following task completion, gaze overlay videos were extracted and analysed.

Results: Eye tracking was feasible and reliable for most children with DCD (n=9); 3 children had poor gaze fixation for calibration affecting the reliability of their data. These children had visual impairments and significantly lower MABC-2 percentile (t(6)=0.07; p<0.05) than the group without calibration difficulties (t(10)=2.75; p<0.05). Attention difficulties were formally diagnosed and/or reported by parents in 9 children, including 2 of the 3 children with poor calibration; however, no differences were found between groups with and without poor calibration based on Conners-3 data. Difficulties maintaining posture, sensory challenges, fit of the eye tracking glasses, and corrective eyewear were additional factors hindering data collection.

Discussion: Eye tracking appears to be a feasible approach to use with most children with DCD during a real-world visual motor task. However, the nature and heterogeneity of DCD, as well as practical challenges, may

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monthly seizure frequency in 16 cases of suspected motor problem were significantly higher than the other 35 cases.

Discussion: Approximately 30% of children with epilepsy were suspected motor problem. Motor problem was correlated with symptomatic epilepsy, more than two anti-epileptic drugs and more than monthly seizure frequency. In epilepsy medical care, we should pay more attention to the motor problem, and the support is necessary.

This study was supported, in part, by a Grant-in-Aid for Scientific Research from the Japan Society for the Promotion of Science.


Keywords: Epilepsy; Motor problem; Symptomatic epilepsy; Anti-epileptic drugs; Seizure frequency.

Longitudinal prediction of psychosocial maladaptation and educational achievement in elementary school based on development assessment of fine and gross movement by nursery teachers

M. Katagiri, H. Ito, Y. Murayama, M. Hamada, A. Uemiya & M. Tsuji

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Aim: We examined the extent to which nursery teachers’ development assessment of fine and gross movement predicts later psychosocial maladaptation and educational achievement in elementary schools. The Developmental Scale for Nursery Record (DNSR) we developed yielded nine subscales in principal component analysis, including fine and gross movement. We have already confirmed reliability and validity in this scale.

Method: A 7-year longitudinal investigation was conducted on 2,501 children (female 1,209; male 1,292) from all nursery and elementary schools in a suburban city. We used the DNSR for the development assessment by nursery teachers. Preschool children were assessed by their nursery teacher right before entering elementary school using the DNSR. We conducted multiple regression analysis on the collected data. The independent variables were fine and gross movement in the DNSR subscales. The dependent variable was later educational achievement (a deviation score on an academic achievement test), friendship, behavioral problems, and emotional problems (subscale scores on the Strengths and Difficulties Questionnaire).

Results: We found that fine movement suffers significantly under the influence of educational achievement. Furthermore, gross movement suffers significantly under the influence of friendship and emotional problems. There was no relationship between motor skills and behavioral problems.

Discussion: These findings indicated that fine motor skill predicts later educational achievement, and gross motor skill predicts later friendship and anxiety and/or depressive tendency. Thus, problems with motor skills in preschool children lead to the potential for lower educational achievement and psychosocial maladaptation. In conclusion, assessment of motor skills in preschool children may enable early detection and appropriate treatment of children who have special educational needs and/or psychosocial maladaptation. In addition, elementary schools need to contribute to educational planning after due consideration of motor skills in children.

Keywords: Fine motor skill, Gross motor skill, Psychosocial maladaptation, Educational achievement.

Motor imagery in children with Developmental Coordination Disorder: a complex hand rotation task

S. Kerrigan, J. Reynolds, M. Licari, C. Elliott, B. Lay & J. Williams

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Aims: It has been hypothesised that deficits in the functioning of internal modelling may contribute to the motor impairments associated with DCD. This process can be explored behaviourally through motor imagery paradigms. This study examined motor imagery proficiency of children with and without DCD using a complex hand rotation task.

Method: 47 boys aged 7-13 yrs participated in this study. The DCD group (mean age=9.66 yrs±1.56) and normal control group (mean age=9.69 yrs±1.61). Children were tested on the MACB-2, with children in the DCD group ≤40th percentile and controls ≥20th percentile. Motor imagery proficiency was measured using a complex hand rotation task administered via E-Prime 2.0. Images were presented in two rotational axes – palmar view and back view, and eight 45° rotational steps between 0° and 360°.

Participants completed the task twice: first with no instructions, and the second time with motor imagery instructions. To explore the effects of instructions and whether response patterns followed biomechanical constraints, response time (RT) and accuracy (ACC) data were submitted to separate RM-ANOVA's [2(Instructions) x 2[View] x 2[Laterality] x 2[Group]]. RM-ANOVA's [2(Instructions) x 5[Angle] x 2[Group]] were then conducted to explore RT and ACC response patterns for back and palmar view separately.

Results: Significant effects for instructions (p<0.001), view (p<0.001) and laterality (p<0.001) were revealed for both RT and ACC, indicating both groups were faster and more accurate with instructions, for back compared to palmar view, and medial compared to lateral rotations. No significant group effects for RT (p=0.061) or ACC (p=0.076) were identified for response to back view, although both approached significance.

A significant group effect was revealed for palmar view response accuracy (p<0.001), with children with DCD having lower accuracy levels than controls.

Discussion: There was partial support for the hypothesis that children with DCD would display atypical response patterns on the hand rotation task. A large degree of variation was observed within the DCD group, with a number falling within the control response range. It appears, however, that deficits in motor imagery proficiency may become more apparent as the task becomes more complex, with group differences identified for palmar view. A greater understanding of motor imagery performance in children with DCD has the potential to inform intervention programs.

Keywords: Motor imagery, Mental rotation, Internal modelling, Mirror neuron system.


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Aims: The Movement Assessment Battery for Children-Second Edition (MABC2) is a commonly used assessment of children’s motor skills in various countries. However, it has not been standardized in Japan; therefore, we have faced difficulties in diagnosing children with developmental
APPENDIX C: INFOGRAPHICS

The following appendix contains the plain language summaries for stakeholders (parents, children, clinicians, policy makers) for an overview of the thesis and for each study. These summaries optimise the knowledge translation of this behavioural and neuroscience research by allowing it to reach a wider readership.

The following infographics are presented:

- Overview of the thesis and research questions.
- A systematic review of mirror neuron system function in developmental coordination disorder.
- Imitation of unlearned actions in children with developmental coordination disorder.
- Motor imagery performance in children with probable developmental coordination disorder.
- Reduced relative volume in motor and attention regions in developmental coordination disorder.
- Overview of the thesis, research results, and future directions.
PROBLEM?

Cause of Developmental Coordination Disorder remains unknown

1. Understanding based on behavioural research
2. Limited neuroimaging studies
3. Interventions have not been developed to target the cause

Could it be the mirror neuron system?

The MNS is thought to be a cluster of neurons in the brain, that fire when a person observes, acts, or imagines an action performed

Is there evidence in the literature to support deficits in this system?

1) What is the evidence for MNS dysfunction in DCD? A systematic review

Does behavioural evidence support it?

Preliminary evidence for differences in MNS function using imitation and motor imagery assessments
Currently limited research exploring imitation of unlearned actions
More complex assessments are needed to explore motor imagery

2) Imitation of unlearned actions in children with probable DCD
3) Motor imagery performance in children with probable DCD

Does neuroimaging evidence support it?

Using structural and functional MRI, the structure and function of MNS regions can be examined
No published studies have specifically explored MNS function in DCD
Differences in brain activation patterns and connectivity of MNS regions identified

4) Reduced relative grey matter volume regions in DCD: A voxel based morphometry study
5) Mirror Neuron Activation in Children with DCD: A replication fMRI study

It has recently been proposed that a deficit in the functioning of the mirror neuron system (MNS) may be causing the movement difficulties associated with DCD
**A Systematic Review of Mirror Neuron System Function in Developmental Coordination Disorder**

The MNS is thought to be a cluster of multimodal neurons in the central nervous system that fire when a person observes, acts, or imagines an action performed. It has been proposed that deficits in MNS function may contribute to DCD.

For more information please contact: jessellenreynolds@gmail.com


**What is the Mirror Neuron System?**

MNS dysfunction has the potential to disrupt visual learning and lead to delays in motor development.

**Superior Temporal Sulcus**

The main source of visual input during.

**Inferior Parietal Lobule**

What is the movement and how do I do it?

**Ventral Premotor Cortex**

Inferior Frontal Gyrus

Understanding the goal of the movement

**The Systematic Review**

What is the evidence for abnormal functioning of the mirror neuron system (MNS) in children and adults with DCD?

Six electronic databases were searched

5993 articles identified after accounting for duplicates

49 full text articles reviewed

31 articles included

**The Results**

Thirty articles assessed children with DCD and one article assessed adults with DCD.

**Imitation**

- 9 papers
- Traditionally assesses learned or skilled transitive tool use actions
- Most assessments of learned and novel gestures demonstrate deficits

**Motor Imagery**

- 14 papers
- Moderate to strong support for motor imagery deficits
- Differences in motor imagery proficiency more apparent as the task complexity increases

**Neuroimaging**

- 9 papers
- Differences in activation patterns and connectivity of MNS regions
- No fMRI or rsfMRI studies have specifically explored MNS function

**What Are The Implications?**

Preliminary behavioral and neuroimaging evidence provides support for a MNS hypothesis. Potential differences in MNS function opens up the possibility of designing interventions to address potential neurological underpinnings of DCD. Further work to extend the literature regarding MNS function in DCD appears to be a promising research direction.
Imitation of unlearned actions in children with Developmental Coordination Disorder

What is imitation?

Imitation provides a foundation for skill learning via observation. It involves the recognition and understanding of an action, and the transformation and integration of the observed movement and sensory stimuli into motor commands to reproduce actions and acquire skills.

Imitation deficits in DCD?

Imitation is an important learning mechanism from a young age, and steadily improves during the course of typical development. Given the importance of imitation for motor learning, this study aimed to identify whether deficits in imitation and observational learning contribute to the motor deficits characteristic of DCD.

Who participated & What did they do?

- 58 boys, aged 6-13 yrs
- 29 boys with probable DCD
- 29 typically developing controls
- Postural and sequencing praxis imitation tasks

What did we find?

- Children with DCD had difficulty imitating complex novel postures
- Children with DCD had difficulty imitating gesture sequences
- Children with DCD had slower responses than controls
- Differences in imitation performance increased with task complexity
- Not all children with DCD displayed imitation deficits

What are the implications?

Given the importance of imitation for motor development, the imitation difficulties displayed by some children with DCD may impact on movement acquisition. Interventions to target imitation may be beneficial for these children.

Motor imagery performance in children with probable Developmental Coordination Disorder

Motor imagery performance was examined using a complex hand rotation paradigm. Hand stimuli were presented in two rotational axes (palm/back view), and eight 45° rotational steps. Forty-four boys aged 7-13yrs participated, 22 with DCD and 22 controls. Children completed the hand rotation task twice: first without (NI), and then with (WI) motor imagery instructions.

What did we do?

Motor imagery performance was examined using a complex hand rotation paradigm. Hand stimuli were presented in two rotational axes (palm/back view), and eight 45° rotational steps. Forty-four boys aged 7-13yrs participated, 22 with DCD and 22 controls. Children completed the hand rotation task twice: first without (NI), and then with (WI) motor imagery instructions.

What were the main results?

- Children with and without DCD were able to utilise a motor imagery strategy
- Responses of children with DCD were slower and less accurate
- Group differences increased with task complexity
- Not all individuals with DCD displayed motor imagery deficits
- Children with and without DCD benefited from motor imagery instructions

What are the implications?

The response characteristics of children with DCD likely reflects a reduced capacity to mentally manipulate a body schema and reduced visuo-motor processing capabilities. This suggests that deficits in these processes may contribute to the movement difficulties characteristic of DCD. The ability to of children with DCD to improve their performance on the task, suggests the potential for clinical applications of motor imagery interventions in this population.

For more information please contact: jessellenreynolds@gmail.com

Children with DCD were found to have a significant, large, right lateralised reduction in grey matter volume compared to controls in the medial and middle frontal, and superior frontal gyri.

Reduced volumes in DCD

The middle and medial frontal gyri are involved in motor planning and control, executive functioning, reorienting attention, inhibitory control, and response selection. The superior frontal gyrus is reported to be involved in working memory processing, spatial cognition, and voluntary attention control.

Who participated?
44 children aged 8-12 years (22 probable DCD, 22 typically developing controls)

What do these regions do?

What are the implications?

These reductions in grey matter volume support the motor planning and execution, attentional, and executive functioning deficits associated with DCD. They suggest that underlying structural differences in motor and attention regions may contribute to DCD. This may present a possible avenue for targeted intervention programs.

How do we explore brain volumes?

Voxel based morphometry involves comparisons of grey matter volumes, and tests for volume differences anywhere in the brain, rather than focusing on specific anatomical structures. Research in healthy populations has demonstrated that brain volumes can change and are associated with skill level.

For more information please contact: jessellenreynolds@gmail.com
Mirror Neuron Activation in Children with Developmental Coordination Disorder
A functional MRI Study

The MNS is thought to be a cluster of neurons in the brain that fire when a person observes, imagines, or performs an action.

Who participated?
19 8-13 year old right handed boys:
10 boys with probable DCD
9 typically developing controls

What did they do?
Participants performed a right handed side-to-side finger tapping task. Four conditions: watching, imagining, doing, and imitating the sequence.

What brain regions were active?
To identify if mirror neuron regions were active, a series of exploratory whole brain analyses were run to explore the regions that were active during each task condition. Mirror neuron regions were found to be active, as well as areas related to motor control and associated with imagining movements.

What were the group differences?
No group differences in mirror neuron regions were identified during any of the finger tapping task conditions. During imitation, children with DCD had reduced activation in the caudate, thalamus, and posterior cingulate, areas involved in motor planning and attention.

What are the implications?
This study suggests that mirror neuron dysfunction is not a cause of the movement difficulties that children with DCD experience. Instead, differences in the activation of motor planning and attention regions were identified. These differences are likely to impact the way children with DCD plan and perform movements. Further research to explore these processes is required.

For more information please contact: jessellenreynolds@gmail.com
PROBLEM?

Cause of Developmental Coordination Disorder remains unknown

1. Understanding based on behavioural research
2. Limited neuroimaging studies
3. Interventions have not been developed to target the cause

Could it be the mirror neuron system?

The MNS is thought to be a cluster of multimodal neurons in brain that fire when a person observes, acts, or imagines an action performed

Current behavioural and neuroimaging literature provides preliminary support for deficits in this system

Does behavioural evidence support it?

Consistent with possible MNS dysfunction, children with DCD had deficits imitating novel gestures and sequences of gestures
Children with DCD were slower and less accurate than control during a complex motor imagery task
Deficits in these processes are more evident as task complexity increases

Does neuroimaging evidence support it?

Children with DCD had reduced relative grey matter volume in right pre-motor frontal lobe regions
fMRI findings did not support a deficit in the MNS
Structural and functional fMRI findings suggest reduced motor planning capabilities and attentional processing may be involved in the motor deficits

SOLUTION?

Based on behavioural deficits in associated processes, action observation, modified CO-OP, and motor imagery training programs may be beneficial for improving motor skills in this population

Further research to shed light on possible aetiology and mechanisms of DCD could incorporate an analysis of:
- Genetics and links with other neurodevelopmental disorders
- Brain micro- and macrostructure
- Motor planning and attentional processes at a neurological level
- Neural networks
- Combined use of imaging techniques

It has recently been proposed that a deficit in the functioning of the mirror neuron system (MNS) may be causing the movement difficulties associated with DCD

1) What is the evidence for MNS dysfunction in DCD? A systematic review
2) Imitation of unlearned actions in children with probable DCD
3) Motor imagery performance in children with probable DCD
4) Reduced relative grey matter volume regions in DCD: A voxel based morphometry study
5) Mirror Neuron Activation in Children with DCD: A replication fMRI study

Improved quality of life for children with DCD
Appendix D: Ethics and Data Collection

Appendix D includes information related to ethics and data collection procedures. Ethics approval for the research project and information and consent forms are presented.

The three age band assessments of the Movement Assessment Battery for Children -2 (Henderson, Sugden & Barnett, 2007) are presented. Due to copyright restrictions, copies of all other assessments and questionnaires have not been included.

Finally, the functional MRI training slides used for participant familiarisation and the take home booklet are presented.
Dear Professor Licari

HUMAN RESEARCH ETHICS APPROVAL - THE UNIVERSITY OF WESTERN AUSTRALIA

Imitation and Motor Imagery in Children with Developmental Coordination Disorder: Investigation of Mirror Neuron Functioning

Student(s): Jessica Reynolds - PhD - 20151233

Ethics approval for the above project has been granted in accordance with the requirements of the National Statement on Ethical Conduct in Human Research (National Statement) and the policies and procedures of The University of Western Australia. Please note that the period of ethics approval for this project is five (5) years from the date of this notification. However, ethics approval is conditional upon the submission of satisfactory progress reports by the designated renewal date. Therefore initial approval has been granted from 18 December 2013 to 01 December 2014.

You are reminded of the following requirements:

1. The application and all supporting documentation form the basis of the ethics approval and you must not depart from the research protocol that has been approved.
2. The Human Research Ethics Office must be approached for approval in advance for any requested amendments to the approved research protocol.
3. The Chief Investigator is required to report immediately to the Human Research Ethics Office any adverse or unexpected event or any other event that may impact on the ethics approval for the project.
4. The Chief Investigator must inform the Human Research Ethics Office as soon as practicable if a research project is discontinued before the expected date of completion, providing reasons.

Any conditions of ethics approval that have been imposed are listed below:

Special Conditions

None specified

The University of Western Australia is bound by the National Statement to monitor the progress of all approved projects until completion to ensure continued compliance with ethical standards and requirements.

The Human Research Ethics Office will forward a request for a Progress Report approximately 60 days before the due date. A further reminder will be forwarded approximately 30 days before the due date.

If your progress report is not received by the due date for renewal of ethics approval, your ethics approval will expire, requiring that all research activities involving human participants cease immediately.

If you have any queries please contact the HREO at hreo-research@uwa.edu.au.

Please ensure that you quote the file reference – RA/4/1/6492 – and the associated project title in all future correspondence.
Yours sincerely

[Signature]

Dr Mark Dixon
Associate Director, Research Ethics and Biosafety
Assistant Professor Melissa Licari  
School of Sport Science, Exercise and Health  
MBDP: M408

Dear Professor Licari

HUMAN RESEARCH ETHICS OFFICE – ETHICS APPROVAL RENEWED

Imitation and Motor Imagery in Children with Developmental Coordination Disorder: Investigation of Mirror Neuron Functioning

Student(s): Jessica Ellen Reynolds

Thank you for submitting your Progress Report for the above project. The report is satisfactory and ethics approval for the project has been renewed.

You will receive a request for your next progress report approximately one month before the next renewal date of 01 December 2015.

If you have any queries, please contact the Human Ethics office at humanethics@uwa.edu.au.

Please ensure that you quote the file reference – RA/4/1/6492 – and the associated project title in all future correspondence.

Yours sincerely

Dr Caixia Li  
Manager, Human Ethics
Our Ref: RA/4/1/6492  

10 December 2015

Dear Dr Melissa Licari

School of Sport Science, Exercise and Health
MBDP: M408

Dear Doctor Licari

HUMAN RESEARCH ETHICS OFFICE – ETHICS APPROVAL RENEWED

Imitation and Motor Imagery in Children with Developmental Coordination Disorder: Investigation of Mirror Neuron Functioning

Student(s): Jessica Ellen Reynolds, Sophie Jane Kerrigan

Thank you for submitting your Progress Report for the above project. The report is satisfactory and ethics approval for the project has been renewed.

You will receive a request for your next progress report approximately one month before the next renewal date of 01 December 2016.

If you have any queries, please contact the Human Ethics office at humanethics@uwa.edu.au.

Please ensure that you quote the file reference – RA/4/1/6492 – and the associated project title in all future correspondence.

Yours sincerely

Dr Caixia Li
Manager, Human Ethics
Imitation and Motor Imagery Ability of Children with and without Movement Difficulties: a
behavioural assessment

Investigators: Asst. Prof. Melissa Licari, Assoc. Prof. Brendan Lay, Assoc. Prof. Catherine Elliott, Dr. Jacqueline Williams, and Jess Reynolds BSc (Hons), BScTech

Participant Information Sheet

Purpose
Visual learning and learning by imitation is thought to be our main form of learning new skills through modelling behaviour and action of others. It has been proposed that visual learning difficulties may contribute to the movement difficulties seen in children with Developmental Coordination Disorder/Motor Dyspraxia.

The aim of this research is to explore imitation and motor imagery ability of children with and without movement difficulties.

This project is a part of a PhD study being conducted by Jess Reynolds.

Benefits
This research may potentially reveal difficulties in motor learning strategies responsible for causing a wide variety of movement difficulties seen in children. This may then lead to the development of intervention programs specifically targeting these areas.

Procedures
Participation in this research is voluntary. If you and your child choose to participate, there will be one approximately 1.5 hour session at UWA to attend.

During the session your child will:
- Undergo a movement assessment to confirm that they are eligible for participation in the study (approximately 30-45 mins).
- Undergo three short assessments of imitation ability, including imitation of non-meaningful postures, meaningful gestures (such as brushing teeth) and hand and finger clapping and tapping sequences (approximately 20 mins).
- Perform a motor imagery hand rotation task on a computer where they will be presented with hands and will be required to determine whether they are left or right (approximately 10 mins).

Your child will be videotaped during these assessments to allow their performance to be reviewed at a later time.
Risks/Restrictions
There are no foreseeable risks to participants taking part in this study. Assessments are not invasive or embarrassing in any way.

Participant Rights
Participation in this research is voluntary and you are free to withdraw your child from the study at any time and for any reason, without prejudice in any way. You do not need to provide a reason or justification for such a decision. In such cases, the research records of your child will be destroyed.

Your child’s participation in this study does not prejudice any right to compensation, which you may have under the statute of common law.

Participant confidentiality will be respected at all times. The results of this research may be published, however, neither your child’s name nor identity shall be revealed, all data will be coded so as to preserve the identity and confidentiality of your child.

If you have any queries or questions regarding this information, please do not hesitate to contact Asst. Prof. Melissa Licari (melissa.licari@uwa.edu.au) or Jess Reynolds (reynoj01@student.uwa.edu.au). Thank you for your time and consideration.

Yours sincerely,
A/Prof Melissa Licari
Chief Investigator
6488 7282
melissa.licari@uwa.edu.au

Approval to conduct this research has been provided by the University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time.

In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at the University of Western Australia on (08) 6488 3703 or by emailing to hreo-research@uwa.edu.au

All research participants are entitled to retain a copy of any Participant Information For and/or Participant Consent Form relating to this research project.
Imitation and Motor Imagery Ability of Children with and without Movement Difficulties: a behavioural study

Parent Consent Form

I ___________________________ have read the information provided and discussed this study with my child. Any questions I have asked have been answered to my satisfaction. I agree and my child agrees to participate in this study, realising that I may withdraw my child at any time without reason and without prejudice. I understand that my child will be video recorded in order to assess their movement and imitation performance.

I understand that all information provided is treated as strictly confidential and will not be released by the investigator unless required to by law. I have been advised as to what data is being collected, what the purpose is, and what will be done with the data upon completion of the research.

I agree that research data gathered for the study may be published provided my child’s name or other identifying information is not used.

______________________
Child's Name

______________________      __________________ ______________________
Parent/Guardian Signature      Date           Contact Number

Consent to use video recordings in future presentations

I (full name of parent/caregiver) ___________________________ give permission for video recordings of my child (full name) ___________________________ to be used in presentations provided my child’s name is not used.

Approval to conduct this research has been provided by The University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time.

In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at The University of Western Australia on (08) 6488 3703 or by emailing to hreo-research@uwa.edu.au

All research participants are entitled to retain a copy of any Participant Information Form and/or Participant Consent Form relating to this research project.
Imitation and Motor Imagery Ability of Children with and without Movement Difficulties

Participant Consent Form

Dear Participant,

Before you become a part of our study, there are a few things we need to make sure you are aware of:

You will be asked to come to UWA. You will be asked to do some movement, imitation and imagery activities, and to fill out a questionnaire about which hand you use to do things. While you are participating in the movement activities you will be asked to do tasks such as hopping, catching and balancing. During the imitation activity you will be asked to copy body positions that you are shown and during the imagery activity you will be asked to decide whether you are being shown a left or right hand on a computer screen. In addition you will also be video recorded to enable us to look at how you move during these tasks.

Name of child: _________________________________ Date: ____/____/____

Verbal consent will be obtained from the child at the following time points during the study. If the child agrees to continue a ✓ must be placed in the box. If the child does not want to continue, a ❌ must be placed in the box.

<table>
<thead>
<tr>
<th>Session</th>
<th>Order</th>
<th>Time Point</th>
<th>Child Agrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>Details of study and video recording explained, child asked if they are happy to continue</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Edinburgh handedness assessment completed, child asked if they are happy to continue</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MABC-2 performed, child asked if they are happy to continue</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Imitation tasks performed, child asked if they are happy to continue</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Motor imagery task performed, child asked if they are happy to continue</td>
<td>✓</td>
</tr>
</tbody>
</table>

Approval to conduct this research has been provided by The University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time.

In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at The University of Western Australia on (08) 6488 3703 or by emailing to hreo-research@uwa.edu.au

All research participants are entitled to retain a copy of any Participant Information Form and/or Participant Consent Form relating to this research project.
Mirror Neuron System Functioning in Children with and without Movement Difficulties: a functional MRI study

Investigators: Asst. Prof. Melissa Licari, Assoc. Prof. Brendan Lay, Assoc. Prof. Catherine Elliott, Clin. Assoc. Prof. Michael Bynevelt, Dr. Jac Billington, and Jess Reynolds BSc (Hons), BScTech

Purpose
Mirror neurons are cells in the brain which play a vital role in the acquisition of movement skills by allowing us to imitate and imagine the actions that we see others performing. Important for visual learning, which is thought to be our main form of learning new skills, mirror neurons are active during action observation, motor imagery, motor execution and imitation. These neurons are suspected to contribute to the movement difficulties seen in children with Developmental Coordination Disorder/Motor Dyspraxia.

The aim of this research is to explore the activation of mirror neurons. This will be done through the use of functional magnetic resonance imaging (fMRI) during the performance of imitation, motor imagery, motor execution and observation tasks in children with and without movement difficulties. Properties of the mirror neuron system at rest will also be explored using resting state fMRI (rsfMRI).

This project is a part of a PhD study being conducted by Jess Reynolds.

Benefits
This research may potentially reveal areas within the brain responsible for causing a wide variety of movement difficulties seen in children. This may then lead to the development of intervention programs specifically targeting these neural areas.

Procedures
Participation in this research is voluntary. If you and your child choose to participate, there will be two sessions to attend; one at the University of Western Australia (UWA) and one at Sir Charles Gardiner Hospital (SCGH).

In session 1, your child will attend the School of Sport Science, Exercise and Health at UWA. Session one will take approximately 1.5 hours. During this session your child will:

- Undergo a movement assessment to confirm they are eligible for participation in the study (30-45 mins).
- Be familiarised with the procedure for their fMRI and rsfMRI. This will be done through a storybook about having an MRI, and undertaking a simulated scan. This involves listening to the sounds of the MRI unit, wearing headphones and watching a DVD of a child having an MRI. Your child will also get to practice a similar task to the one they will perform in the scan. As a parent you will also have the opportunity to ask questions during the practice session and also discuss if you would like to be in the room with your child when they have their scan.
In session 2, the same person who did the MRI training will meet you at the Department of Radiology at SCGH for your child’s MRI, rsfMRI and fMRI scan. Your child will be shown through the scanning and control room to familiarise them with the scanning procedure and devices, and to familiarise them with the task they will be performing.

The MRI session will take approximately 30 minutes. Although it is noisy, an MRI exam is completely safe and painless. There will be three components to the MRI scan:

- Structural anatomical scans will be completed first and will take approximately four and a half minutes, during which the only thing your child needs to do is to lie still.
- During the rsfMRI scan, which will last six minutes, your child will be instructed to lie still with their eyes closed, and to try not to move or think of anything.
- During the fMRI, which will be broken into two, eight minute scans, your child will be able to see a screen which will prompt them with the task to be performed at each stage of the scan. While the child is having their scan they are able to talk to you and the researcher through an intercom system.

Following the scanning, your child will undergo short assessments of imitation and motor imagery ability during which they will be videotaped to allow their performance to be reviewed. This will take approximately 30 minutes and will incorporate:

- Three short assessments of imitation ability, including imitation of non-meaningful postures, meaningful gestures (such as brush your teeth) and hand and finger clapping and tapping sequences (20 mins).
- Perform a motor imagery hand rotation task on a computer where they will be presented with hands and will be required to determine whether they are left or right (10 mins).
Risks/Restrictions

Functional MRI is very safe; in fact it makes use of natural forces and has no known harmful effects. It is important to know that MRI will not expose you or your child to any ionizing radiation.

Because MRI machines use a strong magnetic field, and certain metal objects are attracted to the magnetic fields, it is important that your child does not have any jewellery on them when they do the scan or any metal on their clothing (zips, studs or glittery writing). If they do have metal on their clothing they will be supplied with a gown to change into before the scan.

Children who have any of the following should not participate in this study:
- Pacemaker
- Aneurysm clips
- Cochlear implant
- A neuron-stimulator
- Metal implants
- Steel surgical staples or clips
- Dental Braces
- An implanted drug infusion device
- Any implant made partially or wholly or iron or steel

There are no restrictions for your child after the scan and they can go right back to their everyday activities. If you would like to be in the room with your child while they have a scan you must also let the radiologist know if you have any of the above and make sure you have no metal objects on.

There is potential that the MRI may cause anxiety in some children. To minimise any anxiety which may be caused by MRI scanning, participants will undergo a familiarisation session during which they will participate in a simulated scan. If any anxiety is experienced during scanning, the scan will be stopped immediately and the participant will come out of the scanner.

If anything unusual is detected on your child’s MRI, you will be informed and they will be referred to Princess Margaret Hospital.

Participant Rights

Participation in this research is voluntary and you are free to withdraw your child from the study at any time and for any reason, without prejudice in any way. You do not need to provide a reason or justification for such a decision. In such cases, the research records of your child will be destroyed.
Your child’s participation in this study does not prejudice any right to compensation, which you may have under the statute of common law.

Participant confidentiality will be respected at all times. The results of this research may be published, however, neither your child’s name nor identity shall be revealed. All data will be coded so as to preserve the identity and confidentiality of your child.

If you have any queries or questions regarding this information, please do not hesitate to contact Asst. Prof. Melissa Licari (melissa.licari@uwa.edu.au) or Jess Reynolds (reynoj01@student.uwa.edu.au). Thank you for your time and consideration.

Yours sincerely,

A/Prof Melissa Licari
Chief Investigator
6488 8781
melissa.licari@uwa.edu.au

Approval to conduct this research has been provided by the University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time.

In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at the University of Western Australia on (08) 6488 3703 or by emailing to hreo-research@uwa.edu.au

All research participants are entitled to retain a copy of any Participant Information Form and/or Participant Consent Form relating to this research project.
Imitation and Motor Imagery Ability of Children with and without Movement Difficulties: a behavioural study

Parent Consent Form

I ___________________________ have read the information provided and discussed this study with my child. Any questions I have asked have been answered to my satisfaction. I agree and my child agrees to participate in this study, realising that I may withdraw my child at any time without reason and without prejudice. I understand that my child will be video recorded in order to assess their movement and imitation performance.

I understand that all information provided is treated as strictly confidential and will not be released by the investigator unless required to by law. I have been advised as to what data is being collected, what the purpose is, and what will be done with the data upon completion of the research.

I agree that research data gathered for the study may be published provided my child’s name or other identifying information is not used.

__________________________
Child’s Name

__________________________  ____________________________
Parent/Guardian Signature      Date           Contact Number

Consent to use video recordings in future presentations

I (full name of parent/caregiver) ___________________________ give permission for video recordings of my child (full name) ___________________________ to be used in presentations provided my child’s name is not used.

Approval to conduct this research has been provided by The University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time.

In addition, any person not satisfied with the response of researchers may raise ethics issues or concerns, and may make any complaints about this research project by contacting the Human Research Ethics Office at The University of Western Australia on (08) 6488 3703 or by emailing to hreo-research@uwa.edu.au

All research participants are entitled to retain a copy of any Participant Information Form and/or Participant Consent Form relating to this research project.
Mirror Neuron System Functioning in Children with and without Movement Difficulties: a functional MRI study

Participant Consent Form

Dear Participant,

Before you become a part of our study, there are a few things we need to make sure you are aware of:

You will be asked to take part in two sessions. For the first session you will come to UWA to do a movement activity, fill out a questionnaire about which hand you use to do things, and to have a practice MRI scan. During the practice scan you will get the opportunity to see what it will be like in the real scanner. While you are doing movement activity you will be asked to perform a range of tasks such as hopping, catching and balancing.

The second session will be at Sir Charles Gairdner Hospital, where you will get to participate in a series of MRI scans and in imitation and imagery activities. During the imitation activity you will be asked to copy body positions and sequences of hand and finger movements that you are shown. In addition you will also be video recorded to enable the researchers to assess your movement during these tasks. During the imagery task you will be asked to decide whether the hands you are shown on a computer screen are left or right hands.
Mirror Neuron System Functioning in Children with and without Movement Difficulties: a functional MRI study

Participant Consent Form

Name of child: _________________________________ Date: ____/____/____

Verbal consent will be obtained from the child at the following time points during the study. If the child agrees to continue a ✓ must be placed in the box. If the child does not want to continue, a ✗ must be placed in the box.

<table>
<thead>
<tr>
<th>Session</th>
<th>Order</th>
<th>Time Point</th>
<th>Child Agrees?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>Details of study and video recording explained, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>MABC performed, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>fMRI training performed, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>Child arrives at SCGH and shown through the scanning room, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Tasks are practiced outside scanner, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Child completes structural scan, and during dephase, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Child completes resting state scan, and during dephase, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Child completes first run of scanning, and during dephase, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Child completes second run of scanning, and during dephase, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>Imitation tasks performed, child asked if they are happy to continue</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>Motor imagery task performed, child asked if they are happy to continue</td>
<td></td>
</tr>
</tbody>
</table>

Approval to conduct this research has been provided by The University of Western Australia, in accordance with its ethics review and approval procedures. Any person considering participation in this research project, or agreeing to participate, may raise any questions or issues with the researchers at any time.

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## Movement Assessment Battery for Children – 2

### Test Record Form Age Band 1 (3-6 years)

<table>
<thead>
<tr>
<th>Name:</th>
<th>Gender: M / F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home address:</td>
<td></td>
</tr>
<tr>
<td>School:</td>
<td>Class/year/grade:</td>
</tr>
<tr>
<td>Assessed by:</td>
<td></td>
</tr>
<tr>
<td>Referral source:</td>
<td></td>
</tr>
<tr>
<td>Preferred (writing) hand:</td>
<td></td>
</tr>
</tbody>
</table>

**Movement ABC-2 Checklist completed? Y / N**

<table>
<thead>
<tr>
<th>Item code</th>
<th>Name of item</th>
<th>Raw score (best attempt)</th>
<th>Item Standard Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD 1*</td>
<td>Posting Coins preferred hand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD 1*</td>
<td>Posting Coins non-pref hand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD 2</td>
<td>Threading Beads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD 3</td>
<td>Drawing Trail 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A&amp;C 1</td>
<td>Catching Beanbag</td>
<td></td>
<td></td>
</tr>
<tr>
<td>A&amp;C 2</td>
<td>Throwing Beanbag onto mat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 1*</td>
<td>One-Leg Balance best leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 1*</td>
<td>One-Leg Balance other leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 2</td>
<td>Walking Heels forward</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 3</td>
<td>Jumping on Mats</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Three Component Scores**

- **Manual Dexterity**
  - MD 1 + MD 2 + MD 3
  - Component score
  - Standard Score
  - Percentile

- **Aiming & Catching**
  - A&C 1 + A&C 2
  - Component score
  - Standard Score
  - Percentile

- **Balance**
  - Bal 1 + Bal 2 + Bal 3
  - Component score
  - Standard Score
  - Percentile

**Total Test Score**

- Sum of 8 item standard scores

*For: Posting Coins and One-Leg Balance, look up standard score for each limb, add these and divide by 2. If the result is above 10, round up; if below 10, round down.

*For confidence intervals, see Examiner's Manual p139 (Chapter 7)
Manual Dexterity 1: POSTING COINS
Note: 6 coins for 3-4 years, 12 for 5-6 years

Record: Preferred hand: R / L (should be same as for Drawing Trail); Time taken (secs), F for failure; R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>Preferred hand</th>
<th>Non-preferred hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trail 1</td>
<td>Trail 1</td>
</tr>
<tr>
<td>3:15</td>
<td>3:15</td>
</tr>
<tr>
<td>3:25</td>
<td>3:25</td>
</tr>
<tr>
<td>4:35</td>
<td>4:45</td>
</tr>
<tr>
<td>5:35</td>
<td>5:45</td>
</tr>
<tr>
<td>6:35</td>
<td>6:45</td>
</tr>
<tr>
<td>7:35</td>
<td>7:45</td>
</tr>
</tbody>
</table>

Qualitative observations
Posture/body control
Sitting posture is poor
Holds materials too close to face
Holds head at an odd angle
Does not look at bead while inserting tips of lace
Does not use pincer grip to pick up beads
Holds lace too far from tip
Holds lace too near tip
Finds it difficult to push tip with one hand and pull it through with the other

Changes threading hands during a trial
Hand movements are jerky
Moves constantly/fidgets
Adjustment to task requirements
Sometimes misses hole with tip of lace
Can thread lace on false side
Sometimes uses beads to thread lace
Other

Comments:

---

Manual Dexterity 2: THREADING BEADS
Note: 6 beads for 3-4 years, 12 for 5-6 years

Record: Time taken (secs), F for failure; R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of seconds</th>
<th>Preferred hand</th>
<th>Non-preferred hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trail 1</td>
<td>Trail 2</td>
<td></td>
</tr>
<tr>
<td>7:10</td>
<td>7:10</td>
<td></td>
</tr>
<tr>
<td>7:20</td>
<td>7:20</td>
<td></td>
</tr>
<tr>
<td>7:30</td>
<td>7:30</td>
<td></td>
</tr>
<tr>
<td>7:40</td>
<td>7:40</td>
<td></td>
</tr>
<tr>
<td>8:10</td>
<td>8:10</td>
<td></td>
</tr>
</tbody>
</table>

Qualitative observations
Posture/body control
Sitting posture is poor
Holds materials too close to face
Holds head at an odd angle
Does not look at bead while inserting tip of lace
Does not use pincer grip to pick up beads
Holds lace too far from tip
Holds lace too near tip
Finds it difficult to push tip with one hand and pull it through with the other

Changes threading hands during a trial
Hand movements are jerky
Moves constantly/fidgets
Adjustment to task requirements
Sometimes misses hole with tip of lace
Can thread lace on false side
Sometimes uses beads to thread lace
Other

Comments:
### Manual Dexterity 3: DRAWING TRAIL 1

**Note:** Bero! pen to be used

Record: **Hand used:** R/L/Both; **No. of errors:** F for failure; R for refusal; I if inappropriate (note reasons below). Number of errors should be counted after testing using scoring criteria provided in Appendix A of the Manual.

<table>
<thead>
<tr>
<th></th>
<th>Trial 1</th>
<th>Trial 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No. of errors</strong></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Do not administer a second trial if the child completes the first trial perfectly (i.e. no errors).

### Qualitative observations

**Posture/body control**
- Sitting posture is poor
- Holds head too near paper
- Holds head at an odd angle
- Does not look at trail
- Holds pen with an odd/im mature grip
- Holds pen too far from point
- Holds pen too close to point
- Does not hold paper still

**Changes hands during trial**
- Moves constantly/fidgets

**Adjustment to task requirements**
- Progresses in short jerky movements
- Uses excessive force, pressure on hand or paper
- Is exceptionally slow
- Goes too fast for accuracy
- Other

**Other**

**Comments:**

### Aiming & Catching 1: CATCHING BEANBAG

**Note:** Trapping allowed for 3-4 year olds, not for 5-6

Record: **Number of correctly executed catches out of 10:** R for refusal; I if inappropriate (note reasons below)

**Practice:**

<table>
<thead>
<tr>
<th>Practice</th>
<th>10 Trials</th>
<th>Total</th>
</tr>
</thead>
</table>

**Qualitative observations**

**Posture/body control**
- Standing posture is poor
- Does not follow trajectory of beanbag with eyes
- Turns away or closes eyes as beanbag approaches
- Arms are not raised symmetrically for catching
- Holds hands out flat with fingers stiff as the beanbag approaches
- Hands and arms held wide apart; fingers extended
- Fingers close too early or too late
- Does not move until beanbag strikes body

**Movements lack fluency**

**Adjustment to task requirements**
- Does not adjust body position for catching
- Does not adjust position of feet as necessary
- Does not adjust to height of throw
- Does not adjust direction of throw
- Does not adjust to force of throw
- Other

**Other**

**Comments:**

3 223
Aiming & Catching 2: THROWING BEANBAG ONTO MAT

Note: Target is the whole mat, not just the orange circle

Record: Hand used: R / L / Both; Number of successful hits: R for refusal; I if inappropriate (note reasons below)

Practice: 10 Trials:

Qualitative observations

Posture/body control

Balance while throwing is poor.
Does not keep eyes on target.
Does not use a pendular swing of the arm.
Does not follow through with the throwing arm.
Releases beanbag too early or too late.
Changes hands from trial to trial.
Movements lack fluency.

Adjustment to task requirements

Errors are consistently to one side of target (asymmetry striking).
Control of direction variable.
Judges force of throw poorly (too much or too little).
Control of force is variable.
Other.

Comments:

Balance 1: ONE-LEG BALANCE

Record: Time balanced (sec); R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of seconds</th>
<th>No. of seconds</th>
</tr>
</thead>
<tbody>
<tr>
<td>Right Leg</td>
<td>Trial 1</td>
</tr>
<tr>
<td>Left Leg</td>
<td>Trial 2</td>
</tr>
</tbody>
</table>

Qualitative observations

Posture/body control

Body appears rigid/tense.
Body appears limp/floppy.
Sways wildly to try to maintain balance.
Does not hold head and eyes steady.
Makes no or few compensatory arm movements to help maintain balance.

Exaggerated movements of arms and trunk disrupt balance.
Does extremely poorly on one leg (asymmetry striking).
Other.

Comments:
Balance 2: WALKING HEELS RAISED

Record: Number of correct consecutive steps from the beginning of the line; Whether entire line was walked successfully; R for refusal, I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of steps</th>
<th>Entire line?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>YES / NO</td>
</tr>
<tr>
<td>Trial 2</td>
<td>YES / NO</td>
</tr>
</tbody>
</table>

Qualitative observations
Posture/body control

- Body appears rigid/tense
- Body appears limp/floppy
- Sways wildly to try to maintain balance
- Does not keep head steady
- Does not compensate with arms to maintain balance
- Exaggerated arm movements disrupt balance

Do not administer a second trial if the child completes 15 steps or completes the whole line in fewer than 15 correctly executed steps.

Comments: -----------------------------------

Balance 3: JUMPING ON MATS

Note: Need only be continuous at 5-6 years

Record: Number of correct consecutive jumps (maximum of 5); R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of jumps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
</tr>
<tr>
<td>Trial 2</td>
</tr>
</tbody>
</table>

Qualitative observations
Posture/body control

- Body appears rigid/tense
- Body appears limp/floppy
- Makes no preparatory crouch
- Jumps with stiff legs on flat feet
- Arms swing out of phase with legs
- Arm movements are exaggerated
- Does not use arms to assist jump
- Lacks springiness/no push-off from feet

Do not administer a second trial if the child completes 5 perfect jumps on the first trial

Comments: -----------------------------------
NON-MOTOR FACTORS THAT MIGHT AFFECT MOVEMENT

Complete the sections below by noting any features of the child’s behaviour during testing that you suspect might have affected his or her motor performance. Headings (with examples) are given as guidelines only. Although negative aspects are given more emphasis, remember to note positive aspects of the child’s behaviour.

1. Disorganised (e.g. scattered clothes slows up dressing after PE; puts on shoes before socks).
2. Hesitant/forgetful (e.g. slow to start complex actions; forgets what to do in the middle of an action sequence).
3. Passive (e.g. hard to interest; requires much encouragement to participate).
4. Timid (e.g. fearful of activities such as jumping/climbing; constantly asks for assistance).
5. Anxious (e.g. trembles; becomes flustered in a stressful situation).
6. Impulsive (e.g. starts before instructions are complete; impatient of delays).
7. Distractible (e.g. looks around; responds to irrelevant noises).
8. Overactive (e.g. squirms and fidgets; moves constantly when listening to instructions, fiddles with clothes).
9. Overestimates own ability (e.g. tries to make tasks more difficult; tries to do things too fast).
10. Underestimates own ability (e.g. complains of task difficulty; anticipates failure before starting).
11. Lacks persistence (e.g. gives up quickly; is easily frustrated).
12. Upset by failure (e.g. looks tearful; refuses to try task again).
13. Unable to get pleasure from success (e.g. fails to respond to praise).

Other (please specify).

Overall, do you think these problems prevent the child from demonstrating his or her true movement capability? (please circle)

Not at all
A little
A great deal

PHYSICAL FACTORS THAT MIGHT AFFECT MOVEMENT

Anatomical/postural defect: YES/NO Specify, if possible
Vision defect: YES/NO
Hearing defect: YES/NO
Judgement of weight: average/overweight/underweight
Judgement of height: average/tall/short
Other
SUMMARY OF QUALITATIVE OBSERVATIONS

MANUAL DEXTERITY (Body control/posture; functioning of limbs; spatial accuracy; control of force/effort; timing of actions; other observations including response to feedback during informal testing)

AIMING & CATCHING (Body control/posture; functioning of limbs; spatial accuracy; control of force/effort; timing of actions; other observations including response to feedback during informal testing)

STATIC AND DYNAMIC BALANCE (Body control/posture; functioning of limbs; spatial accuracy; control of force/effort; timing of actions; other observations including response to feedback during informal testing)
## ASSESSMENT SUMMARY AND INTERVENTION PLAN

<table>
<thead>
<tr>
<th>Name:</th>
<th>Gender: M/F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home address:</td>
<td></td>
</tr>
<tr>
<td>School: Class/Year/Grade:</td>
<td>Referral Source:</td>
</tr>
<tr>
<td>Movement Coach: Date of meeting:</td>
<td></td>
</tr>
</tbody>
</table>

### A. Movement Competence

1. Results on standardised tests (enter total scores and mark percentiles)

<table>
<thead>
<tr>
<th>Movement ABC-2 Test</th>
<th>Total Test Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement ABC-2 Checklist</td>
<td>Total Motor Score</td>
</tr>
</tbody>
</table>

2. Profile of competence on Test and Checklist

<table>
<thead>
<tr>
<th>Movement ABC-2 Test</th>
<th>Manual Dexterity</th>
<th>Aiming &amp; Catching</th>
<th>Balance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement ABC-2 Checklist</td>
<td>Section A Score</td>
<td>Comments</td>
<td>Section B Score</td>
</tr>
</tbody>
</table>

3. Summary of motor organisation on Test and Checklist (Include qualitative data from test, along with individual item data from Checklist)

4. Other test data (summarise and describe outcome)

5. Child interview (summarise and list three main movement concerns)

6. Parent interview (summarise and list three main movement concerns)

7. School concerns in relation to movement
B. Non-motor factors that might affect the child’s ability to perform/learn movement skills

The Movement ABC-2 Test and Checklist provide information on factors that might affect the child’s ability to learn or perform movement skills. Examine the appropriate sections in the Test and Checklist, combine with any other data available, and summarise these here.

C. Overall profile of child’s strengths and weaknesses

For some children the results of formal assessments of various kinds will be available. For others, school reports and interviews will provide enough information. Describe here any information you consider relevant to planning a movement programme for the child.

D. Environmental context

Varying amounts of support will be available for the child. Summarise here the potential – give rates and degree of commitment where possible and specify the contribution to be made.

At home:

At school:

From the health services:

In the community:

E. Objectives and main priorities

Summarise here the agreed short-term movement objectives for the child (and non-motor if any). Specify the target time for achievement and date of first review. On a separate sheet(s) outline in more detail how and where each target will be taught, and sketch the longer-term objectives.
AB1
Practice

Trial 1

Trial 2
Name:
Home address:
School:
Assessed by:
Referral source:
Preferred (writing) hand:

Movement ABC-2
Checklist completed? Y / N

Date tested
Date of birth
Chronological age

Gender: M / F
Class/year/grade:

Day

Item Scores and Equivalent Standard Scores

<table>
<thead>
<tr>
<th>Item code</th>
<th>Name of item</th>
<th>Raw score (Best attempts)</th>
<th>Item Standard Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD 1*</td>
<td>Placing Pegs preferred hand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD 1*</td>
<td>Placing Pegs non-preferred hand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD 2</td>
<td>Threading Lace</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD 3</td>
<td>Drawing Trail 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABC 1</td>
<td>Catching with Two Hands</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABC 2</td>
<td>Throwing Beanbag onto Mat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 1*</td>
<td>One-Board Balance best leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 1*</td>
<td>One-Board Balance other leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 2</td>
<td>Walking Heel-to-Toe Forwards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 3*</td>
<td>Hopping on Mats best leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 3*</td>
<td>Hopping on Mats other leg</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Test Score: Sum of 7 item standard scores

For Placing Pegs, One-Board Balance and Hopping on Mats, look up standard score for each limb, add these and divide by 2. If the result is above 10, round up; if below 10, round down.

For confidence intervals, see Examiner's Manual p.139 (Chapter 7)
Manual Dexterity 1: PLACING PEGS

Record: Preferred hand: R / L (should be same as for Drawing Trail); Time taken (secs); F for failure; R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th></th>
<th>Preferred hand</th>
<th>Non-preferred hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>7.0-7.11</td>
<td>6.0-6.11</td>
</tr>
<tr>
<td>Trial 2</td>
<td>3.7 secs</td>
<td>3.3 secs</td>
</tr>
</tbody>
</table>

Qualitative observations
Posture/body control

Sitting posture is poor
Holds head too close to task
Holds head at an odd angle
Does not look at board while inserting pegs
Does not use pincer grip to pick up pegs
Exaggerates finger movements in releasing pegs
Does not use the supporting hand to hold board steady
Does extremely poorly with one hand (asymmetry striking)
Changes hands or uses both hands during a trial

Comments:

---

Manual Dexterity 2: THREADING LACE

Record: Time taken (secs); F for failure; R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of seconds</th>
<th>As part of the first trial, or faster than the time stated below</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>7.0-7.11 6.0-6.11 9.0-9.11 10.0-10.11</td>
</tr>
<tr>
<td>Trial 2</td>
<td>3.7 secs 3.4 secs 2.9 secs 2.7 secs</td>
</tr>
</tbody>
</table>

Qualitative observations
Posture/body control

Sitting posture is poor
Holds materials too close to face
Holds head at an odd angle
Does not look at board while inserting tip of lace
Does not use pincer grip to hold lace
Holds lace too far from tip
Holds lace too near tip
Finds it difficult to push tip with one hand and pull it through with the other

Changes threading hands during a trial
Hand movements are jerky
Moves constantly/fidgets
Adjustment to task requirements
Sometimes misses hole with tip of lace
Gets muddled in the threading sequence
Is exceptionally slow/does not change speed from trial to trial
Goes too fast for accuracy
Other

Comments:

---
## Manual Dexterity 3: DRAWING TRAIL 2

**Note:** BIC Atlantis pen to be used

**Record:** Hand used: R/L/Both; No. of errors: F for failure; R for refusal; I if inappropriate (note reasons below)

Number of errors should be counted after testing using scoring criteria provided in Appendix A of the Manual.

<table>
<thead>
<tr>
<th>Trial</th>
<th>No. of errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td></td>
</tr>
<tr>
<td>Trial 2</td>
<td></td>
</tr>
</tbody>
</table>

Do not administer a second trial if the child completes the first trial perfectly (i.e. no errors).

### Qualitative observations

#### Posture/body control
- Sitting posture is poor
- Holds head too near paper
- Holds head at an odd angle
- Does not look at trail
- Holds pen with an odd/mature grip
- Holds pen too far from point
- Holds pen too close to point
- Does not hold paper still

#### Adjustment to task requirements
- Changes hands during a trial
- Moves constantly/fidgets
- Changes hands during a trial
- Holds head too near paper
- Holds head at an odd angle
- Does not look at trail
- Holds pen with an odd/mature grip
- Holds pen too far from point
- Holds pen too close to point
- Does not hold paper still

### Aiming & Catching 1: CATCHING WITH TWO HANDS

**Note:** With a bounce at 7 and 9, without a bounce at 9 and 10

**Record:** Number of correctly caught balls: R for refusal; I if inappropriate (note reasons below)

**Practice:**

<table>
<thead>
<tr>
<th>10 Trials:</th>
<th>Total:</th>
</tr>
</thead>
</table>

**Qualitative observations**

#### Posture/body control
- Standing posture is poor
- Does not follow trajectory of ball with eyes
- Turns away or closes eyes as ball approaches
- Arms are not aligned symmetrically for catching
- Holds hands out flat with fingers stiff as ball approaches
- Hands and arms held wide apart, fingers extended
- Arms and hands do not give to meet impact of ball
- Fingers close too early or too late
- Movements lack fluency

#### Adjustment to task requirements
- Does not adjust body position for catching
- Does not adjust position of feet as necessary
- Judges force of throw poorly (too much or too little)
- Does not adjust to height of rebound
- Does not adjust to direction of rebound
- Other

**Comments:**

---

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**Aiming & Catching 2: THROWING BEANBAG ONTO MAT**

Note: Target is the orange circle, not the whole mat

Record: Hand used: R / L / Both; Number of successful hits: R for refusal; I if inappropriate (note reasons below)

Practice:

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Trial 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Qualitative observations

**Posture/body control**

- Balance while throwing is poor
- Does not keep eyes on target
- Does not use a pendular swing of the arm
- Does not follow through with the throwing arm
- Releases beanbag too early or too late
- Changes hands from trial to trial
- Movements lack fluency

**Adjustment to task requirements**

- Errors are consistently to one side of target (asymmetry striking)
- Control of direction variable
- Judges force of throw poorly (too much or too little)
- Control of force is variable
- Other

**Comments:**

---

**Balance 1: ONE-BOARD BALANCE**

Record: Time balanced (sec); R for refusal; I if inappropriate (note reasons below)

<p>| | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No of seconds</td>
<td>No of seconds</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Right Leg</td>
<td>Trial 1</td>
<td>Left Leg</td>
<td>Trial 1</td>
<td>Right Leg</td>
<td>Trial 2</td>
<td>Left Leg</td>
</tr>
<tr>
<td>Trial 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Do not administer a second trial if the child maintains balance for 30 seconds

Qualitative observations

**Posture/body control**

- Body appears rigid/tense
- Body appears limp/floppy
- Sways wildly to try to maintain balance
- Does not hold head and eyes steady
- Makes no or few compensatory arm movements to help maintain balance

**Exaggerated movements of arms and trunk disrupt balance**

**Does extremely poorly on one leg (asymmetry striking)**

**Other**

**Comments:**
### Balance 2: WALKING HEEL-TO-TOE FORWARDS

**Record:** Number of correct consecutive steps from the beginning of the line; Whether entire line was walked successfully; R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of steps</th>
<th>Entire line?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>YES / NO</td>
</tr>
<tr>
<td>Trial 2</td>
<td>YES / NO</td>
</tr>
</tbody>
</table>

**Qualitative observations**

**Posture/body control**
- Body appears rigid/tense
- Body appears limp/floppy
- Sways wildly to try to maintain balance
- Does not keep head steady
- Does not compensate with arms to maintain balance
- Exaggerated arm movements disrupt balance

**Comments:**

Do not administer a second trial if the child completes 15 steps OR completes the whole line in fewer than 15 correctly executed steps.

### Balance 3: HOPPING ON MATS

**Record:** Number of correct consecutive hops (maximum of 5); R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of hops</th>
<th>Right Leg</th>
<th>Left Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>Trial 1</td>
<td>Trial 2</td>
</tr>
<tr>
<td>Trial 2</td>
<td>Trial 2</td>
<td></td>
</tr>
</tbody>
</table>

**Qualitative observations**

**Posture/body control**
- Body appears rigid/tense
- Body appears limp/floppy
- Non-supporting leg held up in front of body
- Hops with stiff leg on flat feet
- Lacks springiness/no push-off from feet
- Arm movements are exaggerated
- Arms swing out of phase with legs

**Comments:**

Do not administer a second trial if the child completes 5 perfect hops on the first trial.
**NON-MOTOR FACTORS THAT MIGHT AFFECT MOVEMENT**

Complete the sections below by noting any features of the child’s behaviour during testing that you suspect might have affected his or her motor performance. Headings (with examples) are given as guidelines only. Although negative aspects are given more emphasis, remember to note positive aspects of the child’s behaviour.

<table>
<thead>
<tr>
<th></th>
<th>Yes</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Disorganised (e.g. scattered clothes slows up dressing after PE; puts on shoes before socks).</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Hesitant/forgetful (e.g. slow to start complex actions; forgets what to do in the middle of an action sequence).</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Passive (e.g. hard to interest; requires much encouragement to participate).</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Timid (e.g. fearful of activities such as jumping/climbing; constantly asks for assistance).</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Anxious (e.g. trembles; becomes flustered in a stressful situation).</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Impulsive (e.g. starts before instructions are complete; impatient of details).</td>
<td></td>
</tr>
<tr>
<td>7.</td>
<td>Distractible (e.g. looks around; responds to irrelevant noises).</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Overactive (e.g. squirms and fidgets; moves constantly when listening to instructions, fiddles with clothes).</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Overestimates own ability (e.g. tries to make tasks more difficult; tries to do things too fast).</td>
<td></td>
</tr>
<tr>
<td>10.</td>
<td>Underestimates own ability (e.g. complains of task difficulty; anticipates failure before starting).</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Lacks persistence (e.g. gives up quickly; is easily frustrated).</td>
<td></td>
</tr>
<tr>
<td>12.</td>
<td>Upset by failure (e.g. looks tearful; refuses to try task again).</td>
<td></td>
</tr>
<tr>
<td>13.</td>
<td>Unable to get pleasure from success (e.g. fails to respond to praise).</td>
<td></td>
</tr>
<tr>
<td>Other (please specify).</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Overall, do you think these problems prevent the child from demonstrating his or her true movement capability (please circle)

- not at all
- a little
- a great deal

**PHYSICAL FACTORS THAT MIGHT AFFECT MOVEMENT**

- Anatomical/postural defect: YES/NO. Specify, if possible.
- Vision defect: YES/NO
- Hearing defect: YES/NO
- Judgement of weight: average/overweight/underweight
- Judgement of height: average/tall/short
- Other
SUMMARY OF QUALITATIVE OBSERVATIONS

MANUAL DEXTERITY (Body control/posture; functioning of limbs; spatial accuracy, control of force/effort, timing of actions; other observations including response to feedback during informal testing)

AIMING & CATCHING (Body control/posture; functioning of limbs; spatial accuracy; control of force/effort; timing of actions; other observations including response to feedback during informal testing)

STATIC AND DYNAMIC BALANCE (Body control/posture; functioning of limbs; spatial accuracy, control of force/effort; timing of actions; other observations including response to feedback during informal testing)
## ASSESSMENT SUMMARY AND INTERVENTION PLAN

**Name:**
**Gender:** M/F

**Home address:**

**School:**
**Class/Year/Grade:**
**Referral Source:**

**Movement Coach:**
**Date of meeting:**

### A. Movement Competence

1. Results on standardised tests (enter total scores and mark percentiles)

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Score Type</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement ABC-2 Test</td>
<td>Total Test Score</td>
<td>(Enter score)</td>
</tr>
<tr>
<td>Movement ABC-2 Checklist</td>
<td>Total Motor Score</td>
<td>(Enter score)</td>
</tr>
</tbody>
</table>

2. Profile of competence on Test and Checklist:

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Score Type</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement ABC-2 Test</td>
<td>Manual Dexterity</td>
<td>(Enter score)</td>
</tr>
<tr>
<td></td>
<td>Aiming &amp; Catching</td>
<td>(Enter score)</td>
</tr>
<tr>
<td></td>
<td>Balance</td>
<td>(Enter score)</td>
</tr>
<tr>
<td>Movement ABC-2 Checklist</td>
<td>Section A Score</td>
<td>(Enter score)</td>
</tr>
</tbody>
</table>

3. Summary of motor observations from Test and Checklist (use qualitative data from Test, along with individual item data from Checklist)

4. Other test data (summarise and describe outcome)

5. Child interview (summarise and list three main movement concerns)

6. Parent interview (summarise and list three main movement concerns)

7. School concerns in relation to movement

Continued on reverse.
B. Non-motor factors that might affect the child's ability to perform/learn movement skills

The Movement ABC-2 Test and Checklist provide information on factors that might affect the child's ability to learn or perform movement skills. Examine the appropriate sections in the Test and Checklist, combine with any other data available, and summarise these here.

---

C. Overall profile of child's strengths and weaknesses

For some children the results of formal assessments of various kinds will be available. For others, school reports and interviews will provide enough information. Describe here any information you consider relevant to planning a movement programme for the child.

---

D. Environmental context

Varying amounts of support will be available for the child. Summarise here the potential contributions and degree of commitment where possible and specify the contribution to be made.

At home:

At school:

From the health services:

In the community:

---

E. Objectives and main priorities

Summarise here the agreed short-term movement objectives for the child (and non-motor if any). Specify the target time for achievement and date of first review. On a separate sheet(s) outline in more detail how and where each target skill will be taught, and sketch the longer-term objectives.
Movement Assessment Battery for Children – 2
Test Record Form Age Band 3 (11-16 years)

Name: ___________________________ Gender: M / F ____________
Home address: ____________________
School: ___________________________ Class/year/grade: ____________
Assessed by: _______________________
Referral source: ____________________
Preferred (writing) hand: ____________

Movement ABC-2 Checklist completed? Y / N ____________

Date tested: ________________________
Date of birth: _______________________
Chronological age: __________________

Item Scores and Equivalent Standard Scores

<table>
<thead>
<tr>
<th>Item code</th>
<th>Name of Item</th>
<th>Raw score (best attempt)</th>
<th>Item Standard Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>MD 1*</td>
<td>Turning Pegs preferred hand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD 2</td>
<td>Turning Pegs non-preferred hand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MD 3</td>
<td>Triangle with Nuts and Bolts</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABC 1*</td>
<td>Drawing Trial 3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABC 2</td>
<td>Catching with one hand - best hand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ABC 3</td>
<td>Catching with one hand - other hand</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 1</td>
<td>Throwing at Wall Target</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 2</td>
<td>Two-Board Balance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 3*</td>
<td>Walking Toe-to-Heel Backwards</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 4</td>
<td>ZigZag Hopping best Leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bal 5</td>
<td>ZigZag Hopping other Leg</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Total Test Score: Sum of 8 item standard scores:

*For Turning Pegs, Catching with one hand and Zig Zag Hopping, look up standard score for each limb, add these and divide by 2. If the result is above 10, round up; if below 10, round down.

Three Component Scores

<table>
<thead>
<tr>
<th>Component</th>
<th>Standard Score</th>
<th>Percentile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Dexterity*</td>
<td>MD 1 + MD 2 + MD 3</td>
<td></td>
</tr>
<tr>
<td>Aiming &amp; Catching*</td>
<td>ABC 1 + ABC 2</td>
<td></td>
</tr>
<tr>
<td>Balance*</td>
<td>Bal 1 + Bal 2 + Bal 3</td>
<td></td>
</tr>
</tbody>
</table>

*In each case sum the item standard scores.

For confidence intervals, see Examiner’s Manual p139 (Chapter 7)
Manual Dexterity 1: TURNING PEGS

Record: Preferred hand: R / L (should be same as for Drawing Trail); Time taken (secs); F for failure; R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>Preferred hand</th>
<th>Non-preferred hand</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>Trial 1</td>
</tr>
<tr>
<td></td>
<td>11.01</td>
</tr>
<tr>
<td></td>
<td>12.01</td>
</tr>
<tr>
<td></td>
<td>13.01</td>
</tr>
<tr>
<td></td>
<td>14.01</td>
</tr>
<tr>
<td></td>
<td>15.01</td>
</tr>
<tr>
<td></td>
<td>16.01</td>
</tr>
<tr>
<td>Trial 2</td>
<td>25 secs</td>
</tr>
<tr>
<td></td>
<td>22 secs</td>
</tr>
<tr>
<td></td>
<td>22 secs</td>
</tr>
<tr>
<td></td>
<td>11 secs</td>
</tr>
</tbody>
</table>

Qualitative observations

Posture/body control
- Sitting posture is poor
- Holds head too close to task
- Holds head at an odd angle
- Does not look while manipulating pegs
- Does not use pincer grip to pick up pegs
- Exaggerates finger movements in releasing pegs
- Does not use the supporting hand to hold board steady
- Changes hands or uses both hands during a trial
- Changes hands or uses both hands during a trial

Comments:

Manual Dexterity 2: TRIANGLE WITH NUTS AND BOLTS

Record: Time taken (secs); F for failure; R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of seconds</th>
<th>Only achieve a second trial if the first trial takes longer than the time stated below:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15.01-15.51 15.61-16.01 15.61-16.01 15.61-16.01 15.61-16.01 15.61-16.01</td>
</tr>
<tr>
<td>Trial 1</td>
<td>55 secs 45 secs 45 secs 45 secs 45 secs 45 secs</td>
</tr>
<tr>
<td>Trial 2</td>
<td>65 secs 65 secs 65 secs 65 secs 65 secs 65 secs</td>
</tr>
</tbody>
</table>

Qualitative observations

Posture/body control
- Sitting posture is poor
- Holds materials too close to face
- Holds head at an odd angle
- Does not look at hole while inserting bolt
- Does not use pincer grip to hold nuts and bolts
- Finds it difficult to hold bolt with one hand and screw nut on with the other
- Changes hands during a trail

Comments:
Manual Dexterity 3: DRAWING TRAIL 3

Note: Bic Atlantis pen to be used

Record: Hand used: R/L/both; No. of errors; F for failure; R for refusal; I if inappropriate (note reasons below)

Number of errors should be counted after testing using scoring criteria provided in Appendix A of the Manual.

<table>
<thead>
<tr>
<th>No. of errors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
</tr>
<tr>
<td>Trial 2</td>
</tr>
</tbody>
</table>

Qualitative observations

Posture/body control

Sitting posture is poor
Holds head too near paper
Holds head at an odd angle
Does not look at trail
Holds pen with an odd/mature grip
Holds pen too far from point
Holds pen too close to point
Does not hold paper still

Changes hands during a trial
Moves constantly/fidgets
Adjustment to task requirements
Progresses in short jerky movements
Uses excessive force, press very hard on paper
Is exceptionally slow
Good too fast for accuracy
Other

Comments:

Aiming & Catching 1: CATCHING WITH ONE HAND

Record: Number of correctly caught catches; R for refusal; I if inappropriate (note reasons below)

Right Hand Practice: [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] 10 Trials: [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] Total: [ ]

Left Hand Practice: [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] 10 Trials: [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] [ ] Total: [ ]

Qualitative observations

Posture/body control

Standing posture is poor
Does not follow trajectory of ball with eyes
Turns away or closes eyes as ball approaches
Holds hand out flat with fingers stiff as the ball rebounds
Hands and arms held wide apart, fingers extended
Arm and hand do not 'give' to meet impact of ball
Fingers close too early or too late
Does extremely poorly with one hand (asymmetry striking)
Movement lacks fluency

Changes body position for catching
Does not adjust position of feet as necessary
Judges force of throw poorly (too much or too little)
Does not adjust to height of rebound
Does not adjust to direction of rebound
Other

Comments:

3
Aiming & Catching 2: THROWING AT WALL TARGET

Record: Hand used: R / L / Both; Number of successful hits: R for refusal; I if inappropriate (note reasons below)

Practice: ______ 10 Trials: ______ Total: ______

Qualitative observations
Posture/body control
Balance while throwing is poor
Does not keep eyes on target
Does not follow through with the throwing arm
Releases ball too early or too late
Changes hands from trial to trial
 Movements lack fluency

Adjustment to task requirements
Errors are consistently to one side of the target
(asymmetry striking)
Control of direction is variable
Judges force of throw poorly (too much or too little)
Control of force is variable
Other

Comments: __________________________

Balance 1: TWO-BOARD BALANCE

Record: Time balanced (secs): R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of seconds</th>
<th>Trial 1</th>
<th>Trial 2</th>
</tr>
</thead>
</table>

Do not administer a second trial if the child maintains balance for 30 seconds

Qualitative observations
Posture/body control
Body appears rigid/tense
Body appears limp/floppy
Sways wildly to try to maintain balance
Does not hold head and eyes steady
Makes no or few compensatory arm movements to help maintain balance

Exaggerated movements of arms and trunk disrupt balance
Cannot hold feet in a straight line
Other

Comments: __________________________
Balance 2: WALKING TOE-TO-HEEL BACKWARDS

Record: Number of correct consecutive steps from the beginning of the line; Whether entire line was walked successfully; R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of steps</th>
<th>Entire line?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>YES / NO</td>
</tr>
<tr>
<td>Trial 2</td>
<td>YES / NO</td>
</tr>
</tbody>
</table>

Do not administer a second trial if the child completes 15 steps OR completes the whole line in fewer than 15 correctly executed steps.

Qualitative observations

Posture/body control

Body appears rigid/tense
Body appears limp/floppy
Sways wildly to try to maintain balance
Does not look behind to check position on track
Does not compensate with arms to maintain balance
Exaggerated arm movements disrupt balance
Is very wobbly when placing feet on line

Adjustments to task requirements

Goes too fast for accuracy
Individual movements lack smoothness and fluency
Sequencing of steps is not smooth/pauses frequently

Other

Comments:

Balance 3: ZIG-ZAG HOPPING

Record: Number of correct consecutive hops (maximum of 5); R for refusal; I if inappropriate (note reasons below)

<table>
<thead>
<tr>
<th>No. of hops</th>
<th>Right Leg</th>
<th>Left Leg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trial 1</td>
<td>Trial 1</td>
<td></td>
</tr>
<tr>
<td>Trial 2</td>
<td>Trial 2</td>
<td></td>
</tr>
</tbody>
</table>

Do not administer a second trial if the child completes 5 perfect hops on the first trial.

Qualitative observations

Posture/body control

Body appears rigid/tense
Body appears limp/floppy
Non-supporting leg held up in front of body
Hops with stiff legging flat feet
Lacks springiness/no push-off from feet
Arm movements are exaggerated
Does not use arms to assist hop
Stumbles on landing

Adjustments to task requirements

Does extremely poorly with one leg (symmetry striking)
Goes too fast for accuracy
Does not combine upward and forward movements effectively
Uses too much effort

Other

Comments:
NON-MOTOR FACTORS THAT MIGHT AFFECT MOVEMENT

Complete the sections below by noting any features of the child's behaviour during testing that you suspect might have affected his or her motor performance. Headings (with examples) are given as guidelines only. Although negative aspects are given more emphasis, remember to note positive aspects of the child's behaviour.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td><strong>Disorganised</strong> (e.g. scattered clothes slows up dressing after PE; puts on shoes before socks).</td>
</tr>
<tr>
<td>2.</td>
<td><strong>Hesitant/forgetful</strong> (e.g. slow to start complex actions; forgets what to do in the middle of an action sequence).</td>
</tr>
<tr>
<td>3.</td>
<td><strong>Passive</strong> (e.g. hard to interest; requires much encouragement to participate).</td>
</tr>
<tr>
<td>4.</td>
<td><strong>Timid</strong> (e.g. fearful of activities such as jumping/climbing; constantly asks for assistance).</td>
</tr>
<tr>
<td>5.</td>
<td><strong>Anxious</strong> (e.g. trembles; becomes flustered in a stressful situation).</td>
</tr>
<tr>
<td>6.</td>
<td><strong>Impulsive</strong> (e.g. starts before instructions are complete; impatient of details).</td>
</tr>
<tr>
<td>7.</td>
<td><strong>Distractible</strong> (e.g. looks around; responds to irrelevant noises).</td>
</tr>
<tr>
<td>8.</td>
<td><strong>Overactive</strong> (e.g. squirms and fidgets; moves constantly when listening to instructions, fiddles with clothes).</td>
</tr>
<tr>
<td>9.</td>
<td><strong>Overestimates own ability</strong> (e.g. tries to make tasks more difficult; tries to do things too fast).</td>
</tr>
<tr>
<td>10.</td>
<td><strong>Underestimates own ability</strong> (e.g. complains of task difficulty; anticipates failure before starting).</td>
</tr>
<tr>
<td>11.</td>
<td><strong>Lacks persistence</strong> (e.g. gives up quickly; is easily frustrated).</td>
</tr>
<tr>
<td>12.</td>
<td><strong>Upset by failure</strong> (e.g. looks tearful; refuses to try task again).</td>
</tr>
<tr>
<td>13.</td>
<td><strong>Unable to get pleasure from success</strong> (e.g. fails to respond to praise).</td>
</tr>
</tbody>
</table>

Other (please specify): __________

Overall, do you think these problems prevent the child from demonstrating his or her true movement capability (please circle): not at all, a little, a great deal.

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PHYSICAL FACTORS THAT MIGHT AFFECT MOVEMENT

- **Anatomical/postural defect**: YES/NO Specify, if possible
- **Vision defect**: YES/NO  
- **Hearing defect**: YES/NO
- **Judgement of weight**: average/overweight/underweight
- **Judgement of height**: average/tall/short
- **Other**:

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SUMMARY OF QUALITATIVE OBSERVATIONS

MANUAL DEXTERITY (Body control/posture; functioning of limbs; spatial accuracy; control of force/effort; timing of actions; other observations including response to feedback during informal testing)

AIMING & CATCHING (Body control/posture; functioning of limbs; spatial accuracy; control of force/effort; timing of actions; other observations including response to feedback during informal testing)

STATIC AND DYNAMIC BALANCE (Body control/posture; functioning of limbs; spatial accuracy; control of force/effort; timing of actions; other observations including response to feedback during informal testing)
# ASSESSMENT SUMMARY AND INTERVENTION PLAN

<table>
<thead>
<tr>
<th>Name:</th>
<th>Gender: M/F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Home address:</td>
<td></td>
</tr>
<tr>
<td>School:</td>
<td>Class/Year/Grade:</td>
</tr>
<tr>
<td>Movement Coach:</td>
<td>Date of meeting:</td>
</tr>
</tbody>
</table>

## A. Movement Competence

1. Results on standardised tests (enter total scores and mark percentages)

<table>
<thead>
<tr>
<th>Movement ABC-2 Test</th>
<th>Total Test Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Movement ABC-2 Checklist</td>
<td>Total Mark Score</td>
</tr>
</tbody>
</table>

2. Profile of competence on Test and Checklist

| Movement ABC-2 Test | Manual Dexterity | Aim & Catching | Balance |
| Movement ABC-2 Checklist | Section A Score | Comment: | Section B Score |

3. Summary of movement observations, comments on Test and Checklist (Use qualitative data from Test, along with individual item data from Checklist)

4. Other test data (summarize and describe outcome)

5. Child interview (summarize and list three main movement concerns)

6. Parent interview (summarize and list three main movement concerns)

7. School concerns in relation to movement

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Continued on reverse.
B. Non-motor factors that might affect the child's ability to perform/learn movement skills

The Movement ABC-2 Test and Checklist provide information on factors that might affect the child's ability to learn or perform movement skills. Examine the appropriate sections in the Test and Checklist, combine with any other data available, and summarise these here.


C. Overall profile of child's strengths and weaknesses

For some children the results of formal assessments of various kinds will be available. For others, school reports and interviews will provide enough information. Describe here any information you consider relevant to planning a movement programme for the child.


D. Environmental context

Varying amounts of support will be available for the child. Summarise here the potential - give names and degree of commitment where possible and specify the contribution to be made.

At home:

At school:

From the health service:

In the community:


E. Objectives and main priorities

Summarise here the agreed short-term movement objectives for the child (and non-motor if any). Specify the target time for achievement and date of first review. On a separate sheet(s) outline in more detail how and where each target skill will be taught, and sketch the longer-term objectives.
Magnetic Resonance Imaging

How does MRI work?

Lots of images are taken...
What does an MRI machine look like?

These images are then put together

What will you need to do?

MRI Machine  Control Room

Lie very still...
How long will you have to lie still for?

How to lie still...

Relax...

Will every part of your body need to remain still?

You will get to wear a special helmet
Why do we need you to move your hand?

**Functional MRI**

Before your MRI

We also need to see how well you can hold still...

We will be playing a *signal game*.

What does the MRI machine sound like?

You will get special earphones to wear.

Let's have a practice.
Hand Clenching

Colours to look out for...

Stop and Watch

Imagine

Green is Go

When you are resting, you will see these two images. They will change every second. Just lie there and watch the pictures...
Let's have a quick practice...

Stop and **Watch**
Green is Go

Ready for one more go?

Great Work!

On your next visit...

Enter at 'G' Block
Walk down the corridor...

Follow the signs to Radiology

Radiology
X-Ray, CT, Ultrasound, MRI

We will meet you at the Reception

MRI Machine
Control Room

Then it will be your turn...

Have fun!
Get ready to embark on your journey to Sir Charles Gairdner Hospital to have a special MRI and fMRI scan. It is going to be an adventure!
It is time to prepare for take-off! We will show you around the control room, and what the MRI machine looks like.

Follow the signs that direct you to the radiology reception.

We will meet you there!
Soon it will be time for your adventure to begin!

The MRI machine will take pictures of your brain using super conducting magnets...

So please remember not to wear anything that has metal in it (e.g. zips)! You can remove any loose metallic items you forget about before take off...

The MRI machine is like a rocket ship!

There are two special items of equipment you will need to wear during your voyage:

A helmet to help keep your head very still,

and headphones to block out the noise.
NAME

YOUR MRI ADVENTURE

GET READY TO LAUNCH!

10, 9, 8, 7, 6, 5, 4, 3, 2, 1…. Lift Off!

During take off you will need to lie very still.

It will take around 4 minutes to leave the Earth’s atmosphere. We will take lots of photos of your brain while you are travelling so we can see what it looks like.

You will have time for a quick break after you leave the Earth’s atmosphere…

IMPORTANT!

Please lie very still!

This will help us to take clear pictures of your brain.

For your mission to be successful, there is one thing you will need to remember:

Please lie very still!
It is now time to lie back and relax while you travel through outer space. This part of our voyage will take 6 minutes. During this time we will ask you to lie still, close your eyes and try not to think about anything. We will take more pictures of your brain, this time so we can look at which parts are active.

Now our real adventure begins! We will take 2 sets of pictures of your brain while you are doing an activity with your hand. You will get a short break in between.

This will help us see what parts of your brain you used to move your hand.
Before you know it, you will have returned to Earth and your MRI adventure will be over. We will have a special surprise to say thanks.
When you are resting, you will see these two images and hear the metronome.

Any questions?

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