Manchester Metropolitan University

Marshall, Ben (2018) *Exploring the use of combined action observation and motor imagery forimproving eye-hand coordination in children with developmentalcoordination disorder.* Doctoral thesis (PhD), Manchester Metropolitan University.

Downloaded from: http://e-space.mmu.ac.uk/623336/

Usage rights: Creative Commons: Attribution-Noncommercial-No Derivative Works 4.0

Please cite the published version

https://e-space.mmu.ac.uk

Exploring the use of combined action observation and motor imagery for improving eye-hand coordination in children with developmental coordination disorder

Ben Marshall

A thesis submitted in partial fulfilment of the

requirements of Manchester Metropolitan University

for the degree of Doctor of Philosophy

Research Centre for Musculoskeletal Science and Sports Medicine

Department of Exercise and Sport Science

Manchester Metropolitan University

2018

Acknowledgements

My heartfelt thanks to my long-suffering supervisor Dr Greg Wood for all his help in getting me to this stage. It took a while, but we got there! Thank you for keeping me on track and for telling it like it is. I know I'm probably not the easiest PhD student you'll ever have and I truly appreciate your patience and guidance. Enormous thanks also to the other members of my supervisory team Dr David Wright and Prof. Paul Holmes. Thank you both for your excellent guidance throughout this process.

Thanks also to my fellow PhD student Martin Riach for being an almost constant (but welcomed) source of distraction when in the office. A big thank you goes to Dr Chesney Craig and Dr Zoe Franklin for all their help, encouragement, and offerings of cake. I would also like to give a massive thank you to all the various students and members of staff at MMU who took part in testing.

For all their help and support I would like to thank the technical staff at MMU Cheshire. I would also dearly like to thank the staff at MMU All Saints for helping to make special arrangements for my testing sessions at very short notice and for teaching me that bees drop like a stone when the lights go out.

An extra special thanks to all of the children and parents who gave up time on their half-term holidays or took time off school to come in and participate in my studies, travelling from near and far even in blizzard conditions! Without your help and enthusiasm, completing this series of studies would have been impossible and it was a pleasure meeting and working with you all. To the children, you have each taught me more about DCD than I could ever hope to learn from a textbook and for that, I am grateful. To the parents, I am humbled by the lengths to which you will go to help your children and others like them. On the same note, thank you to Rachel Tucker for her incredible help enabling me to communicate with the global DCD community via social media and thanks to Stuart Pinkerton and his family for his help in rounding up the peerless FC Aztec.

I could not have made it through these last few years without my family and special thanks must go to them. Thanks to each of you for being so supportive of everything I have ever tried to do and for being a much-needed source of respite when times were hard. I appreciate everything you have done for me and I am boundlessly grateful.

Finally, I wish to thank Imogen for her infinite patience and support throughout this process. It's impossible for me to express the level of gratitude I have for you putting up with me over these last few years. You have had to deal with my growing daily anxiety regarding every single aspect of working towards this thesis and I simply could not have done it without you. Thank you so much.

Publications and presentations associated with this thesis

Full peer review journal articles directly associated with this thesis

1. Marshall, B., Wright, D. J., Holmes, P. S., and Wood, G. (in press) Combining action observation and motor imagery improves eye-hand coordination during novel visuomotor task performance. *Journal of Motor Behavior*

Additional full peer review journal articles

2. Marshall, B., and Wright, D. J. (2016). Layered stimulus response training versus combined action observation and imagery: Effects on golf putting performance and imagery ability characteristics *Journal of Imagery Research in Sport and Physical Activity*, *11*(1), 35-46.
3. Wright, D. J., Wood, G., Franklin, Z. C., Marshall, B., Riach, M., and Holmes, P. S. (2018). Directing visual attention during action observation modulates corticospinal excitability. *PloS one*, *13*(1), e0190165.

International and national presentations directly associated with this thesis

4. Marshall, B., Wright, D. J., Holmes, P. S., and Wood, G. (2017, May). Combining action observation and motor imagery improves eye-hand coordination during the learning of a novel visuomotor task. Paper presented at the 12th Annual Research in Imagery and Observation (RIO) Conference. Roehampton University, London, United Kingdom.
5. Marshall, B., Wright, D. J., Holmes, P. S., and Wood, G. (2018, April). Combined action observation and motor imagery improves eye-hand coordination in children with developmental coordination disorder. Paper presented at the 13th Annual Research in Imagery and Observation (RIO) Conference. Bielefeld University, Bielefeld, Germany.
6. Marshall, B., Wright, D. J., Holmes, P. S., and Wood, G. (2018, August). PhD summary: Combined action observation and motor imagery improves eye-hand coordination in children with developmental coordination disorder. Paper presented at the Exeter Vision Research conference. University of Exeter, Exeter, United Kingdom.

Additional international and national presentations

7. Marshall, B., and Wright, D. J. (2016, April). Layered stimulus response training versus combined action observation and imagery: Effects on golf putting performance and imagery ability characteristics. Paper presented at the 11th Annual Research in Imagery and Observation (RIO) Conference. Manchester Metropolitan University, Manchester, United Kingdom.

Poster presentations directly associated with this thesis

8. Marshall, B., Wright, D. J., Holmes, P. S., and Wood, G. (2016, September). Preliminary findings for how different observation instructions effect gaze control during learning of a novel visuomotor task. Poster presented at the European Summer School for Eye Movements, University Mental Health Research Institute, Athens, Greece.
9. Marshall, B., Wright, D. J., Holmes, P. S., and Wood, G. (2018, June). Combined action observation and motor imagery improves eye-hand coordination in children with developmental coordination disorder. Poster presented at the 7th Biennial Academic and Practitioner Conference on Developmental Coordination Disorder, Brunel University, London, United Kingdom.

Additional poster presentations

10. Marshall, B., and Wright, D. J. (2015, October). Layered stimulus response training versus combined action observation and imagery: Effects on golf putting performance and imagery ability characteristics. Poster presented at the 8th Annual MMU Postgraduate Research Conference, Manchester Metropolitan University, United Kingdom.

Abstract

This thesis documents a series of studies that are the first to demonstrate the efficacy of combined action observation and motor imagery (AOMI) for improving eye-hand coordination and task performance in individuals with and without developmental coordination disorder (DCD). First, a comparison of the effectiveness of AOMI, observing to imitate, and passive observation training interventions is reported. The results indicated that, in comparison to a control group, AOMI training produced a statistically significant increase in both task performance and eye-hand coordination, but no such improvements were found following observing to imitate or passive observation instructions. These findings suggest that AOMI facilitated the development of proactive eye movements that enhanced task performance. Second, the eye-hand coordination and task performance of children with and without DCD on a novel visuomotor task was explored. The findings from this study, in accordance with similar studies, indicated that the novel visuomotor task used in the study might have lacked the necessary complexity required to find significant differences in visuomotor performance between children with and without DCD. Third, the development of a new visuomotor task of higher complexity and suitable for use in an AOMI training intervention for children with DCD is reported. Analysis indicated a higher number of trials were required before performance plateaued and the best task performers adopted a distinct movement pattern. These results confirmed that the new task required a longer period of adaptation and supported the application of this task with DCD children in an AOMI training intervention. In the final study, the effects of an AOMI training intervention upon eye-hand coordination and performance in children with DCD are reported. Analysis of the data revealed that the AOMI training produced significant improvements in completion time and gaze control. It was concluded that children with DCD may benefit from AOMI training as the technique may aid their ability to update internal models of movement. This series of studies was the first to explore the effectiveness of AOMI training for improving eye-hand coordination and extend those findings to a clinical population. The results of these studies describe a conclusion that AOMI facilitates the development of proactive gaze, which in turn assists performance.

Table of Contents

Tables

Figures

List of appendices

1. Introduction

Developmental coordination disorder (DCD) is a neurodevelopmental disorder that is estimated to affect between 1.7% and 6% of children worldwide (American Psychological Association [APA], 2013). The condition is characterised by slow and inaccurate performance of age appropriate motor skills, which may affect the successful execution of both gross and fine movements associated with activities of daily life, sports and leisure activities (Barnhart et al., 2003). In addition to the poor execution of motor skills that interfere with daily living, there are also specific criteria outlined in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5) for diagnosing DCD. These additional criteria stipulate a deficit in motor skill acquisition and that the coordination difficulties exhibited by an individual are not the result of an intellectual disability or neurological condition (APA, 2013). Although the onset of symptoms manifests during the early developmental period for both sexes, they can last until adolescence and adulthood if not addressed during childhood (Barnhart et al., 2003). These motor skill impairments can also lead to further psychosocial issues that influence participation in typical childhood activities (Bart et al., 2011) and may be linked to long term health risks such as obesity and heart disease (Cairney and Veldhuizen, 2013). Developing techniques that facilitate the learning of skilled movements for these affected children is therefore of significant importance and was an aim of this thesis.

Although the precise cause of the disorder is unknown, the suboptimal performance of coordinated movements is widely believed to result from an impaired internal capacity to predict the outcome of their movements and make use of this in controlling motor acts. This diminished ability to form and update internal models has been termed the internal modelling deficit hypothesis (IMD: Wilson et al., 2013). According to Wolpert (1997), internal models have several functions. One such function is to provide internal feedback of movement outcomes before slower sensory feedback becomes available, allowing for rapid online correction. A lack of predictive control based on an internal model could result in an increased reliance on sensorimotor feedback that may manifest as the awkward movement patterns that are characteristic of children with DCD.

Evidence supporting the IMD has been described by numerous studies assessing the ability of children with DCD to perform motor imagery (MI) (see Adams et al., 2014 for a review). MI is a process of mental rehearsal, in which the multi-sensory consequences of an action are simulated in the absence of any overt physical movement (Jeannerod, 2006). In this way, MI may incorporate both the visual elements associated with a movement and the accompanying physiological sensations. MI has been shown to be an effective method for improving motor processes in sport (Cumming and Ramsey, 2009) and for restoring motor function lost as a result of Parkinson's disease (Tamir et al., 2007) and stroke (Page et al., 2005; 2007). With neurotypical participants, this technique has also been found to access the internal model and use it to predict the sensory outcomes of a simulated action (Kilteni et al., 2018). In addition, it has improved the motor function of children with DCD (Wilson et al., 2002; 2016). Despite these positive findings, little is known about the extent to which MI training may be beneficial in improving the ability of children with DCD to form and update internal models of movement.

Action observation (AO) is another simulation process that has been applied to motor learning contexts across a variety of domains such as sport (see Holmes and Calmels, 2008 for a review) and, more recently, clinical settings (see Buccino, 2014 for a review). AO involves the observation of an actor (either oneself or a model) successfully executing a desired action (Neuman and Gray, 2013). The task performance being modelled may reflect expert levels of skill execution (Calvo-Merino et al., 2004; 2006) or may be more representative of a learning process in which execution progressively improves (Lei et al., 2016). These modelled routines for the observer may be performed via video or live performance. This method has also been shown to produce positive behavioural outcomes for children with movement disorders, such as cerebral palsy (Buccino et al., 2018) but few have explored its use with the DCD population.

Although both forms of mental simulation are similar, there are some key differences. In AO, visual and temporal cues are presented to the observer through the means of the observed stimuli, implicitly providing information essential to successful task execution, whereas in MI the individual is required to generate these elements themselves (Holmes and Calmels, 2008). MI scripts, however, also tend to incorporate kinaesthetic components relating to the physiological sensations associated with the intended action that cannot be easily replicated in typical AO. The versatile, cost-effective and non-invasive nature of both techniques are also advantages for a wider variety of populations, such as children with DCD.

Recently, researchers have proposed combining the observation of an action with concurrent MI of the same action (AOMI: Vogt et al., 2013; Eaves et al., 2016) and subsequent studies have reported behavioural benefits in aiming (Romano-Smith et al., 2018); postural sway (Taube et al., 2014); and strength (Scott et al., 2017). The rationale for combining AO with concurrent MI stems from neurophysiological studies that have identified MI and AO as both activating similar, but not identical, neural structures to those active during physical movement (Hardwick et al., 2018). AOMI has also been shown to produce increased neural activity in cortical areas linked to planning and executing movement when compared to either AO or MI in isolation (Neuper et al., 2009; Nedelko et al., 2012; Villiger et al., 2013; Taube et al., 2015; Wright et al., 2016). AOMI allows for the provision of visual and temporal cues associated with movement that would otherwise have to be generated by the participant when using MI alone. In this way, AOMI is believed to facilitate performance by enabling an individual to devote cognitive resources to the generation of kinaesthetic imagery associated with the observed movement (Vogt et al., 2013; Eaves et al., 2016). Although an increasing number of studies are demonstrating the effects of AOMI interventions on movement outcomes, little is known regarding the effects of AOMI on eye-hand coordination and this gap in the literature is addressed within this thesis.

Regarding DCD, although MI is an effective technique for improving affected individuals' ability to update the internal model, there is a significant gap in the literature regarding further exploration of this and other simulation processes, such as AO and AOMI. Furthermore, no studies have yet explored the effect of these methods on the gaze behaviour of children with DCD and these gaps are explored within this thesis. Further evidence that may support the IMD hypothesis has described children with DCD as exhibiting impairments in visuospatial processing that may influence their ability to produce and control coordinated movements (Wilson and Mckenzie, 1998). These visuospatial impairments include the tracking of objects (Robert et al., 2014), the maintenance of fixations on targets (Sumner et al., 2016)), and the use of predictive information to guide action (Debrabant et al., 2013). Recent research, however, has demonstrated that for a ball throwing and catching task, the ability to fixate on a target location and subsequently track the flight of the thrown ball is receptive to training and can enhance the performance of catching skills (Miles et al., 2015; Wood et al., 2017). These findings are encouraging for the development of intervention techniques supporting the acquisition of skilled movements in the DCD population. It is of interest, therefore, to examine the effect of simulation processes on not only task performance but also the development of eye movements that support the acquisition of skilled performance.

Skilled execution of visually guided reaching actions requires a precise coupling between eye and hand in which gaze leads movement of the hand. In unskilled movement and the early stages of motor skill learning, gaze fixates upon the hand or tool being used as vision is used to monitor performance of the movement and sensorimotor mapping rules between vision and proprioception are established (Sailer et al., 2005). Once the relationship between vision and proprioception has been made clear, proactive eye movements become established and this is seen as essential to the successful planning and control of visually guided actions (Flanagan and Johansson, 2003). It is also widely held that using vision for the online maintenance of a movement is cognitively demanding and deprives other systems of cognitive resources. To date, no studies have sought to identify the extent to which simulation processes may facilitate the development of sensorimotor mapping rules that enable the production of proactive eye movements. By identifying a suitably effective simulation process, it may be possible to develop intervention programmes that can be applied within occupational therapy and education settings, as well as for use by parents at home.

This introductory discussion has outlined the challenges faced by those with DCD and identified the considerable need for intervention programmes that can assist affected children in improving their ability to learn and perform coordinated movements associated with daily activities. The potential for simulation processes to facilitate the forming and updating of internal models has also been discussed. Furthermore, the need to explore the extent to which simulation processes facilitate the development of proactive eye movements that support skilled task performance has also been described.

This thesis aimed to address gaps in the current literature associated with mental simulation processes, eye-hand coordination, and DCD. Specifically, the influence of AOMI upon task performance and the acquisition of proactive eye movements in neurotypical adults was explored. Subsequent findings were then extended to the DCD population, examining the effects of AOMI upon task performance and the development of proactive eye movements.

2. Literature review

Characteristics of DCD

Children with DCD are often casually perceived as being 'clumsy' due to the nature of the coordinative issues that characterise the disorder. The movements of a child with DCD are slow, awkward, jerky, and inaccurate in comparison to typically developing (TD) children (Missiuna, 1994). Children with DCD exhibit impaired balance control and increased postural sway (Geuze, 2005) which in turn affects gross motor abilities such as walking (Woodruff et al., 2002) and running (Chia et al., 2013). Woodruff et al. (2002) identified that although children with DCD exhibited abnormal walking patterns, they did not show signs of any systematic pattern in differences of individual gait patterns. Analysis of the gait patterns of children with DCD, however, did reveal increased variability compared to TD children, indicating the heterogeneous nature of the condition. The disorder is diagnosed four to seven times more often in boys than girls (Hendrix et al., 2014). This disparity in the prevalence of DCD across sexes may be the result of parents and teachers expecting higher levels of performance from boys. This may result in them noticing even minor impairments in movement ability of males more readily than in females, resulting in higher diagnosis rates in males. Alternatively, the inequality in occurrence may be related to the rate at which DCD co-occurs with other disorders such as ADHD that are more common in boys than girls (Cairney et al., 2005).

The fine motor abilities of children with DCD are also impaired making tasks such as the manipulation of shirt buttons difficult when getting dressed or handling cutlery when eating (Geuze, 2007; Summers et al., 2008). Furthermore, skilled actions that require movement prediction and planning that place greater emphasis on attention and working memory are compromised (Smits-Engelsman et al., 2003; Cantin et al., 2014). These actions may include many skills needed for successful participation in sports, such as throwing and catching objects (Utley et al., 2007; Wilson et al., 2013), and drawing and handwriting skills that are crucial in educational settings (Smits-Engelsman et al., 2001). A deficit in motor learning is also commonly associated with DCD in which the learning of new skills and the planning and automatization of movement are impaired (Geuze, 2005). A deficit in motor learning ability is also commonly associated with DCD (Geuze, 2005) but the evidence is equivocal. Sequence learning in DCD has been shown to be both preserved (Lejeune et al.,

2013) and impaired (Gheysen et al., 2011) and a recent study by Smits-Engelsman et al. (2015) ascertained that over a five week training period children with DCD learned a ski slalom computer game task at the same rate as their TD peers.

Impact on daily life and psychosocial issues associated with DCD

The impact upon daily life of coordination problems resulting from DCD is a considerable issue for affected individuals. Dewey et al. (2002) identified that children both with, and suspected to have, DCD scored significantly poorer on measures concerning reading, writing and spelling. In addition, those same children also displayed lower levels of psychosocial adjustment in comparison to TD children. Deficits in these skill areas may also lead to children with DCD performing poorly on standardised tests of intelligence (Dewey et al., 2001). Chen et al. (2013) reported that children with DCD demonstrated deficits in everyday memory, characterised by significantly lower scores for visual and verbal memory than TD children. They concluded that although children with DCD may be capable of independently performing complex daily activities involving a variety of memory domains, assistance may need to be provided for tasks that place greater emphasis on verbal abilities. These deficits in everyday memory are likely to have a negative effect upon academic achievement along with associated emotional factors regarding self-efficacy. Poor academic performance in relation to peers may also result in disruptive classroom behaviour as a means for acquiring recognition (May-Benson et al., 2002).

These impairments may precipitate into further psychosocial issues without appropriate intervention. For example, movement difficulties and a perceived inability to successfully execute motor skills may lead to decreased participation in, and enjoyment of, typical childhood activities. Bart et al. (2011) found that parents of children with DCD reported that their children experienced lower levels of enjoyment in play, leisure activities, social participation and educational tasks when compared with control groups without DCD. In a study of DCD and TD children, Liberman et al. (2013) also identified significant differences in enjoyment and parental satisfaction between children with and without DCD. In addition, they showed that children with DCD displayed decreased self-efficacy and lower scores on emotional factors related to coherence, hope and effort that in turn predicted participation in activities.

Children learn social interaction and develop physical fitness and motor control through play and engagement in everyday activities. Lack of participation in such activities may then lead to the development of less competent social skills, poor motivation, low self-esteem, depression, social isolation, hypoactivity and distractibility, all of which are associated with DCD (Skinner and Piek, 2001; Missiuna et al., 2004; Cairney et al., 2005; Jarus et al., 2011; Campbell et al., 2012). Subsequently, this may contribute to health-related fitness concerns such as the prevalence of overweight or obesity in children with DCD that are associated with lower levels of physical activity. In a review of literature seeking to ascertain the strength of the causal impact of DCD on physical activity and health-related fitness of children, Cairney and Veldhuizen (2013) identified several studies that reported considerable health related issues. They discussed a number of longitudinal studies that demonstrated an increased risk of developing overweight or obesity for children with DCD. They also found evidence suggesting a bidirectional relationship for dose-response in which lower performance scores on standardised motor coordination tests are associated with a greater chance of obesity and that gross motor coordination can be improved in relation to weight loss. Cairney and Veldhuizen (2013) also discussed several longitudinal studies that indicated a decline in activity levels for children with DCD compared to their TD peers across a range of age groups using a variety of different methods, such as self-report, observation and using pedometers or accelerometers. In addition to this, several studies showed a consistent association between DCD and poorer physical fitness. This relationship, in much the same way as with overweight and obesity, is likely to be mediated by physical inactivity.

Aetiology of DCD

Although the precise cause of DCD is unknown, a number of risk factors are now thought to be associated with its prevalence including lower gestational age and birth weight (Zwicker et al., 2012; Larson et al., 2013) and maternal smoking (Larson et al., 2013). No clear neurological problem has been offered to explain the nature of the motor deficits exhibited by those with DCD. One of the hypotheses concerning its aetiology is the atypical brain development hypothesis (Gilger and Kaplan, 2001). This account postulates that the heterogeneous nature of developmental disabilities such as DCD and ADHD are indicative of an overall functional deficit and suggests that specific symptoms may manifest depending on brain growth and development factors that could vary in terms of their timing and location.

More recently, behavioural and neuroimaging evidence has led to the formation of two new hypotheses: the human mirror neuron system hypothesis and the IMD hypothesis.

The human mirror neuron system and DCD

Motor simulation as a means to aid skill learning or enhance performance is now widely believed to be reliant on specific cortical structures within the brain that form the human mirror neuron system (hMNS). Mirror neurons are a class of neurons that discharge during both observation and physical execution of a motor act. The mirror neuron system was first identified in area F5 of the premotor cortex and in the rostral section of the inferior parietal lobule of macaque monkeys (di Pellegrino et al., 1992; Gallese et al., 1996; Rizzolatti et al., 1996) and it has been proposed that the mirror neuron system codes the observation of actions, both those performed by oneself and those performed by others, into neural representations of those same actions. These neural representations of actions are believed to play a role in action imitation as well as action and intention understanding. Since these discoveries, considerable evidence has been produced using a variety of methods, such as electroencephalography (EEG), positron emission tomography (PET) and transcranial magnetic stimulation (TMS), to support the presence of homologous cortical structures in humans that may form a putative hMNS (Fadiga et al., 1995; Altschuler et al., 1997; 2000; Cochin et al., 1998; 1999; Filimon et al., 2007).

Whilst the hMNS is believed to be recruited during the physical execution and mental simulation of actions (Rizzolatti et al., 2001; Fabbri-Destro and Rizzolatti, 2008; Caspers et al., 2010), its precise role is unclear. Recent critiques have argued that mirror neurons alone cannot account for the conceptual processing of action (Caramazza et al., 2014) and that motor simulation is not required to retrieve knowledge of an observed action (Vannuscorps and Caramazza, 2016). These contentions may be partially explained by substantial evidence that suggests a wider network of ventral and dorsal parieto-frontal areas participate during both processes. This broader involvement of sensorimotor areas has been described as the AO network and the functional distinction between the two systems is debated. Earlier research has suggested that activation of the hMNS only occurs in relation to goal-directed actions (Gallese et al., 1996) but, more recently, movements with no definable goal have also been shown to recruit mirror neurons (Raos et al., 2014). Advancements in neuroimaging technology and experimental design have allowed for further examination of the functional organisation of these neural areas during action execution and observation. Filimon et al. (2007) demonstrated that dorsal premotor areas are responsive during executed and simulated reaching movements, rather than ventral premotor regions. This suggests that the neural areas recruited for both AO and execution may be somatotopically organised. This assertion is supported by evidence of rough somatotopic organisation of upper limb movements in the premotor cortex (Sakreida et al., 2005) and hand, foot, and mouth movements in the posterior parietal cortex (Buccino et al., 2001).

As individuals with DCD are frequently reported to experience deficits in imitation and motor simulation, a dysfunction of the hMNS may underpin the disorder (Werner et al., 2012; Reynolds et al., 2015). Alternatively, the IMD hypothesis proposes an impaired capacity for children with DCD to form and update internal models of movement, resulting in a comparable lack of predictive control that could be the cause of the slow and jerky movement patterns exhibited by children with the disorder (Wilson et al., 2013). The hMNS may be implicated in this respect as it can be considered part of the broader cortical network that is involved in internal modelling. Neuroimaging studies investigating the primary source of dysfunction in DCD have consistently proposed hMNS regions such as the cerebellum (Zwicker et al., 2011; Zwicker et al., 2012; Debrabant et al., 2013) and parietal cortex (Querne et al., 2008; Kashiwagi et al., 2009; Zwicker et al., 2011) as being central to the deficits observed in the disorder. These neural areas are also believed to be integral to predictive control and the formation and adaptation of internal models of movement.

These studies, however, did not involve any elements of imitation or simulation that could have directly recruited the hMNS, although a study by Licari et al. (2015) provides stronger evidence of these findings as their participants imitated observed finger sequencing actions during fMRI scanning. Overall, not enough studies of DCD have employed experimental paradigms designed to explicitly recruit and explore the hMNS and the subsequent neuroimaging evidence can only peripherally implicate the impaired involvement of frontal, parietal, and temporal hMNS regions in this population (Reynolds et al., 2015). Further evidence for a dysfunctional hMNS in children with DCD can be found in behavioural studies examining the various impairments characteristic of the population.

Cerebellar dysfunction

The cerebellum is a neural region associated with the hMNS that is widely held to contribute to the coordination of motor actions by playing a role in the timing of movements (Ivry and Keele, 1989) and maintaining movement accuracy (Thach et al., 1992). Studies of the performance of adults with cerebellar lesions on precise timing tasks have reported results that share similarities with the symptoms exhibited by children with DCD (Ivry, 2003). The cerebellum is also associated with postural control and several studies have demonstrated that children with DCD display impairments in this area of gross motor function (Johnston et al., 2002; Geuze, 2005). In addition, neuroimaging studies have shown children with DCD to exhibit different patterns of neural activity across the cerebellar network when compared to their TD peers. Specifically, Zwicker et al. (2011) demonstrated that children with DCD had less activation in cerebellar-parietal and cerebellar-prefrontal networks in addition to further regions of the brain associated with visuospatial learning than TD children.

Cerebellar dysfunction has also been illustrated using visuomotor adaptation paradigms. Tasks of this nature require individuals to adapt their movements in response to incongruent visual feedback. For example, a movement made by a performer results in a mismatch between sensorimotor and visual feedback and subsequent movements must be adapted to produce the desired outcome, such as drawing a line to a target. In this type of motor skill learning it is believed that an internal model of an action is formed from the differences calculated between anticipated errors and the actual errors derived from sensorimotor feedback. This model is then subsequently used to plan future movement. Learning of this type, based on the comparison of expected and actual error signals, can be thought of as implicit and is believed to be supported by neural activity in the cerebellum (Imamizu et al., 2000; 2003; Anguera et al., 2010). Specifically, the contribution of the cerebellum is believed to lie in its involvement in the formation of internal models of movement (Ramnani, 2006; Ito, 2008). Internal models of the dynamics of a movement are formed in the cerebellum during learning and are updated and adapted as a movement is repeated (Ito, 2008). The role of the cerebellum in motor skill learning has also been shown to change over time as learning progresses, with the cerebellum exhibiting greater activity during the early phase of learning and the primary motor cortex becoming more active for retention of motor skills (Imamizu et al., 2000).

Although visuomotor adaptation has often been thought of as a product of an implicit learning mechanism, recent evidence suggests both implicit and explicit mechanisms are at work (Taylor et al., 2014). In this recent study, participants relayed continuous verbal reports of their aiming direction whilst learning to adapt to a visuomotor rotation. Taylor et al. (2014) found that explicit learning was driving the production of target errors achieved through exploration of different aiming trajectories ranging from larger to smaller adjustments as training progressed. In contrast, they found that implicit learning of an internal model based on sensory-prediction error was slower. These findings suggest that visuomotor adaptation includes both the quick acquisition of an explicit aiming direction and the slower learning of a forward model. This of interest with regard to certain populations that experience motor learning impairment, such DCD, as deficits in the formation and access of internal forward models are held as one possible explanation for the deficient motor control exhibited by those individuals (Wilson et al., 2013).

Few studies, however, have investigated visuomotor adaptation in children with DCD and equivocal results have been reported. Kagerer et al. (2004) used a line drawing task on a digitised tablet in which two groups of children (children with DCD and TD controls) performed under three conditions: a baseline condition with no visuomotor rotation, an exposure condition with a 45° rotation, and a post-exposure condition (again without any visuomotor rotation). The researchers found that during baseline performance children with DCD produced significantly slower and jerkier movements with longer trajectories than their TD counterparts. During the exposure condition, however, in which the relationship between visual and motor space was altered, the children with DCD were less affected by the perturbation than the TD controls and did not experience any after effects of the rotation during the post-exposure condition. Kagerer et al. (2004) suggested that the children with DCD may have been less affected by the visuomotor rotation due to having noisier visuomotor maps as evidenced by the greater variability of their baseline performance. This additional noise may have 'absorbed' (p. 458) some of the effects of the visuomotor distortion. The TD children, however, may have visuomotor maps that are much better defined and were subsequently more affected by the incompatibility of visual and sensorimotor feedback. These findings are of interest as they suggest a deficit in the internal model. Only seven children with DCD, however, were examined over 60 trials and this training period may not have been sufficient for either group to adapt to the visuomotor rotation and produce after-effects. In a follow up study with DCD and TD children using a similar experimental task but a larger sample size and double the number of trials, Kagerer et al. (2006) investigated visuomotor adaptation to both gradual and abrupt visuomotor rotations. In the gradual exposure condition, the visuomotor rotation increased by 10° every 21 trials until 60° of rotation was achieved, whereas the visuomotor rotation was immediately 60° in the abrupt condition. Participants again performed several baseline trials before entering the exposure conditions. This time clear after-effects were found for the TD children after both gradual and abrupt visuomotor distortion, but the children with DCD produced no significant after-effects following exposure to the gradual condition. After the abrupt condition, however, after-effects were present for the children with DCD. The finding that children with DCD were better able to adapt to abrupt rather than gradual visuomotor distortions was suggested by Kagerer at al. (2006) to be indicative of an impaired capacity to use small error signals to modify an internal model. This diminished capability could have been the result of a deficiency of the cerebellum or other structures within the cerebellar network.

An alternative method of altering visual feedback and testing for cerebellar dysfunction is the prism adaptation paradigm, in which visual feedback is displaced using prismatic glasses. Using a 16° prism adaptation task in which participants had to throw clay balls a short distance onto a target, Brookes et al. (2007) reported that children with DCD displayed an impaired rate of adaptation. Although their sample included children with comorbid dyslexia, it does also provide valuable evidence of a potential cerebellar impairment that would appear to impact performance. In contrast, Cantin et al. (2007) demonstrated contrasting results using the same prism adaptation task. They demonstrated that whilst children with DCD were more variable and less accurate in their performance on the throwing task they were able to adapt to the gaze shift induced by the prisms. Cantin et al. (2007) suggested that it was possible that the baseline throwing performance of the DCD group may have masked some of the effects of the prism adaptation. In addition, the heterogeneity of the DCD population was highlighted by the finding that some of the children in the DCD group adapted, suggesting that a cerebellar dysfunction may have indeed been present in other members of the group.

Taken together, this evidence implicates the involvement of the hMNS and supports the IMD hypothesis in suggesting that an impaired capacity to utilise the internal model for providing state estimations and enabling effective predictive control may underpin the coordinative deficits that characterise DCD. This body of research also suggests that the ability of individuals with DCD to update internal models is mediated by task difficulty and complexity.

Parietal dysfunction

The parietal cortex is a cortical region associated with the hMNS that, like the cerebellum, is thought to be involved in the processing of sensorimotor transformations and the formation of internal models as evidenced by research investigating MI and mental rotation (Zwicker et al., 2009). Dysfunction of the parietal cortex in DCD has been linked to visuospatial processing (Wilson and McKenzie, 1998) and MI deficits (Wilson et al., 2013). These deficits also concern the dorsal and ventral streams of visual processing (Goodale and Milner, 1992). According to this perception-action model, the ventral stream is directed into the inferior temporal cortex and is associated with object recognition, whereas the dorsal stream terminates in the posterior parietal cortex and is believed to be responsible for spatial perception and visuomotor performance. Although the two streams may be generally specialised, it is also likely that they interact dynamically (McIntosh and Schenk, 2009). Dysfunction of the parietal area may therefore disrupt visual processing using the dorsal stream and increase dependence on the ventral stream. There is evidence of these effects in children with DCD exhibiting a reduced capacity to plan movements (Andersen et al., 1997; Cohen and Andersen, 2002), perform online movement correction (Buneo and Andersen, 2006) and control feedback (Desmurget and Grafton, 2000). Furthermore, the nature of these deficits may inform the methods used to teach children with DCD by targeting specific visual processing streams.

Visuospatial processing deficits in DCD

A number of studies have found evidence of visuospatial deficits that may be attributable to parietal dysfunction. In a meta-analysis, Wilson and McKenzie (1998) identified a host of information processing deficits that characterised DCD. In their review of the literature, they discussed that although children with DCD typically displayed poorer performance across most measures of information processing, the impact of deficits in visuospatial processing were particularly conspicuous, with a number of studies indicating an association between motor impairment and a diminished capacity for visual information processing.

Since the review by Wilson and McKenzie (1998), additional research has also highlighted an association between visuospatial processing deficits and DCD. Sigmundsson et al. (2003) found that children with DCD exhibited evidence of impaired visual sensitivity on dynamic and static measures of visual function when compared to TD children. They suggested that these findings could be indicative of impaired visual sensitivity in the dorsal and ventral streams in a pattern sharing commonalities with those seen in cases of cerebellar lesion. Although Sigmundsson et al. (2003) did not measure eye movements in their study they do suggest that differences in eye gaze metrics alone are unlikely to explain the distinct patterns of performance they observed.

Children with DCD have also been shown to display a reduced capacity to process visual information in the absence of any motor component. Tsai et al. (2008) found that performance on a test of visual-perceptual ability was significantly poorer for children with DCD compared to TD children. They also identified that not all of the children with DCD in their study exhibited the same pattern of deficits, again emphasising the heterogeneity of the DCD population.

Evidence also shows that the capacity of children with DCD to use predictive information to assist with mapping of movement patterns is impaired. Smits-Engelsman et al. (2003) showed that in the performance of a goal-directed aiming task, children with DCD demonstrated a lower ability to predict the consequences of self-initiated motor actions. They suggested that as an aiming movement is comprised of distinct phases of initial ballistic movement and secondary smaller, corrective movements, the motor deficits exhibited by children with DCD could indicate an impairment in motor pre-programming during the initial phase. The reduced capability to incorporate feed-forward control in motor planning and execution is again supportive of the IMD hypothesis.

A further aspect of how inefficient visuospatial information processing impacts motor skill performance in DCD is exemplified by deficits in predictive timing. The ability to temporally predict upcoming events and pre-select appropriate motor commands is vital for successful motor skill execution. Using a visuomotor reaction time task, Debrabant et al. (2013) found children with DCD exhibited slower reaction times and produced fewer anticipatory responses. They suggested that this evidence supports the IMD hypothesis as children with DCD find it difficult to shift toward a feedforward mode of control in response to predictive stimuli and instead remain reliant on visually guided online control. Furthermore, the neuroimaging results of their study implied that children with DCD need to produce greater processing efforts to perform visually guided motor actions. Mon-Williams et al. (2005) also reported that children with DCD experience deficient predictive control as a result of impaired visuospatial processing and found that for reach to grasp movements, children with DCD were unable to take advantage of visual precues to efficiently plan movements. These findings are also supported by Wilmut and Wann (2008) who identified that individuals with DCD experienced greater difficulty in exploiting predictive motion cues than their TD counterparts did. Furthermore, they ascertained that there were no significant differences in visual attention between individuals with DCD and TD participants.

An implication for future research in this area could relate to the specificity of these visuospatial processing deficiencies. In a review of DCD literature, Piek and Dyck (2004) suggested that poor visuospatial organisation could be specifically characteristic of DCD and may allow the disorder to be differentiated from other comorbid disorders such as ADHD and autism.

Whilst it is apparent from the research that children with DCD struggle with a reduced capacity to interpret advanced environmental cues and utilise these in the efficient pre-planning of movements, there is also evidence to suggest their ability to employ effective online control of movement is impaired. Buneo and Andersen (2006) illustrated the role the posterior parietal cortex typically serves by integrating sensory information with previous and current motor commands in order to provide a continuously updated estimate of limb position during visually guided movement. This ability would appear to be disrupted for individuals with DCD. Hyde and Wilson (2011a; 2011b) used a double-step reaching task to demonstrate that children with DCD showed impairment in the ability to update forward models of movement online. They concluded that the delayed corrections to reaching trajectory evidenced by the children with DCD were telling of a diminished ability to incorporate initial error signals and subsequently generate and monitor forward predictions of limb position in relation to the target. They are cautious in suggesting that this deficit in predictive control is the sole cause of the motor control problems experienced by those with DCD and surmise that developmental delay may also be implied. There is some evidence to suggest that predictive control deficits in DCD may be mediated by task factors. Using an experimental task that included two variations with differing speeds, Mak (2010) found that the ability to reach and grasp a moving target is impaired in children with DCD but observed that the DCD group performed favourably when compared to their TD peers in the higher speed variation. These equivocal results could suggest that children with DCD are able to utilise predictive control to effectively modify movement speed but not necessarily movement direction. It is also important to note a considerable disparity in sample size for the two experimental groups of 16 children with DCD and only 11 controls.

Visuospatial processing deficits have also been evidenced through the study of eye movements of children with and without DCD. Langaas et al. (1998) conducted the first study that directly measured the eye movements of children with DCD in a comparison with children born prematurely. Langaas et al. (1998) identified differences in horizontal pursuit eye movements in the DCD group that they suggested were an indicator of impaired predictive control as opposed to any specific deficit of the visual control system. As this study also included a separate group of children born prematurely who also demonstrated the same reduction in pursuit eye movements, it may provide evidence for eye gaze metrics to be used as an indicator of developmental motor deficits. In an extension of the study by Langaas et al. (1998), Robert et al. (2014) found evidence of significant impairment in vertical smooth pursuit eye movements but not for horizontal eye movements. This finding is of interest as both studies examined this particular pattern of eye movement using groups of DCD children at different ages, suggesting that maturation of the individual vertical and horizontal smooth pursuit systems is chronologically distinct. In any case, poor performance of smooth pursuit eye movements has previously been linked to cerebellar network dysfunction (Moschner et al., 1999). Visual attention is also implicated as an important factor behind the adaptive changes required for smooth pursuit, and subsequently poor pursuit may be the result of poor visual attention (Robert et al., 2014).

In a further study comparing the oculomotor control of children with DCD and their neurotypical peers, Sumner et al. (2018) also evidenced a visual attention deficit in children with DCD. They found that although low-level oculomotor processes were equally intact between both groups, children with DCD experienced greater difficulty with saccadic inhibition and maintaining attention on visual targets. Sumner et al. (2018) attributed these deficits in higher order oculomotor processes to an impairment of top-down cognitive control that could also be indicative of a broader attentional problem.

Wilmut et al. (2006) examined the temporal coupling between eye and hand movement of children with DCD and that of TD children and adults and found that those with DCD had difficulty with producing the pattern of sequential eye movements needed in order to complete the experimental task, with a rate of error comparable to their peers. The findings of this study suggested that TD children made efficient use of a feedforward mode of control for hand movements whereas children with DCD demonstrated the use of a feedback model that relied on eye position data to be relayed before movement of the hand could be initiated. This can be interpreted as further evidence of deficits in internal modelling in children with DCD.

Motor imagery deficits in DCD

Further evidence linking the parietal cortex to the coordination deficits characteristic of DCD can be found in studies of MI, which have shown children with DCD to exhibit varying levels of impaired performance on such tasks. These deficits in MI ability can be seen as evidence of hMNS dysfunction (Reynolds et al., 2015) and the IMD hypothesis, which states that the motor control issues associated with DCD are the result of impaired predictive motor control stemming from disrupted cognitive representations of movement (Wilson et al., 2013).

Maruff et al. (1999) performed a study using mental chronometry of real and imagined movements using a visually guided pointing task. In studies such as this, it is possible to determine if simulated and actual movements conform to Fitts' Law, in which movement speed in goal-directed aiming tasks is determined by the size of the targets and the distance separating them (Fitts, 1954). It was hypothesised that if DCD children exhibited performance impairments for both types of task then the root of their motor impairment problems may be the motor control system but if performance were only impaired for imagined movements then it would imply that disruptions to cognitive representations are primarily responsible. For TD children the speed accuracy trade off conformed to Fitts' law for both real and imagined movements. In the DCD group, however, only real movements conformed to Fitts' law. This may therefore be evidence of motor dysfunction resulting from a reduced capability for generating internal representations of movements.

Further investigation into the ability of children with DCD to utilise MI has employed the use of mental rotation tasks. In a study of 16 children with DCD and 18 control children performing mental rotation of hands, Wilson et al. (2004) found that TD children responded in a typical pattern but those with DCD responded with a smaller trade-off between response time and angle of rotation. They concluded that their findings represent a reduced ability for children with DCD to use MI when making judgements about visuospatial relationships. As the accuracy of the DCD group's judgements were relatively preserved, Wilson et al. argued that they may have employed an alternative strategy in which the hand stimuli were represented as concrete objects or body parts viewed from an external perspective. Using a design in which participants performed mental rotations of hands and whole-body movements, Williams et al. (2008) assessed the MI ability of 42 children with DCD stratified into two groups (DCD severe and DCD mild based on percentile scores on the Movement ABC test) compared with 21 age matched controls. Williams et al. (2008) found that children with severe DCD had a generalised MI deficit and did not benefit from being given specific imagery instructions. The mild DCD group, however, could perform less complex MI transformations and did benefit from being given specific imagery instructions. This suggests that MI ability in DCD may be linked to the level of motor impairment and task complexity. Furthermore, the more pronounced MI deficits for the children with severe DCD may be further evidence of a reduced ability to form accurate internal models of motor control that may be central to the underlying cause of DCD.

With a group of DCD and a group of TD children, Deconinck et al. (2009) used a mental rotation task in which the stimuli were hands rotated at –90°, –30°, +30°, or +90° or mirror reversed letters. Measures of accuracy and response time revealed DCD children to be slower and more prone to making errors. For both groups longer response times were observed for larger rotations. A relationship between the observed rotation of the hand and the participants own hand orientation was also discerned in which response times were longer when the posture of the participants own hands was opposite to the posture of the hands on display. This implies the presence of a MI strategy for both groups and Deconinck et al. concluded that the children with DCD utilised a MI strategy that was compromised by a less well-defined internal model. In a similar study, Noten et al. (2014) demonstrated that MI was affected in children with DCD but only under the more complex task constraints, such as hands being in unnatural positions. Reynolds et al. (2015) also used a hand rotation paradigm to illustrate that although children with probable DCD retained the capacity to engage in MI strategies, task complexity modulated the efficiency of their responses. Contrary to Williams et al. (2008), Reynolds et al. also suggested that performance was facilitated through the provision of imagery instructions, which they suggested to be indicative of potential functional benefits of MI training in this population. This combined body of research using mental rotation paradigms supports the assertion of Williams et al. (2008) in that MI deficits in DCD may be mediated by task complexity, and offers partial evidence for internal modelling deficits.

The collective evidence from a variety of motor adaptation and MI studies provides a persuasive case for impaired predictive control resulting from an IMD as being central to the coordination issues experienced by those with DCD, but also highlights relative task complexity and individual differences as mediating factors. The current body of research would also seem to indicate that while children with DCD are indeed capable of acquiring and retaining new skills, this process may be slower and less efficient than with TD children. In terms of intervention, this suggests that children with DCD may need to be afforded more time when being taught new skills and should be provided with exposure to a variety of learning approaches to counteract persistence with ineffective strategies.

Taken together, there is considerable evidence from behavioural and neuroimaging studies that is indicative of cerebellar and parietal impairments in children with DCD. These impairments may imply the involvement of a dysfunctional hMNS and associated deficits in internal modelling that result in the movement impairments that characterise the condition.

Shared neural correlations and simulation implications for research in DCD

If a deficit in internal modelling is central to the impaired motor performance of children with DCD then motor simulation techniques that share neurophysiological networks may be beneficial. Research of the hMNS has demonstrated that there is a coactivation of neurons in the premotor cortex and posterior parietal area during movement execution and simulation. Jeannerod's simulation theory (2001; 2006) suggests that the overlapping patterns of neural activation observed across simulation states are indicative of shared neural representations of actions and accessing these representations through either action execution, AO or MI may serve to facilitate neuroplastic change in motor pathways as a result of Hebbian learning (Hebb, 1949). According to this theory, covert task-related elements associated with movement, such as action intention and movement planning and preparation, may be primed and modulated through simulation conditions. This has been confirmed by numerous meta-analyses of neuroimaging data, which show an extensive overlap of the neural substrates associated with AO, MI, and motor execution (Rizzolatti et al., 2001; Fabbri-Destro and Rizzolatti, 2008; Caspers et al., 2010; Hétu et al., 2013; Hardwick et al., 2018).

In a review of fMRI and PET experiments, Caspers et al. (2010) identified that although AO and imitation both recruited frontal premotor, parietal, and temporo-occipital cortical regions, several other neural areas were activated only during one of the states. They also suggested that cortical activation of these regions during AO was not effector dependent and appears to be somatotopically organised in some cortical areas, such as the dorsal premotor cortex.

A similar review by Hétu et al. (2013) focusing on the neural correlates of MI, also found strong evidence of a fronto-parietal network that is active during the mental simulation of actions. This network also included several areas that have consistently been shown to play a role in motor execution, including the inferior frontal gyrus and supplementary motor area that comprise the premotor cortex. They also identified additional cerebellar and subcortical areas that are active during MI, such as the basal ganglia, putamen, and pallidum, which have also been implicated in the selection of motor representations during action execution. In contrast to the evidence presented by Caspers et al. (2010), Hétu and colleagues found the neural substrates associated with MI to be effector, task, and modality dependent.

A recent meta-analysis conducted by Hardwick et al. (2018) extended these findings to compare the neural correlates of MI, AO, and action execution using the results of 622 neuroimaging studies. They found that each state shared a common premotor-parietal and somatosensory network but also identified key differences in how the motor and parietal cortices, in addition to several subcortical structures, are recruited in each instance. Taken together, these recent meta-analyses provide a strong indicator that the cognitive processes underlying action execution, AO and MI share similar, but not identical, neural networks. These overlapping neural networks may allow simulation states to target the IMD associated with DCD and facilitate improvements in predictive control through simulated sensory feedback.

In addition to the compelling neurological evidence supporting Jeannerod's simulation theory (2001; 2006), there are also direct, physiological and behavioural signs that indicate the presence of shared neural representations for actions; these include mental chronometry, autonomic nervous system responses, and eye movements. The physical constraints of Fitts' Law have been used in conjunction with mental chronometry to provide compelling evidence for Jeannerod's simulation theory (2001; 2006). In most mental chronometry paradigms, participants are asked to mentally image the performance of a familiar movement and indicate completion of the action. Research using paradigms designed to manipulate task-complexity has subsequently shown that movement time is similar in action execution and mental simulation suggesting that the kinematic constraints affecting physical movement extend also to simulated action (Guillot and Collet, 2005).

Physiological responses may also be viewed as evidence supporting simulation theory. Collet et al. (2013) suggested that changes in heart rate and respiratory frequency during simulation are indicative of motor planning being used to physiologically prepare the body for the movement that is being planned. Various studies that have employed the use of heart rate and respiration frequency have found evidence of a relationship between action execution and observation (Paccalin and Jeannerod, 2000; Brown et al., 2013) and action execution and MI (Decety et al., 1991). Only one study by Mulder et al. (2005) has thus far compared these variables across all three processes and these researchers found that respiration frequency was increased during both observation and MI. Taken together, this evidence implies activation of the autonomic nervous system during simulation in a manner similar to that seen during action execution.

The study of behavioural markers, such as eye-movements, is another avenue for the examination of shared motor representations. Flanagan and Johansson (2003) showed that a pattern of eye-movements produced during physical performance of a block-stacking task, in which eye-gaze led movement of the hand to targets, was also replicated during observation of the same task being performed. Heremans et al. (2008) used a cyclical aiming task, in which wrist flexion and extension produced rhythmical movement of a cursor, to demonstrate that participants produced task-related eye movements during imagery and action execution. McCormick et al. (2012) directly compared eye movements across AO and MI and identified common eye-gaze metrics shared by both processes. These findings are indicative of a neural coupling between the neural substrates for eye and hand movements during both physical performance and simulation. Recent research, however, has identified that predictive eye movements can also occur during AO even in the absence of an established motor repertoire for the movement being observed. Vannuscorps and Caramazza (2016) examined the eye movements of an adult born without upper limbs as he observed reaching movements and found he produced predictive eye movements to objects despite his lack of any possible motor representation for the observed action. As this finding was produced using a single case study design, it is possible that the participant's predictive eye movements were the result of learned visual and inferential processes that would otherwise require motor simulation in a typically developed participant. These findings are of particular interest as children with DCD have been shown to exhibit visuospatial processing deficits associated with a deficit in internal modelling. If motor simulation can facilitate the acquisition of optimal visuomotor commands, this could lead to positive consequences for motor performance. Taken together, this evidence of shared neural correlations between simulation states and action execution provides the basis for the application of motor simulation interventions that facilitate motor (re)learning and have potentially useful implications for research and practice in DCD.

Application of mental simulation processes for motor (re)learning in DCD

Action observation

Extensive evidence outlines how AO accesses a shared motor representation that facilitates cortical activity in areas of the brain associated with the planning and execution of movement and subsequently promotes neuroplastic change through a process of Hebbian learning (Hebb, 1949). This has led to the technique being advocated for enhancing skilled performance and therapeutic outcomes in motor (re)learning contexts and therefore may have profound implications for its application within the field of DCD research.

Concerning the application of AO in the context of sport, there is a body of literature covering a diverse range of activities that encompass a myriad of skills ranging from fine motor skills to gross, whole body movements (Ashford et al., 2006; Maslovat et al., 2010). Using a three-ball cascade juggling task, Hayes et al. (2008) found that observational learning facilitated performance to a greater extent than a verbal instruction control condition. The authors suggested that observational learning was more effective than discovery learning in this type of task as it provided the means to achieve an end-goal, such as the specific movement pattern and timing required to throw a ball into the air ahead of catching another. In another study of throwing dynamics, AO has also been shown to enhance the rate at which a novel movement coordination pattern is assimilated (Horn et al., 2007). Studies have also compared the relative effectiveness of AO and MI techniques in the context of sport. Ram et al. (2007) established that modelled performance of a free weight squat lifting task enabled novice lifters to adopt a more appropriate lifting form than those that performed MI or a control intervention. A more recent study by Neuman and Gray (2013) demonstrated that when used as a preparation technique with expert and novice baseball players prior to performance, both AO delivered via video and MI had a beneficial impact on successful hitting performance. AO has also been suggested to be beneficial to an athlete during times of illness or injury as the shared patterns of cortical activation of AO and physical execution suggest access to motor representations is made even in the absence of physical practice (Holmes and Calmels, 2008).

The benefits of using AO to support motor learning are not limited only to the sport and exercise domains, evidence for the efficacious use of AO interventions in clinical settings includes research involving a number of diverse populations with motor impairment. For example, Ertelt et al. (2007) combined AO with physical training in a neurorehabilitative programme for patients with moderate to chronic motor deficits resulting from stroke. They found that following a 4-week course of treatment combined AO therapy resulted in significant improvements in motor function compared to baseline and these improvements were still present eight weeks after the intervention had finished. Interestingly, the study conducted by Ertelt et al. (2007) also incorporated functional magnetic resonance imaging to examine the potential neuroplastic effects of the training intervention and this analysis revealed significant rises in activity in several motor control areas, which can be attributed to the training intervention. In a similar study with stroke survivors using a combination of physical training and observation of actions for daily activities, Franceschini et al. (2012) also reported significant improvements on measures of motor impairment and functional ability. The combined findings that treatment incorporating AO is advantageous in the field of stroke rehabilitation are of particular interest as they suggest the potential to promote neuroplastic change in damaged areas of the brain responsible for motor control even with the reduced capacity for physical practice.

Although AO training in isolation has not been explored within DCD, the technique has been shown to be an effective adjunct to therapy for another neurodevelopmental movement disorder in the form of cerebral palsy. Buccino et al. (2012; 2018) found a combination of AO and subsequent imitation to be significantly better than a control treatment for improving the upper limb motor functions of children with cerebral palsy. Furthermore, Buccino et al. (2018) collected neuroimaging data that established AO training contributed to reorganisation of the neural circuits that subserved impaired functions. In studies of DCD, Wilson et al. (2002; 2016) also incorporated elements of AO within their MI training programmes. No studies, however, have yet examined the use concurrent AO and MI within this population.

Although several studies advocate for the use of observation interventions as motor (re)learning techniques, guidelines for their optimal execution are unclear with appropriate dosage, training period length and delivery method still debatable. For example, there is currently no definitive body of research to suggest how participants are instructed to view observation stimuli. Wright et al. (2016) examined the effects of different viewing instructions on corticospinal excitability, finding that corticospinal excitability was more greatly facilitated by AO with concurrent MI compared to passive observation alone.

Motor imagery

In research, both MI and AO are closely linked and a number of neuroscientific studies present a similarly strong case to that offered for AO in advocating the use of MI in motor (re)learning contexts and, therefore, may have potential for use with the DCD population. Much of this evidence cites the partial neural overlap between the areas associated with mental simulation and those involved in the planning and execution of motor functions. Studies have shown MI to be useful in enhancing skilled performance across a range of sports (Cumming and Ramsey, 2009), such as golf (Smith et al., 2008), hockey (Smith et al., 2001), and tennis (Robin et al., 2007). Studies such as these provide evidence of the positive behavioural outcomes that can be attained by healthy individuals using MI that can be extended to therapeutic scenarios.

Most of the studies in this domain have addressed the application of MI as an effective treatment approach for improving motor function. In the treatment of Parkinson's disease, Tamir et al. (2007) determined that a combination of physical and imaged practice enabled patients to demonstrate significantly higher gains in motor function and cognitive performance compared to a group who received only physical therapy. Braun et al. (2011), however, reported findings that suggest MI therapy may be less effective for patients more severely affected by the disease.

As with AO, there is also considerable evidence supporting the efficacy of MI as a tool for restoring motor function during post-stroke rehabilitation. Liu et al. (2004) found that three weeks of MI therapy promoted better relearning of daily living tasks practiced in the programme that also transferred to other untrained tasks. Numerous studies by Page and colleagues have also advocated the use of MI in stroke recovery and have reported significant reductions in arm impairment (Page et al., 2001) along with increases in daily arm function (Page et al., 2005; 2007). Whilst much research in this area appears to focus on restoring upper limb function, others have also advocated the use of MI for gait rehabilitation (Dickstein et al., 2004; Dunsky et al., 2006; 2008). Additional benefits of using MI or simulated practice in general within these contexts are its non-invasive nature and low cost that increases its potential for application in both specific therapeutic and home-based settings (Page et al., 2001; Tamir et al., 2007).

MI training has also been successfully applied with the DCD population. Wilson et al. (2002) compared an MI training protocol with a traditional perceptual motor training programme that consisted of gross, fine, and perceptual motor activities such as hopping, skipping, throwing, catching, walking on balance beams, and handwriting. The MI training consisted of initially observing video sequences of skilled peers performing fundamental motor skills, such as throwing a tennis ball, striking a softball, jumping onto a target, balancing a ball on a bat while walking, and placing objects using a form board, before then imagining themselves performing each skill. Upon completing their mental practice, several trials of physical practice and mental rehearsal were employed. During the MI exercises, each child was encouraged to focus on kinaesthetic imagery with the instruction to concentrate on 'the feel of the movement in their muscles' (p. 493). Participants underwent five hours of training over five weeks and performed the Movement Assessment Battery for Children (MABC: Henderson and Sugden, 1992) at pre-test and post-test. The results of the study revealed that MI training was equally as effective as traditional perceptual motor training in producing improved scores on the MABC at post-test. Wilson et al. (2002) suggested that their findings were also evidence of deficits in internal modelling and that the MI training allowed children to develop a motor representation of the intended action and gain an understanding of the movement before engaging in physical practice. Findings from a recent replication of this study (Wilson et al., 2016) indicated the same trends as before, in that imagery training alone appeared to be equally as effective as perceptual motor training. On this occasion however, imagery training also produced greater improvements in children with severe DCD compared to those with milder symptoms. More recently, Adams et al. (2017) performed a pilot study that incorporated a MI training protocol consisting of phases of AO using a first and third person perspective, followed by mental rehearsal and physical practice, which produced a clinically meaningful change in Movement Assessment Battery for Children- 2 (MABC-2: Henderson et al., 2007) scores in two children. As this is a pilot study, however, and utilises a very small sample size of only four children per treatment group, this cannot be taken as conclusive evidence as to the efficacy of MI training for children with DCD.

Combined action observation and motor imagery

Recently, research investigating simulation states has formed a compelling case for combining AO with concurrent MI (Vogt et al., 2013; Eaves et al., 2016). Using healthy participants who engaged in a four-week balance training programme that incorporated either AOMI or MI alone, Taube et al. (2014) found that both AOMI and MI training produced a statistically significant reduction in postural sway. In a study of stroke patients, Sun et al. (2016) assessed the effects of MI guided by either synchronous or asynchronous AO on ten participants with upper limb dysfunction and found that synchronous AO and MI produced significantly greater functional improvements than asynchronous AOMI. Scott et al. (2017) compared the effects of three-week AOMI and MI interventions on hamstring strength and found that only AOMI produced significant gains in strength. They concluded that whilst their findings align with Jeannerod's simulation theory (2001; 2006), a more fitting account is that of the dual-action simulation framework (Vogt et al., 2013; Eaves et al., 2016). In a study examining simultaneous and alternate combinations of AO and MI in comparison with separate AO and MI groups, Romano-Smith et al. (2018) revealed that simultaneous AOMI produced significantly greater improvements in dart throwing performance than either AO or MI in isolation. Interestingly, they also found that participants in the alternate AOMI condition improved significantly more than those in the AO group, implying that either combination of AO and MI may potentially be beneficial to the learning of aiming skills. These recent findings are encouraging in terms of their impact on physical performance and skill learning. With the exception of Sun et al. (2016), however, the application of AOMI with clinical populations is still very much unexplored and no studies using this technique have been conducted in the field of DCD research. Previous research has demonstrated the efficacy of MI training for children with DCD that included elements of AO (Wilson et al., 2002; 2016) and children with cerebral palsy have also been shown to benefit from AO training (Buccino et al., 2012; 2018). Examining the effectiveness of AOMI within the DCD population therefore has important practical and theoretical implications regarding its current position as the best practice for simulated motor learning.

Eye-hand coordination and implications for DCD

Although recent research has indicated that AOMI may be effective for enhancing motor function, little is known about how this particular technique may facilitate improvements in eye-hand coordination in children with DCD. According to simulation theory (Jeannerod, 2001; 2006), eye movements made during action execution should also be produced during simulation, an assertion supported by several studies (Flanagan and Johansson, 2003; Heremans et al., 2008; McCormick et al., 2013), and the effective control of gaze is central to the skilled execution of visually guided actions in neurotypical populations.

During perception of an environmental scene, humans are only able to obtain high quality visual information from a small area surrounding the centre of gaze, termed the fovea. In order to gather visual information from the rest of the scene rapid eye movements, known as saccades, reorient the position of the fovea in relation to the perceived scene (Henderson, 2003). Saccades are made approximately three times a second but do not play a direct role in the extraction of visual information during perception. Instead, saccades serve to direct gaze towards perceived areas of interest within the scene (Henderson, 2003). Once the fovea is oriented toward an important location, saccades are then suppressed and gaze is held in a relatively stable position known as a fixation. A fixation is defined when gaze is dispersed within three degrees of visual angle or less for 100ms or more, which is believed to be the minimum amount of time necessary to obtain visual information from the environment (Vickers, 2007). In turn, gaze control can be defined as the process directing of the fovea to objects of perceived importance within a scene in the service of ongoing perceptual, cognitive and behavioural activity (Henderson, 2003).

Gaze and visually guided action

In his seminal account of the control of upper limb movements, Woodworth (1899) asserted that most goal-directed movements comprise two distinct phases. By controlling the tempo at which participants drew lines between targets on a rotating drum, Woodworth was able to measure the spatial and temporal characteristics of movement trajectories. Woodworth found that the first phase of an aiming attempt is a rapid movement that is intended to bring the limb into the vicinity of the target; this has been referred to as the initial adjustment, ballistic phase or initial impulse. As the limb approaches the target, a second portion of the movement, termed by the current control phase, uses visual and proprioceptive feedback to reduce the error between the position of the target and the limb. In addition to identifying these two components of visually guided action, Woodworth also examined the effects of the availability of visual feedback by utilising an eyes open and eyes closed condition. The results of the study showed a trend in which the difference in aiming error between the two groups decreased as movement time decreased until movement time was approximately 450ms and there was no longer any difference in error between the two groups. Woodworth deduced from these results that participants needed approximately 450ms to make effective use of visual feedback for current control.

Woodworth's two-component model has been used for over a 100 years as the foundation for numerous other accounts of dual-process models of limb control. In recent years, new models have been described that still comprise of distinct prior planning and online control phases which offer more sophisticated accounts of skilled limb control. The iterative correction model (Keele, 1968) challenged the idea that 450ms was needed to use visual feedback in the current control phase and concluded that only between 190 and 260ms was necessary. Elliott et al. (2010) built upon Woodworth's two-component model and outlined a multiple-process model of online control of discrete goal-directed actions. In this model, two sets of online control processes are proposed. The first set compares the expected and actual sensory outcomes of the initial limb impulse whereas the second set take place later in the movement and compares the relative positions of the limb and the target. This model differs from that offered by Woodworth in that the initial impulse phase is not thought of as entirely ballistic but may be regulated through online control and these processes may also overlap during limb trajectory. This model also places an emphasis on developing an internal model that represents expected sensory movement outcomes. This also describes a process that could be severely impacted by any deficit in an individual's ability to form or update the internal model. In the context of DCD, the proposed IMD could, therefore, result in a mismatch of expected and actual sensory outcomes that results in an increased reliance on sensorimotor feedback and the production of slower, jerkier movements.

Gaze impacting movement and implications for DCD

Gaze performs an integral function in many interactions of daily life and research has identified that saccadic eye movement typically precedes goal-directed hand movement

(Bekkering et al., 1995) and that a lack of fixating a visual target impairs movement accuracy (Neggers and Bekkering, 1999). Children with DCD, however, have previously been shown to have problems with maintaining attention on visual targets and saccadic inhibition (Sumner et al., 2018). These findings among others emphasise the role of fixations to targets for the successful execution of aiming movements (Neggers and Bekkering, 2000) but do not adequately explain the specific role of gaze during the learning of visually guided manual tasks.

Sailer et al. (2005) demonstrated the relationship between changes in gaze behaviour and performance during learning of a challenging and novel visuomotor task, in which during adaptation to a visuomotor rotation patterns of eye gaze shift dramatically in accordance with skill level. Using a paradigm in which a mouse cursor was controlled on screen via a unique control scheme requiring a variety of different force inputs, they found that gaze consistently pursued cursor movement during an early exploratory phase of adaptation. Later, during the skill acquisition and refinement phases gaze became proactive and preceded the movement of the cursor, leading it accurately to targets. Sailer et al. (2005) posited that pursuing the cursor with gaze during exploration may be initially useful in learning the mapping between manual actions and cursor movement because it may be that foveal or parafoveal vision are more adept for detecting changes in local movement direction. This pattern of gaze also allows cursor and eye movements to have a common origin in gaze-centred coordinates and may facilitate learning basic correlations between eye motor commands and recent hand motor commands. During the later skill acquisition and skill refinement stages of visuomotor adaptation, gaze was observed to become proactive and lead hand/cursor movement. This may be indicative of extending the newly established sensorimotor mapping rules to longer movements and that peripheral vision may provide adequate information on the position of the cursor to allow refinement of hand movement. Goal directed eye movements therefore appear to derive from the necessity to provide high quality goal related information to the motor system that manifests as fixations that precede motor action. These goal directed eye movements can then be utilised in the in the planning and control of action (Land, 2009). Evidence from eye-tracking studies of children with DCD has demonstrated that they do not perform these goal directed eye movements as effectively or efficiently as their TD peers (Debrabant et al., 2013; Sumner et al., 2018). Using a ball throwing and catching task, Wilson et al. (2013) established that the duration of targeting and tracking fixations were significantly shorter for children with lower motor coordination abilities than those with higher motor capabilities. Taken together, these findings have implications for how children with DCD extract and use visual information when they learn new movement skills.

Neurotypical gaze control and implications for DCD

According to Land (2009), there are three distinct systems involved in the visual control of action, the gaze, visual, and motor systems (see Figure 1). The role of the gaze system is to bring the target object into foveal vision through ocular movements and, if necessary, reorientation of the head and trunk. The visual system is then used to extract information from the scene that can be used to update the motor system, such as checking that the fixated object shares the known characteristics of the intended target and its orientation. This information is then used by the motor system to initiate contact with the desired object. Land postulated that although the visual, gaze and motor systems each have a role in the successful execution of movement there must also be a fourth system acting as a controller. He named this proposed fourth component the schema system and suggested that it serves as a top-down authority with overall control over the other systems, specifying the current task and planning an overall sequence of actions needed to complete that movement. In this arrangement under optimal circumstances, vision is not used to supervise a movement but is instead disengaged from action once other senses such as touch and proprioception assume responsibility for completion. Vision can then be reallocated to the next task-relevant stimulus in the sequence of action as scheduled by the schema system. Prior research has shown gaze to be proactive and move on to the next task-relevant object before manipulation of the current object is complete (Hayhoe et al., 2003). One role of the schema system is to supply in advance what the visual system needs to look out for, with attention rarely being directed to task-irrelevant stimuli the implication is that fixations are controlled via the top down schema system and not through bottom up stimulus salience.

According to this model, individuals are able to look to the right place at the right time to provide accurate visual information to the systems that control goal directed movements and this process appears to be less efficient in children with DCD. Children with DCD exhibit signs of not fixating task-relevant stimuli (Wilson et al., 2013), impairments in maintaining attention on visual targets (Sumner et al, 2018), and an overreliance on visually guided control

(Debrabant et al., 2013) that make a compelling case for an impaired ability to use a feedforward model of control. Improving the ability of children with DCD to perform internal modelling may enable them to acquire optimised gaze behaviours that support the planning and execution of actions.

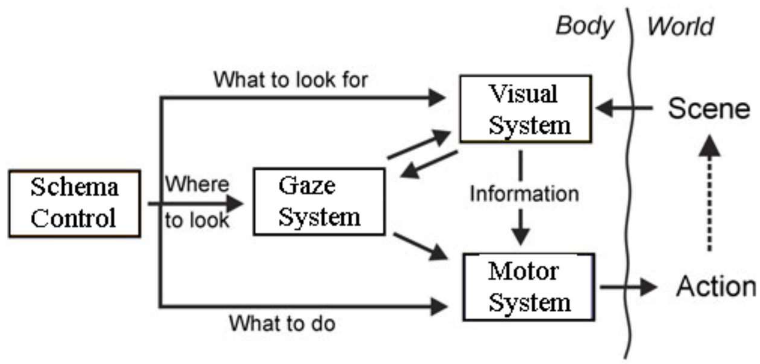


Figure 1. A schematic of the organisation and communication between the schema, gaze, visual, and motor systems during the performance of a visually guided action (taken from Land, 2009).

Aims of the thesis

The primary aim of this thesis was to establish whether AOMI could be used for improving eye-hand coordination and performance in children with DCD. To achieve this, secondary aims were to (1) examine the effect of AOMI in comparison to other AO conditions for the development of eye-hand coordination during the performance of a novel visuomotor task, (2) to examine how eye-hand coordination develops for children with and without DCD during visuomotor adaptation, and (3) to explore the use of an AOMI training intervention on the development of eye-hand coordination and visuomotor adaptation with children with DCD.

These aims seek to address specific gaps in the current literature concerning the use of mental simulation processes and their application for clinical populations. First, neurological evidence increasingly suggests AOMI may be of benefit to improving physical performance but few studies have sought to test this. Furthermore, no studies have examined how AOMI may be used to improve eye-hand coordination through the examination of gaze metrics. Despite the successful application of MI training with DCD children, few studies have explored the use of this technique with this population and none has incorporated AOMI. Finally, no studies have examined the effect of AOMI on the facilitation of skilled eye movements in children with DCD.

By being the first study to identify which AO instructions best facilitate the acquisition of a feedforward gaze behaviour, the first of this series of studies will contribute to the design of effective interventions for populations in which eye-hand coordination has been impaired. The second study builds upon the identification of key differences in visuospatial processing for children with and without DCD but is the first to attempt to do so during visuomotor adaption. In the third study, the findings of the previous study are expanded upon to develop a more complex novel visuomotor task for use with children with DCD. Finally, the fourth study draws upon the findings of the previous three studies by providing a thorough examination of the effects of an AOMI training intervention on eye-hand coordination and skill performance during visuomotor adaptation for children with DCD. This final study contributes to discussions of simulation theory (Jeannerod, 2001; 2006) and the IMD hypothesis (Wilson et al., 2013) and is the first of its kind to incorporate gaze metrics and mental simulation processes in the study of DCD.

In conclusion, this chapter has sought to outline the current state of the literature concerning mental simulation processes, eye-hand coordination, and DCD. By identifying the theoretical linkage between simulated actions, feedforward mechanisms of control, and their implication in the impaired movements of children with DCD, it is hoped that this chapter has provided a solid foundation of empirical knowledge upon which the research discussed throughout this thesis can be built.

3. Study 1: Combining action observation and motor imagery improves eye-hand coordination during novel visuomotor task performance

Introduction

The observation of an action is widely accepted to activate similar, but not identical, neural structures to those active during the physical execution of the same movement (Hardwick et al., 2018). AO has therefore been proposed as a simulation process that has utility for motor (re)learning by facilitating neuroplastic changes in sensorimotor pathways (Buccino, 2014). Consequently, AO interventions have been shown to offer positive behavioural outcomes across a range of clinical settings (Ertelt et al., 2007; Pelosin et al., 2010; Cusack et al., 2016), including neurodevelopmental disorders (Buccino et al., 2012; 2018).

Previous AO research has used a variety of viewing instructions, such as passive observation (e.g., watch the action) and active observation (e.g., watch the action with the intention to imitate) and recent research has suggested that the most effective method for delivering AO interventions is by combining the technique with concurrent motor imagery (AOMI: Vogt et al., 2013; Eaves et al., 2016). This proposition stems from recent findings that identify the production of increased cortico-motor activity when performing AOMI (Wright et al., 2014; 2016; Mouthon et al., 2015) that has also been found to be greater than the sum of activity for independent AO and MI (Sakamoto et al., 2009; Taube et al., 2015). A recent study comparing the effects of passive observation, active observation, and AOMI viewing instructions found AOMI to facilitate corticospinal excitability to a significantly greater extent than passive observation (Wright et al., 2016). The proposed use of AOMI in motor learning settings has recently been supported by several studies that have shown the technique to produce positive effects on performance (Taube et al., 2014; Bek et al., 2016; Scott et al., 2017).

Despite these positive findings, little is understood about *how* AOMI facilitates skilful movement in such tasks. Although research has indicated increased activity in motor regions of the brain associated with AOMI relative to independent AO or MI (Eaves et al., 2016), it is currently unclear how this would serve to facilitate motor skill learning. One possible explanation is offered by Jeannerod's (2001; 2006) simulation theory, which argues that simulation of an action accesses a shared neural network for the same action. This notion can be taken further by asserting that this motor representation is used to predict the sensory consequences of a simulated action (Kilteni et al., 2018) and provide an error signal based on the comparison between the anticipated and simulated sensory outcomes (Ridderinkhof and Brass, 2015). By providing the visual components of the task and explicitly emphasising the use of kinaesthetic imagery, AOMI may enhance the equivalence between the simulated and overt actions and facilitate motor skill learning accordingly.

The concept of a motor representation shared across simulation states also suggests that covert task-related elements (e.g., action intention, movement planning and preparation) might be primed and modulated through simulation Hebbian conditions. Due to this, it has been suggested that during simulation, similar eye movements to those produced during action execution should be recordable. Indeed, evidence suggests that eye movements are congruent during action execution and MI (Heremans et al., 2008), action execution and AO (Flanagan and Johansson, 2003) and MI and AO (McCormick et al., 2012). Taken together, this suggests that these similar eye movement patterns may be indicative of a shared neural network that is used to plan and control visually guided actions. As AOMI allows for the provision and control of the visual elements of simulation, attentional resources are able to be devoted to the kinaesthetic aspects of a movement, which may align this particular simulation condition more closely to overt physical execution and serve to develop sensorimotor mapping rules that include the encoding of associated visuomotor commands.

Little is known as to how AOMI may be able to facilitate the development of effective eye-hand coordination. During the skilled performance of daily activities, gaze is directed towards objects of intended interaction and vision precedes movement execution (Land, 2009) but this pattern of eye-hand coordination is disrupted when learning new skills. Sailer et al. (2005) demonstrated that during the learning of a novel visuomotor skill in which movement produced incongruent visual feedback, vision was initially used to closely monitor effector movement during an exploratory phase in which sensorimotor mapping rules were discovered before progressing to a more proactive gaze strategy in which the eyes lead the effector to targets, enhancing performance. The reliance on bottom-up attentional control in the initial phase impairs the efficiency with which the visual information used to guide movement is extracted from a scene and disrupts effective psychomotor coordination (Neggers and Bekkering, 2000; 2001). Individuals therefore learn spatially congruent eye and motor commands, so that fixations on objects precede motor actions and provide visually acquired goal related information to the motor systems (Neggers and Bekkering, 2000; Sailer et al., 2005; Land, 2009). Task-specific (goal-directed) eye movements of this type support the manner in which manual actions are planned and controlled and are therefore indicative of top-down attentional control and task expertise (Land, 2009).

Proactive gaze behaviour has also been shown to manifest during AO and has been suggested to enable the evaluation of coordinated movement dynamics associated with hand and object interactions (Sciutti et al., 2011; Flanagan et al., 2013). This evidence suggests that training methods that expedite the development of proactive gaze behaviour that allows actions to be planned ahead of time can lead to more efficient and effective movements (Wilson et al., 2010). To date no studies have examined if/how AOMI can be used to facilitate eye-hand coordination in this manner.

The aim of this study was to examine the effect of AOMI in comparison to other AO conditions for the development of eye-hand coordination during the performance of a novel visuomotor task. I hypothesized that AOMI training would facilitate the development of a proactive gaze strategy where the eyes lead movement and that this would lead to significant improvements in task completion time compared to all other simulation conditions.

Methods

Participants

Fifty right-handed participants (28 male and 22 female; age *M* = 24.8, *SD* = 4.73 years) with normal or corrected-to-normal vision, volunteered to take part in the experiment. The number of participants recruited was selected to be comparable to that of similar studies comparing simulation interventions (Wright and Smith, 2009; Taube et al., 2014). This sample size was also determined to be realistic given the long-term goal of testing a similar intervention in a DCD population, based on the past experiences of the research team.

Participants gave their written informed consent prior to taking part and the experimental procedures were granted ethical approval by the local university ethics committee.

Task

Participants performed an experimental task on a vertically oriented touchscreen monitor that was an adaptation of the virtual radial Fitts' task (Heremans et al., 2011). The goal of the task was to use a stylus to guide sequentially a cursor to yellow highlighted target squares whilst under the constraints of an 180^{o} visuomotor reversal along one axis of movement. The reversal resulted in any leftward movements of the stylus on the screen producing an equal rightward movement of the cursor, and vice-versa. This was introduced in order to present participants with a novel task that would disrupt eye-hand coordination (Sailer et al., 2005) and require the development of novel sensorimotor mapping rules. The vertical orientation of the monitor was chosen in order to place the movement of the hand and stylus in the same visuospatial workspace as the cursor as this would be replicable in an AO stimulus. Each target square was 7 mm x 7 mm and the targets were presented in a sequence consisting of four orientations of three squares that were presented on the screen with each square 132 mm from the others (see Figure 2). This sequence of target orientations was designed to increase task complexity by altering the angles required to reach each target with the cursor. The next target square in each sequence was highlighted in yellow in order to increase saliency and lessen the impact of visual search on task performance and once all three onscreen squares were hit, a new three-square pattern was presented. An auditory chime played each time the cursor was successfully guided onto the appropriate target and once 25 targets had been hit successfully one full trial had been completed.

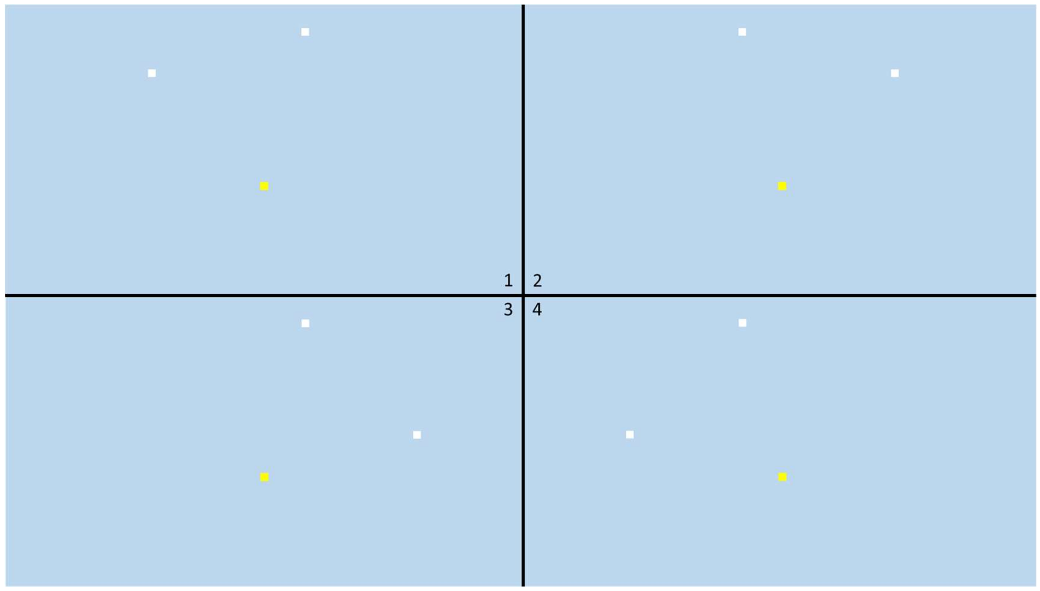


Figure 2. Examples of each of the target orientations with 7 mm x 7 mm targets at a distance of 132mm from each other. Upon each of the three squares being successfully hit in sequence, the next three-square pattern was presented. Each pattern was repeated twice using a different outer square as the initial target in order to balance the number of intended left and right movements.

Apparatus

Testing was performed on a vertically oriented Dell ST2220T touchscreen monitor (Dell, Round Rock, TX) with a 480 mm x 270 mm visual display, situated 210 mm from the edge of the table where the participant was seated (see Figure 3). This monitor had been modified to report input along the x-axis as reversed thereby providing participants with an 180^{o} visuomotor reversal on only one plane of movement that had to be negotiated in order to complete the task successfully. The adapted virtual radial Fitts' task was produced using DMDX software (Forster and Forster, 2003) which allowed the automatic presentation of the next target in the sequence once the previous target had been hit. The software recorded the onset and termination of timing for the task to within 15 ms.

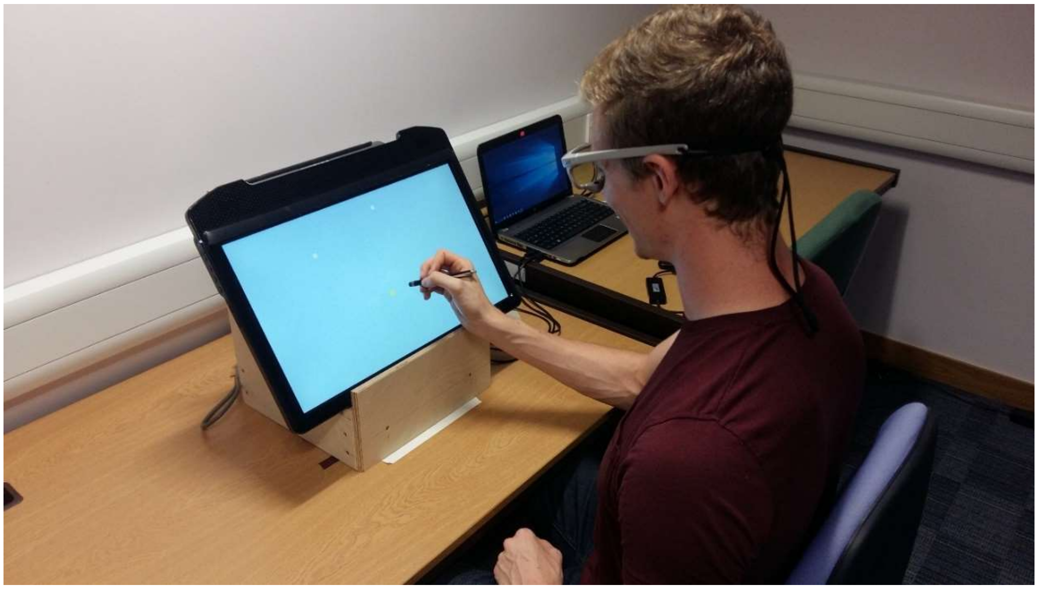


Figure 3. A participant using the stylus and touchscreen to perform the experimental task. Each participant wore eye-tracking glasses during each phase of the experiment.

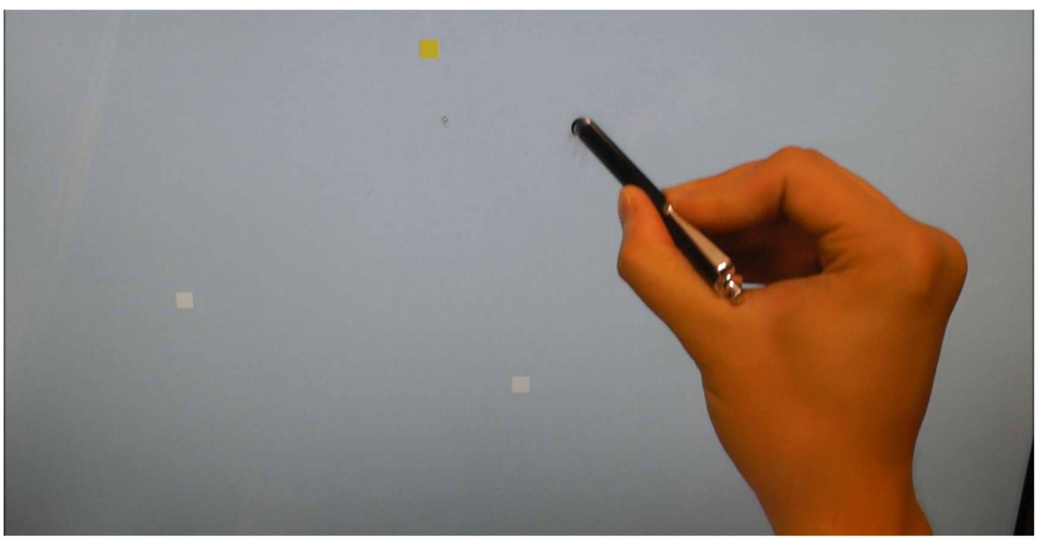


Figure 4. An example of the AO stimulus used in the AOMI, active observation and passive observation training interventions.

Participants’ eye movements were monitored using ETG 2w eye tracking glasses and iView ETG 2.7 software (SMI, Teltow, Germany). The system comprises a pair of lightweight eye glasses that track participants’ binocular eye movements at a sampling rate of 60 Hz with a gaze position accuracy of 0.5°. The eye tracking equipment was calibrated for each participant prior to the pre-test using a 3-point calibration procedure and accuracy of this calibration was monitored prior to each trial by instructing participants to fixate on points on a calibration grid that represented the spatial arrangement of the target sequences. If, during the session, the quality of the calibration was deemed by the experimenter to have deteriorated then the calibration procedure was repeated before testing continued.

Procedure

Pre-test

All participants performed a familiarisation trial that consisted of guiding the cursor to hit three targets under the constraints of the visuomotor x-axis reversal. Only three targets were used to minimise the amount of adaptation to the reversal. Following this, participants were then fitted with eye-tracking glasses and performed a pre-test consisting of one 25-target trial. Prior to the start of the trial participants were instructed to guide the cursor to the targets using the stylus and to attempt to complete the sequence as quickly and accurately as possible (Rentsch and Rand, 2014). Following completion of the trial participants immediately began the training intervention to which they had been randomly assigned.

Training interventions

Physical practice (PP) group. Participants in this group completed 20 trials of physical practice of the same 25-target task completed at pre-test (a total of 500 target hits (Sailer et al., 2005)). This number of trials was deemed appropriate as most participants may adapt to small visuomotor rotations within 240 attempts (Krakauer et al., 1999) but adaptation to 180° visuomotor reversal has been shown to take longer (Werner and Bock, 2010). Participants were given a 30 second rest after completion of each trial. Completing this training phase took approximately 20 minutes.

Intervention groups. In each of the intervention conditions participants watched a video of an expert model completing four trials of the pre-test 25-target task, filmed from a first-person visual perspective (1PP) using a static camera in which only the model's hand and arm were visible (see Figure 4). This perspective was selected in order to increase the visual congruence between the observed action and physical performance (Holmes and Collins,

2001) and has been used in similar task protocols (Ong and Hodges, 2010; Ong et al., 2012; Lim et al., 2014). The expert model had previously performed the task over 100 times and consistently completed the task within 40 seconds. An expert model was selected for consistency and previous visuomotor adaptation research has seen both novice and expert models produce almost identical outcomes (Ong and Hodges, 2010; Ong et al., 2012). The video was shown five times for 20 observed task completions totalling 500 target hits. Prior to watching each video participants were given specific instructions depending on the experimental condition to which they had been assigned. Participants in the AOMI group were instructed to "actively imagine that you are performing the movement as you observe it. Specifically, try to imagine the feelings in your muscles associated with gripping the stylus and moving your arm across the screen". These instructions were selected to encourage the inclusion and use of kinaesthetic imagery during observation of the task performance, as per Stinear et al. (2006) who demonstrated that kinaesthetic imagery facilitated corticospinal excitability to a greater extent than visual imagery. Participants in the active observation group were instructed to "observe the movement closely as you will be asked to imitate the movement sequence later in the experiment", whilst participants in the passive observation group were instructed to "observe the movement sequence shown on screen" and given no further explicit instructions. These instructions were based on those used by Wright et al. (2016) who compared the effects of these three interventions on corticospinal excitability. Following each video, participants were given a 30 second rest. Completion of each training intervention took approximately 20 minutes.

Control group. Participants in this group watched a 20-minute video of a nature documentary that contained no human motor content (Buccino, 2014). This was selected in order to minimise any potential priming of the motor system.

Post-test

Participants then performed a post-test that was identical to that completed at the pre-test.

Measures

Performance

Performance was measured as the time (in seconds) taken to complete one trial of 25 target hits. Previous research (e.g., Chan and Hoffman, 2017) has used task completion time as an indicator of improvement in motor performance in similar goal-directed aiming tasks. The percentage of reduction in completion time from pre-test to post-test was also calculated.

Gaze control

Eye tracking videos of each pre-test and post-test trial were analysed using the semantic gaze mapping function of BeGaze 3.7 software (SMI, Teltow, Germany) and fixations were defined as gaze dispersed over less than 3^{o} of visual angle for a minimum of 80ms. Semantic gaze mapping requires a static reference image of all target orientations to be prepared with areas of interest (AOI) drawn around each target square and the cursor (see Figure 5). Every fixation recorded during the trial can then be registered to this reference image and fixation durations for each AOI can be calculated in milliseconds. In this manner, the total duration of all target and cursor fixations at pre-test and post-test was determined and a target locking measure was then calculated by subtracting the percentage of cursor fixation time from the percentage of target fixation time. This method has previously been used to determine the gaze control of participants performing surgical tasks (Wilson et al., 2010) and whilst controlling a prosthetic hand (Parr et al., 2018). Using this method, a negative score indicates greater time fixating on the cursor than on the target. A score closer to zero indicates an equal amount of time fixating cursor and targets and a score of over 50% indicates a full target locking strategy whereby targets are fixated upon significantly more than the cursor. The percentage of improvement in target locking score from pre-test to post-test was also calculated.

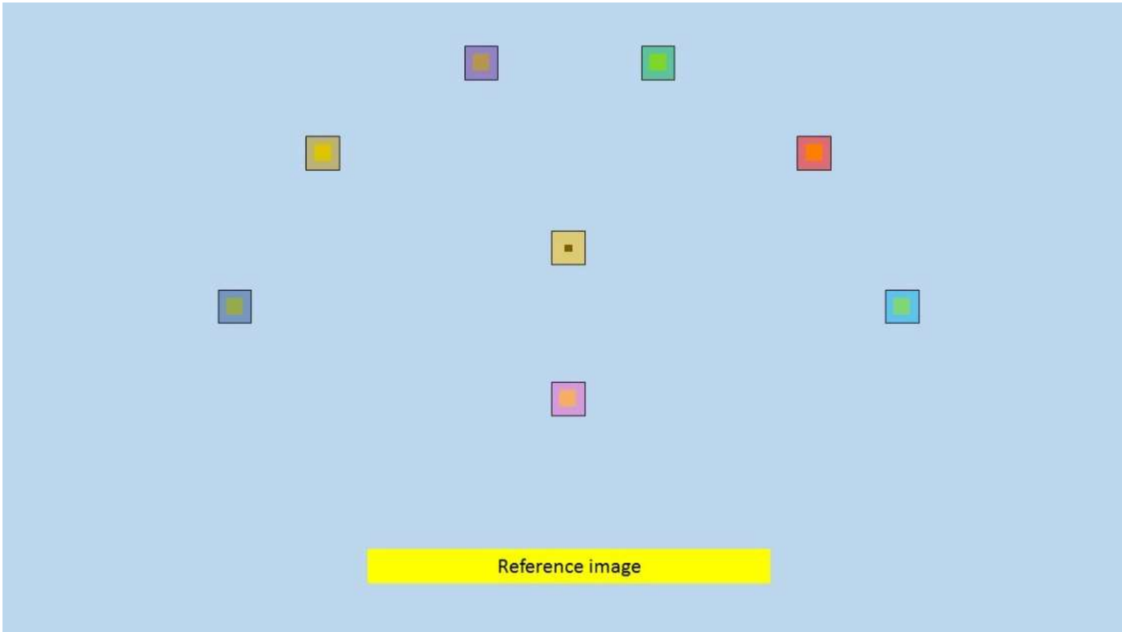


Figure 5. Reference image with areas of interest for targets and the cursor.

Data analysis

Due to the data failing assumptions of normality, separate one-way ANCOVAs were performed to determine a statistically significant difference between groups at the post-test (AOMI; AO; PO; PP; Control) for completion time and target locking score while controlling for performance at pre-test. Post hoc analyses were conducted using pairwise comparisons with the Bonferroni adjustment. Effect sizes are reported as partial eta squared (η_p^2). A linear regression was also performed using the percentage change data to assess if any improvements in target locking score predicted improvements in task completion time.

Results

Preliminary analyses

One way ANOVAs performed on the pre-test performance and eye gaze data revealed no significant differences between groups for task completion time ($F(4, 49_)$ = .12, p = .97, η_p^2 = 0.10) or target locking score ($F(4, 49)$ = .57, p = .69, η_p^2 = 0.05). These analyses indicated that all groups were of the same level of performance at pre-test (see Table 1).

Performance

The results of the one-way ANCOVA performed on the post-test completion time data revealed a significant effect of group after controlling for pre-test results, $F(4, 44) = 16.30$, $p < .001$, $\eta_p^2 = .60$. Pairwise comparisons with the Bonferroni adjustment revealed that the PP group improved significantly more than all the other groups (AOMI, $p = .012$; active observation, $p < .001$; passive observation, $p = .001$; control, $p < .001$). In addition, each intervention group improved their performance to a significantly greater extent than the control group (AOMI, $p < .001$; active observation, $p = .04$; passive observation, $p < .01$) (see Figure 6).

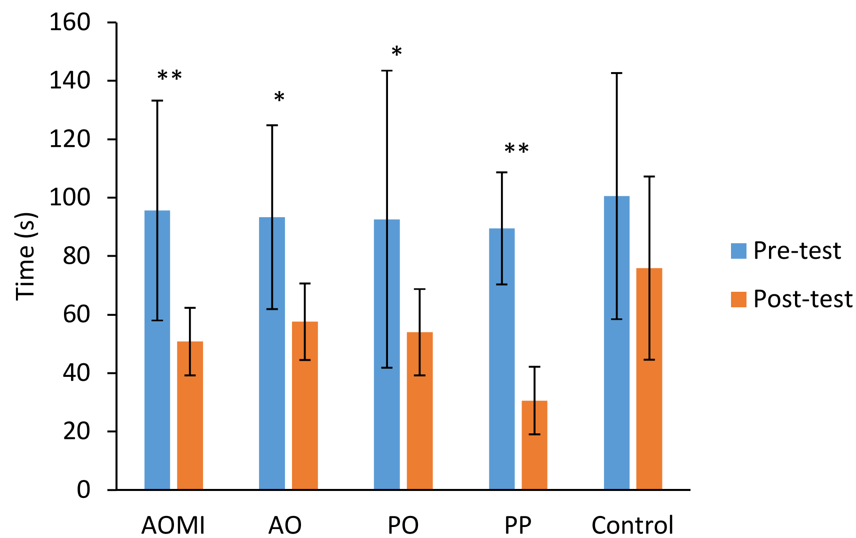


Figure 6. Mean completion times for AOMI, AO, PO, PP, and Control groups at pre-test and post-test. Error bars represent standard deviation (SD). * indicates a significant difference at post-test from control ($p < .05$), ** indicates a significant difference at post-test from control ($p < .001$).

Gaze control

The results of the one-way ANCOVA performed on the post-test target locking score data revealed a significant effect of group after controlling for pre-test results, $F(4, 44) = 8.10$, $p < .001$, $\eta_p^2 = 0.42$. Pairwise comparisons with the Bonferroni adjustment indicated that participants in the PP group acquired a significantly better target locking score than the active observation (p = .007), passive observation (p = .005), and control (p <.001) groups (see Table 1). There was no significant difference, however, between the PP and AOMI groups (p = .40). Furthermore, whilst the AOMI group improved their gaze control to a significantly greater extent than the control group (p = .03), no such improvement was found in the active and passive observation groups (see Figure 7). An example of a scan path typical of the PP group can be seen in Figure 8. This illustrates a wider spread of fixations at pre-test as the movement of the cursor is visually monitored. During the post-test, however, fixations are generally located on, or very close to, the targets.

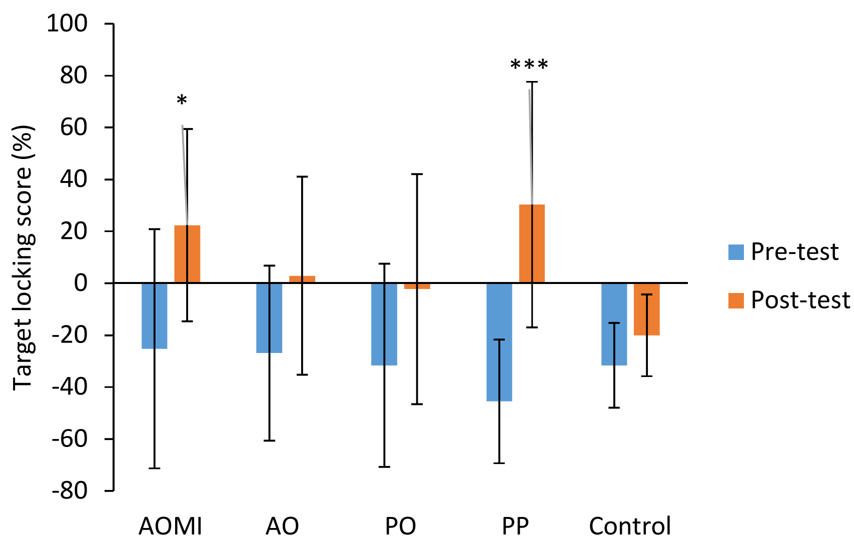


Figure 7. Mean target locking scores for AOMI, AO, PO, PP, and Control groups at pre-test and post-test. Error bars represent SD. * indicates a significant difference from control at post-test (p = .03), *** indicates a significant difference to AO, PO, and control at post-test (p <.05).

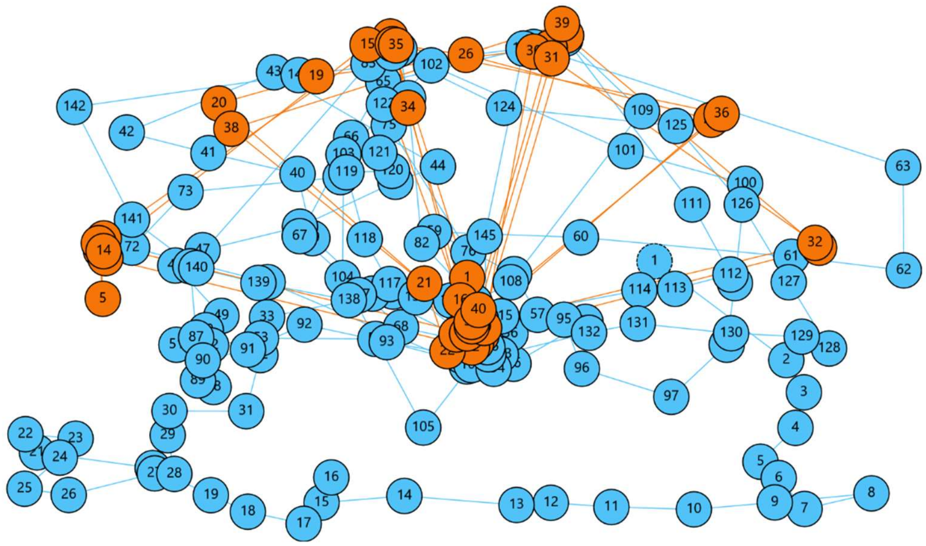


Figure 8. An illustration of the scan path produced by a participant in the PP group. Blue circles represent fixations made during the pre-test; orange circles represent fixations made during the post-test.

Table 1.

Mean scores for completion time and target locking score.

Group	Completion time (s)			Target locking score (%)		
	Pre-test	Post-test	Percentage of reduction from pre-test	Pre-test	Post-test	Percentage of improvement from pre-test
AOMI	95.62	50.77	-46.91	-25.23	22.42	47.65
	(11.89)	(3.65)	(14.56)	(14.57)	(11.72)	(9.03)
AO	93.36	57.54	-38.37	-26.93	2.91	29.84
	(9.95)	(4.14)	(13.15)	(10.66)	(12.07)	(8.12)
PO	92.66	54.00	-41.73	-31.63	-2.23	29.40
	(16.07)	(4.67)	(15.30)	(12.38)	(14.01)	(6.58)
PP	89.51	30.57	-65.85	-45.48	30.33	75.81
	(6.06)	(3.65)	(14.60)	(7.54)	(14.95)	(11.48)
Control	100.58	75.96	-24.47	-31.62	-20.07	11.55
	(13.32)	(9.91)	(5.60)	(5.18)	(4.98)	(4.35)

* indicates a significant difference from control (p = .03), ** indicates a significant difference to all groups (p < .05), *** indicates a significant difference to AO, PO, and control (p < .05)

Regression

This analysis revealed that the percentage of improvement in target locking score was a significant predictor of the percentage of improvement in completion time ($F(1, 49) = 61.47$, $R^2 = .56$, b = .41, $p < .001$) (see Figure 8). This indicated that improvements in proactive gaze behaviour were predictive of improvements in completion time (see Figure 9).

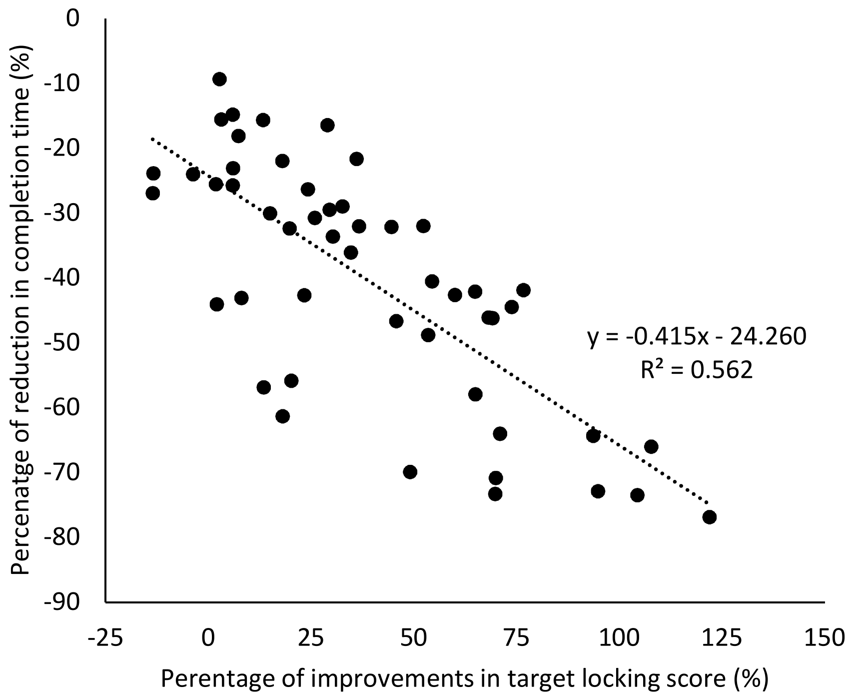


Figure 9. Relationship between percentage of reduction in completion time and percentage of improvements in target locking score.

Discussion

The present study compared the effects of three types of AO viewing instructions (AOMI; active observation; passive observation) and physical practice on the development of eye-hand coordination and performance of a novel visuomotor task. It was predicted that AOMI would lead to greater improvements in performance and facilitate a shift to a proactive gaze strategy than either active or passive observation. The results of this experiment partially support the hypotheses. Each intervention group improved their performance to a significantly greater extent than the control group, and, in the AOMI and PP groups, these improvements were accompanied by significant changes in proactive gaze behaviour. Specifically, after training, the AOMI group exhibited an improvement in gaze behaviour that was not significantly different to the PP group and was significantly better than the control group. Furthermore, a regression analysis indicated that greater proactive gaze is indicative of greater performance.

Despite the growing body of neurological evidence advocating the potential behavioural benefits of AOMI training (Eaves et al., 2016), relatively few studies have assessed its application for enhancing motor control (Taube et al., 2014; Bek et al., 2016; Sun et al., 2016; Scott et al., 2017). The current study extends the body of literature in this area by including gaze metrics in its assessment of AOMI training effects and identifying preliminary evidence suggesting AOMI may be more effective than other AO conditions for facilitating proactive gaze behaviour.

Although these results only partially support the predictions outlined earlier, they do have several theoretical and applied implications. From a theoretical perspective, the results provide some support for Jeannerod's (2001; 2006) simulation theory. According to this account, motor simulation accesses a shared motor representation or internal model that may prime action planning and movement programming resulting in the production of eye movements similar to those made during action execution (Flanagan and Johansson, 2003; Heremans et al., 2008; McCormick et al., 2012). The results of the present study demonstrated that, during the post-test, only the AOMI and PP training groups produced eye movements that were more target-focused than those of the control group. This may be partially indicative of AOMI training facilitating the adaption, or development, of a task-specific motor representation that was more analogous to physical practice than the other simulation conditions. Furthermore, the inclusion of MI alongside the AO stimulus may have resulted in a task-specific motor representation that more effectively encoded visuomotor commands related to the planning and preparation of action execution. MI incorporating kinaesthetic components has previously been shown to utilize forward models to predict sensory outcomes by producing an error signal from the comparison between anticipated and simulated sensory consequences (Kilteni et al., 2018) which may have contributed to the manifestation of proactive eye movements. In a similar manner, Frank et al. (2016) demonstrated that the mental simulation of a golf-putting task produced more elaborate motor representations, facilitating the development of eye movements associated with aiming skills, and incorporated increased QE durations.

According to Land (2009), the visual, gaze and motor systems each have a role in the successful execution of movement but it is the schema system that serves as a top-down authority with overall control over the other systems, specifying the current task and planning an overall sequence of actions needed to complete that movement. In this arrangement under optimal circumstances, vision is not used to supervise a movement but is instead disengaged from action once other senses such as touch and proprioception assume responsibility for completion. Vision can then be reallocated to the next task-relevant stimulus in the sequence of action as scheduled by the schema system. In this way, gaze becomes proactive in relation to effector movement, leading the hand to targets. Prior research has shown gaze to be proactive in this manner and move on to the next task-relevant object before manipulation of the current object is complete (Hayhoe et al., 2003).

The kinaesthetic imagery instructions in the current experiment therefore may have served to update the proprioceptive components of the forward model through simulated sensory error signals and subsequently improved movement planning and control. The development of more proprioceptive modes of motor control are indicative of more expert-like motor control that 'frees-up' vision to be allocated as a feed-forward resource to guide action ahead of time (Sailer et al., 2005). Finally, kinaesthetic imagery has previously been shown to facilitate corticospinal excitability to a greater extent than visual imagery (Stinear et al., 2006). Previous research has illustrated that AOMI interventions elicit greater activity in the motor regions of the brain than independent AO or MI (Eaves et al., 2016). It is therefore possible that the AOMI training may have produced stronger activity in the premotor and motor regions of the brain than active or passive observation (Wright et al., 2016), which is widely believed to be advantageous for promoting neuroplastic changes that facilitate motor processes and behavioural outcomes (see Eaves et al., 2016).

Another possible explanation for the different levels of task performance found between groups is that simulated training improved task memory more than the control condition. The inclusion of kinaesthetic imagery during AOMI training and its role in being used with the internal model to predict sensory outcomes (Ridderinkhof and Brass, 2015; Kilteni et al., 2018) may have enabled participants to learn the spatial characteristics of the task more effectively. This explanation would account for the improvements in performance resulting from the AOMI, active observation, and passive observation training interventions that were greater than those of the control group. The participants in the active observation and passive observation groups were provided with increased access to the visual characteristics of the task stimuli, enabling them to mentally imitate the task and more effectively embed the sequence. Participants in the control group, however, only saw the task sequence twice and therefore might have had to incorporate an increased visual search element during subsequent task performance.

From an applied perspective, whilst it is clear that physical practice offers superior performance benefits to all simulation conditions, AOMI seems to facilitate significant improvements in performance and gaze behaviour when compared to no intervention. Conversely, active or passive observation strategies seem to offer no significant benefits to gaze behaviour compared to doing no intervention at all. Furthermore, the findings of this study may imply AOMI enhances the formation and adaptation of an internal model of novel movement dynamics. Such a technique may prove beneficial for use with children with DCD for whom an impaired ability to form and update the forward model is believed to be central to their motor skill deficits (Wilson et al., 2013). Recent research has also indicated that suboptimal gaze behaviour in this population is receptive to training and can enhance the performance of catching skills (Miles et al., 2015; Wood et al., 2017).

These results also provide interesting avenues for further research in clinical populations where individuals are unable to carry out physical practice due to illness, injury or disease. For example, while AOMI interventions have been shown to increase corticospinal excitability (e.g., Wright et al., 2014), which may be linked to improvement in neural pathways supporting improved functional strength (Scott et al., 2018), they may also serve to facilitate the development of effective eye-hand coordination critical for activities of daily living (e.g., reaching and grasping). This may have potential clinical benefits for recovering stroke patients suffering hemiparesis or for patients learning to use prostheses following upper limb amputation. Future studies should aim to explore the use of AOMI within these populations to support more traditional physical neurorehabilitation techniques.

While these findings are informative, some limitations need to be acknowledged. First, although the sample size for this study was based on similar studies (Wright and Smith, 2009; Taube et al., 2014) increasing the size of the groups may have increased the statistical power of the study and, as such, some caution should be exercised when interpreting these results. Second, it is possible that if participants had been exposed to a longer training period or had completed their AO training alongside physical practice then greater improvements in performance or gaze control may have been revealed. AOMI interventions of similar duration, however, have been shown to improve performance in previous research (Bek et al., 2016). Finally, the nature of the task and its limited range of movements may have also served to restrict the application of kinaesthetic imagery in the AOMI group. Although kinaesthetic propositions (Lang, 1979) were included in the AOMI imagery script, participants may have had difficulty incorporating them into their own imagery based on their limited exposure to the physical characteristics of the task prior to training. Furthermore, imagery ability has previously been identified as a potential moderating factor for the effectiveness of MI interventions (Robin et al., 2007) but the MI ability of participants was not assessed in this study due to the current lack of a suitable measure for AOMI imagery ability characteristics.

In conclusion, these findings suggest that AOMI training can be used to facilitate a shift to a proactive pattern of eye-hand coordination, similar to that observed in physical practice, during performance of a novel visuomotor task. This manifestation of proactive gaze that leads hand movements to targets is also a reliable predictor of task performance. AOMI, even without associated physical practice, may therefore be beneficial for symptomatic populations in which eye-hand coordination is suboptimal, such as children with DCD. In the following chapter, these deficits were assessed in children with and without DCD.

4. Study 2: Comparing the task performance and development of eye-hand coordination of children with and without DCD

Introduction

One method that has been used to examine the internal model deficit hypothesis (IMD) in DCD has been the use of eye tracking to assess differences in gaze behaviour. Previous research has shown children with DCD to experience visuospatial processing deficits that affect eye-hand coordination and serve to underpin many of the motor skill impairments that are symptomatic of DCD (Langaas et al., 1998; Wilmut et al., 2006; Sumner et al., 2018). Effective eye-hand coordination allows for the successful execution of daily activities through a range of actions, such as reaching to grasp, throwing and catching, and other interceptive movements. The visuospatial processing deficits exhibited by children with DCD therefore have a profound influence on how they conduct their daily lives and perform routine activities, such as engaging in physical activity and play.

As described in Chapter 2, several studies have examined the gaze behaviour of both DCD and TD children and have shown children with DCD to display an over-reliance on visually guided online control (Debrabant et al., 2013), an impaired ability to process task-relevant visual information (Wilson et al., 2013), and difficulty maintaining fixations on visual targets (Sumner et al., 2018). In addition, studies have also identified differences in smooth pursuit (Langaas et al., 1998; Robert et al., 2014) and the temporal coupling of eye and hand movements during the performance of complex tasks between the two populations (Wilmut et al., 2006).

As each of these issues is associated with the predictive control of overt eye movements, the differences in visuospatial processing observed between children with DCD and their TD peers may be the product of deficits in the use of feedforward models of control. The IMD hypothesis asserts that an impaired ability to create or update the internal model forms the basis of these disruptions in predictive control (Wilson et al., 2013). The gaze behaviours of children with DCD therefore may be indicative of a disruption in the use of this control process.

Many of the studies described above, which compare the performance of DCD and TD populations, do so using established tasks where eye-hand coordination is already dissimilar. For example, if children with DCD are not extracting visuospatial information from the environment in the same way as their peers at baseline, it is of little surprise perhaps that there are differences in their ability to perform coordinated movements. Previous studies that have examined the eye-gaze behaviour of children with DCD have not investigated how the spatial and temporal coupling of eye and hand movement develops over time in comparison to their typically developing peers during performance of a task in which eye-hand coordination is disrupted for both populations, such as during visuomotor adaptation. In order for children to learn the new sensorimotor mapping rules required to navigate a novel task environment effectively, an internal model must be formed and then adapted using visual and sensorimotor feedback. A limited number of studies have used visuomotor adaptation paradigms to identify differences in visual-motor task performance between children with and without DCD but have not included gaze metrics as part of their analyses. Kagerer et al. (2004) found that, on performance of a 45^{o} visuomotor rotation task, children with DCD were less affected by the distortion to visual feedback than the control group of TD children. They attributed this difference to the DCD group having a less well-defined internal model. In a follow up to this study, Kagerer et al. (2006) showed that children with DCD were able to update their internal model more effectively during exposure to an abrupt visuomotor rotation rather than incremental, smaller rotations. Using a throwing task performed whilst wearing prism adaptation glasses, Cantin et al. (2007) found no significant difference in adaptation between children with and without DCD.

By identifying the nature of the mechanistic processes at work as a coordinative skill is acquired, it may provide further evidence of the IMD hypothesis whilst also expanding our understanding of the slower development of such abilities in children with DCD. Furthermore, specific differences in the trial-by-trial development of eye-hand coordination may be possible to address in a future intervention.

The aim of this study is to incorporate eye gaze metrics in order to identify differences in how eye-hand coordination develops over time for children with DCD and their TD peers during adaptation to a novel visuomotor rotation. As this type of task requires the formation of an internal model that represents a novel relationship between visual and sensorimotor feedback, it was hypothesised that the DCD group would adapt at a slower rate than the TD group in terms of task performance and gaze control. Specifically, the target locking score for the TD group is predicted to increase in a linear relationship with a decrease in movement time as the training period progresses. The target locking score of the DCD group was predicted to remain lower than the TD group for the duration of the training period.

Methods

Participants

Ten children with DCD (six male, four female; age *M* = 9.7, *SD* = 1.25 years) and ten TD children (nine male, one female; age *M* = 10.5, *SD* = 0.85 years) took part in the experiment. Each child had normal or corrected-to-normal vision. The number of participants recruited was selected to be comparable to that of similar studies of visuomotor adaptation and DCD (Kagerer et al., 2004; 2006). The recruitment of large samples of participants with DCD is often difficult and this sample size was deemed sufficient based on both the past experience of the research team and the fact a strict selection criterion for movement ability was to be used.

Participants were recruited through local dyspraxia and DCD support groups, sports and after school clubs. Potential participants were screened using the Developmental Coordination Disorder Questionnaire (DCDQ: Wilson et al., 2007) (see Appendix B). This questionnaire is a 15-item well-validated (Wilson et al., 2009) instrument that parents can use to perform an initial assessment of their child’s control during movement, fine motor skills, and general coordination which may provide a possible indication of a movement disorder (Wilson et al., 2007). Participants with potential DCD were invited to a testing session if they scored within the recommended range of 15-55 on this questionnaire, did not attend a specialist school or have a formal diagnosis of learning difficulties or ADHD, and did not suffer from any other general medical condition known to affect sensorimotor function, such as cerebral palsy, hemiplegia, or muscular dystrophy (Cantin et al., 2014; Hammond et al., 2014; Gonsalves et al., 2015). Parents and children provided written informed consent and assent prior to taking part and the experimental procedures were granted ethical approval by the local ethics committee.

MABC-2

At the start of the laboratory session participants first completed the Movement Assessment Battery for Children-2 (MABC-2: Henderson et al., 2007) in order to provide a quantitative assessment of each child's motor skills. The MABC-2 has been used in a large number of studies focusing on DCD and is one of the most frequently used tests in the diagnosis of the disorder (e.g. Miles et al., 2015; Wilson et al., 2016; Wood et al., 2017). Administration of the test consists of a child performing eight items covering three sub-components: manual dexterity, ball skills, and static and dynamic balance. The test battery is designed to assess children across three age bands: 3 to 6 years (band 1), 7 to 10 years (band 2), and 11 to 16 years (band 3). For the purposes of this study, only children from age bands 2 and 3 were assessed.

For age band 2, three individual manual dexterity tasks (placing pegs in a board, threading a lace, and drawing a trail on paper), two aiming and catching tasks (two handed catching, throwing bean bags onto mats), and three balance tasks (one board balance, walking heel-to-toe forwards, hopping on mats) are performed. For age band 3, the same number of tasks are used to assess each sub-component but they are slightly different to account for developmental differences resulting from age. For manual dexterity, the three tests are turning pegs, forming a triangle using nuts and bolts, and drawing a trail. For aiming and catching, the two tasks are catching with one hand, and throwing a ball at a wall mounted target. For balance, the three tasks are two-board balance, walking heel-to-toe backwards, and zig-zag hopping.

Scoring of the test and subsequent interpretation utilises a 'traffic light' system that can be used to indicate the likelihood of a movement disorder. According to this system, the 'green zone' represents scores above the 16th percentile and reflects the age-expected normal range. The 'amber zone' includes scores between the 6th and 15th percentile and suggests the child may be at risk of a movement problem or may require further monitoring, and the 'red zone' applies to scores at or below the 5th percentile which indicates that it is highly likely the child has a serious movement problem. Only children who scored at or below the 5th percentile were included in the DCD group and children with scores at or above the 16th percentile were included in the control group.

Task

The task used in this study was the same 180° visuomotor rotation task that was used in Study 1 (see Figure 2 in Chapter 3). This task was selected as it would disrupt the coupling between eye and hand movement for both experimental groups and allow for the measurement of changes to task performance and eye-hand coordination over the course of the experiment.

Apparatus

Testing was performed using the same touchscreen monitor described in Chapter 3. Unity3D game engine (Unity Technologies, San Francisco, CA) was used to present the experimental task, collect data on the position of the cursor in both the x and y axes at a sampling rate of 80 Hz, and record onset and termination of timing for the task. The same SMI ETG 2w eye tracking glasses and iView ETG 2.7 software (SMI, Teltow, Germany) used in Chapter 3 were also used in this experiment, however, in this study the eye-tracking equipment was calibrated using a 1-point calibration prior to each physical trial. This was chosen over the alternative 3-point calibration used in the methods previously described for adults in Chapter 3 as the children with DCD in this study experienced difficulty maintaining focus on each individual point long enough to confirm a high-quality calibration. The 1-point calibration was deemed more reliable in this case and less time consuming for participants. Eye tracking data was recorded throughout the pre-test baseline, pre-test, training, post-test and post-test baseline phases of the experiment.

Procedure

Familiarisation

All participants performed two practice trials of the task with no visuomotor rotation applied in order to familiarise themselves with the visual characteristics and goal of the task. At this point participants were then fitted with the eye-tracking glasses and performed the calibration procedure.

Pre-test baseline

All participants performed three pre-test baseline trials of the task with no visuomotor rotation applied. Each participant was instructed to complete the task as quickly and accurately as possible.

Pre-test

Once they had completed the three baseline trials, participants then performed one trial of the task with the 180^o visuomotor rotation applied. Participants commenced training immediately after completing the pre-test trial.

Adaptation training

During adaptation training, participants performed 20 trials of the task under the constraints of a 180^o reversal in which stylus movements to the left produced equal cursor movements to the right and vice versa. Trials were performed in four blocks of five trials and calibration of the eye-tracking equipment was checked before commencing each trial. Rest periods were given after every block and the eye-tracking equipment was recalibrated before each trial as necessary.

Post-test

Each participant completed a final rotation trial as a post-test.

Post-test baseline

Following completion of the adaptation training trials, participants performed three trials of the baseline test with no visuomotor rotation in order to assess the presence of any unintentional after-effects resulting from the training.

Measures

Performance

For each trial, position data were filtered using a 2^{nd} order dual lowpass Butterworth filter with an 8 Hz cut off frequency. The filtered data was then processed with custom written Matlab 2017b (MathWorks Inc, Natick, MA) routines to calculate total path length, root mean square error (RMSE), peak acceleration, and peak velocity. Completion time was calculated as the time taken in seconds to finish the entire 25 target sequence. Total path length (in cm) was calculated between sampled pairs of x and y coordinates using the following formula where x_1, x_2 and y_1, y_2 represent points along the x and y axes respectively. The total units of distance for each sampled point were then summed to provide a total path length per trial.

$$Path\ length = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2}$$

RMSE (in cm) was computed using the following formula where x_a, y_a and x_i, y_i are corresponding points of the actual trajectory (index a) and the ideal trajectory (index i) represented as a straight line between two targets. *N* is the number of points in the path.

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}[(x_a - x_i)^2 + (y_a - y_i)^2]}{N}}$$

RMSE has previously been used as a measure of spatial deviation from an ideal path in similar studies involving visuomotor adaptation (Kagerer et al., 2004; 2006).

Peak acceleration and peak velocity were calculated using the data derived from the path length and movement time calculations and are represented as cm^2/s and cm/s respectively.

Gaze control

Eye tracking videos of each baseline, pre-test, and post-test trial were analysed by the experimenter using BeGaze 3.7 software (SMI, Teltow, Germany). In addition, 10 training trials for each participant were also analysed. This number of trials were selected for analysis based on time considerations and is consistent with similar research in this area (e.g., Vine and Wilson, 2010; Vine et al., 2013). Targets were defined as the target and home squares. Fixations were defined as gaze dispersed over less than 3^o of visual angle for a minimum of 80 ms and a target locking measure was calculated using the method described in Chapter 3.

Data analysis

Performance was quantified on a trial-by-trial basis for completion time, RMSE, total path length, peak acceleration, and peak velocity for each participant. For gaze control, target locking scores were calculated for each baseline, pre-test, and post-test trial and 10 additional training trials. Mean values for each dependent variable on each trial were calculated in addition to mean scores for each of the four training blocks.

Preliminary analyses

As preliminary analyses, participants' pre-test performance data were analysed using separate independent samples t-tests to check for any pre-test differences between groups for completion time, RMSE, total path length, peak acceleration, peak velocity, and gaze control.

Main analyses

For the main analyses of the data, 2 (Group: DCD, TD) x 6 (Pre-test, block 1, block 2, block 3, block 4, post-test) ANOVAs were performed on participants completion time, RMSE, total path length, peak acceleration, peak velocity, and gaze control data.

After effects analyses

After-effects are the unintentional remains of compensatory strategies used to adapt to a novel visuomotor workspace that are present when the performer is reintroduced to an environment in which the use of such strategies is no necessary (Ong and Hodges, 2010). To assess the presence of after-effects following the adaptation training, 2 (Group: DCD, TD) x 2 (Baseline pre-test, baseline post-test) ANOVAs were conducted using the mean value of the three average pre-test baseline trials and the first post-test baseline trial. Where sphericity was violated Greenhouse-Geisser corrections were used. All significant effects are reported at an alpha value of 0.05. Effect sizes are reported as partial eta squared (ηp^2).

Results

Preliminary analyses

The preliminary independent sample t-tests revealed no significant differences between groups at pre-test for completion time ($t(18) = .42$, $p = .68$), RMSE ($t(18) = -.10$, $p = .92$), total path length ($t(18) = 1.28$, $p = .21$), peak acceleration ($t(18) = .89$, $p = .38$), peak velocity ($t(18) = .42$, $p = .68$), or gaze control dependent variables ($t(18) = .36$, $p = .72$). These analyses indicated that all groups were of the same level of performance at pre-test.

Main analyses

Gaze control

Analysis of the target locking data did not reveal a significant interaction, $F(1.67,30.05) = .29$, $p = .71$, $\eta_p^2 = .02$ but a significant main effect for time was found, $F(1.67,30.05) = 124.09$, $p < .001$, $\eta_p^2 = .87$ with both groups significantly improving their target locking score from pre-test ($M = -36.70$, $SD = 22.18$) to post-test ($M = 46.31$, $SD = 21.75$). Pairwise comparisons showed that a significant improvement occurred from pre-test to block 1 ($p < .001$) and a further improvement was made from block 1 to block 2 ($p < .001$), from which point no further significant improvements were made (all $p > .05$) and performance remained at the same level. No main effect for group was found, $F(1,18) = .007$, $p = .93$, $\eta_p^2 = .001$ (see Figure 10).

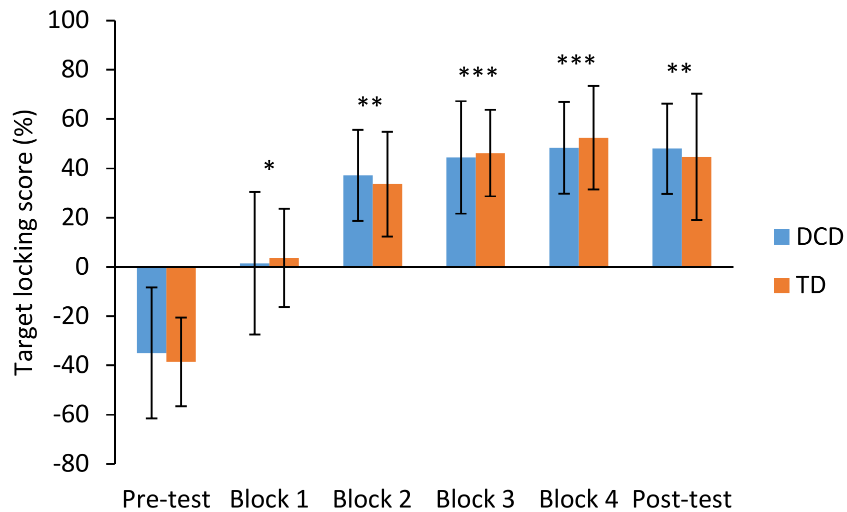


Figure 10. Mean target locking scores for DCD and TD groups at pre-test, block 1, block 2, block 3, block 4, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test ($p < .001$), ** indicates a significant difference from pre-test and block 1 ($p < .001$), *** indicates a significant difference from pre-test, block 1, and block 2 ($p < .05$).

Performance

Completion time

No significant interaction was found, $F(1.44, 25.83) = .11$, $p = .83$, $\eta_p^2 = .01$ for completion time. A significant main effect for time, $F(1.44, 25.83) = 84.65$, $p < .001$, $\eta_p^2 = 0.83$, was found indicating that participants completed the task significantly quicker at post-test (*M*

= 39.97, *SD* = 9.17) than at pre-test (*M* = 123.46, *SD* = 38.92). Pairwise comparisons showed that a significant improvement occurred from pre-test to block 1 ($p < .001$), from block 1 to block 2 ($p < .001$), and block 2 to block 3 ($p <.001$). From block 3 no further significant improvements were made (all $p > .05$) and performance remained at the same level. No significant main effect for group was found, $F(1,18) = .73$, $p = .40$, $\eta_p^2 = .04$. Overall, the DCD group was found to have slower task completion times at pre-test, block 1, block 2, block 3, block 4, and post-test but not to a statistically significant extent (see Figure 11).

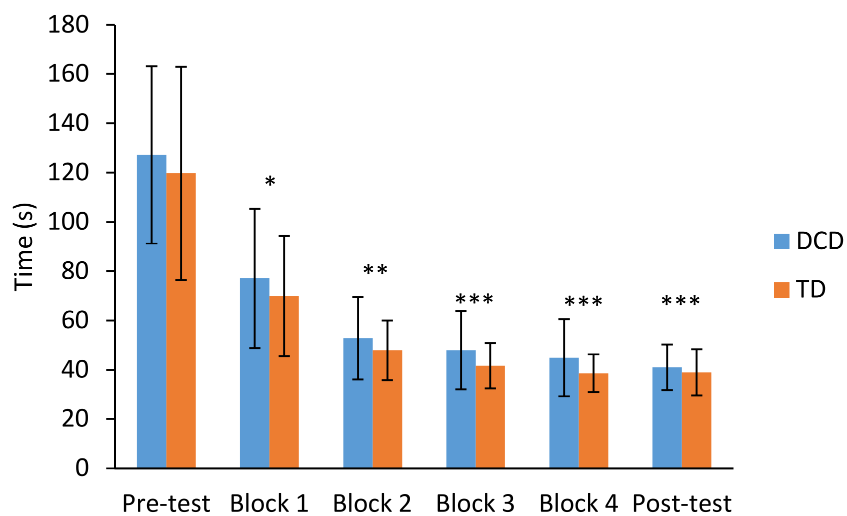


Figure 11. Mean completion times for DCD and TD groups at pre-test, block 1, block 2, block 3, block 4, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test ($p < .001$), ** indicates a significant difference from pre-test and block 1 ($p < .001$), *** indicates a significant difference from pre-test, block1, and block 2 ($p < .001$).

Total path length

No significant interaction was found, $F(1.44, 25.85) = 1.93$, $p = .17$, $\eta_p^2 = .10$ for total path length. A significant main effect for time, $F(1.44, 25.85) = 15.58$, $p < .001$, $\eta_p^2 = .46$, was found which demonstrates that participants produced significantly shorter paths at post-test (*M* = 286.19, *SD* = 66.21) than at pre-test (*M* = 491.35, *SD* = 239.34). Pairwise comparisons showed that a significant improvement occurred from pre-test to block 1 (p = .04) and block 1 to block 2 (p = .02). From block 2 no further significant improvements were made (all $p >$ .05) and performance remained at the same level. No significant main effect for group was found, $F(1,18) = .86$, $p = .36$, $\eta_p^2 = 0.5$. Overall, the DCD group was found to have longer total path lengths at pre-test, block 1, block 2, block 3, and block 4 but not to a statistically significant extent (see Figure 12).

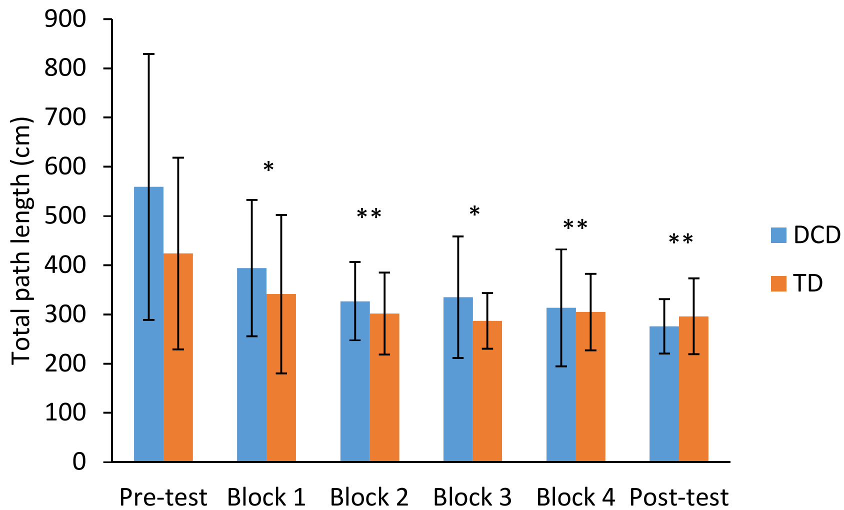


Figure 12. Mean total path length for DCD and TD groups at pre-test, block 1, block 2, block 3, block 4, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test ($p < .05$), ** indicates a significant difference from pre-test and block 1 ($p < .05$).

RMSE

No significant interaction was found, $F(1.93, 34.75) = .59$, $p = .56$, $\eta_p^2 = .03$ for RMSE. A significant main effect for time, $F(1.93, 34.75) = 5.42$, $p = .01$, $\eta_p^2 = .23$, was found indicating that participants produced significantly less error at post-test (M = 120.22, SD = 24.21) than in the first block of training (M = 145.40, SD = 40.44). No significant main effect for group was evident, $F(1,18) = .03$, $p = .87$, $\eta_p^2 = .001$ (see Figure 13).

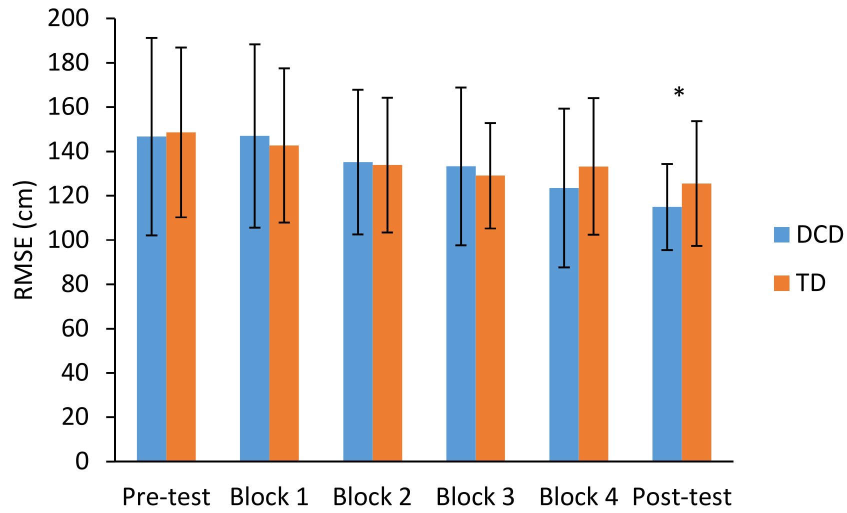


Figure 13. Mean RMSE for DCD and TD groups at pre-test, block 1, block 2, block 3, block 4, and post-test. Error bars indicate SD. * indicates significant difference from block 1 ($p < .01$).

Mean peak acceleration

No significant main effect for time, $F(2.41, 43.39) = .50$, $p = .64$, $\eta_p^2 = .03$, group, $F(1,18) = 3.01$, $p = .10$, $\eta_p^2 = .14$, or interaction was found, $F(2.41, 43.39) = .24$, $p = .82$, $\eta_p^2 = .01$ (see Figure 14).

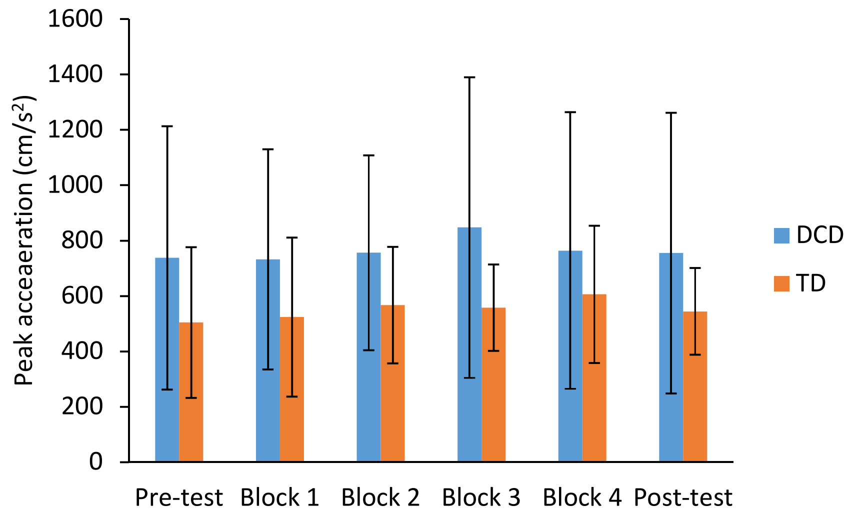


Figure 14. Mean peak acceleration for DCD and TD groups at pre-test, block 1, block 2, block 3, block 4, and post-test. Error bars indicate SD.

Mean peak velocity

A significant main effect for time, $F(2.08, 37.37) = 5.23$, $p = .01$, $\eta_p^2 = .22$, was found indicating that participants produced significantly higher peak velocities at post-test (M = 46.11, SD = 13.72) than at pre-test (M = 37.55, SD = 15.31). Pairwise comparisons revealed that a significant improvement occurred from pre-test to block 3 (p >. 05) and pre-test to block 4 ($p > .05$). However, no significant main effect for group, $F(1,18) = 2.19$ $p = .16$, $\eta_p^2 = .11$, or interaction was found, $F(2.08, 37.37) = .40$, p = . 68, $\eta_p^2 = .02$ (see Figure 15).

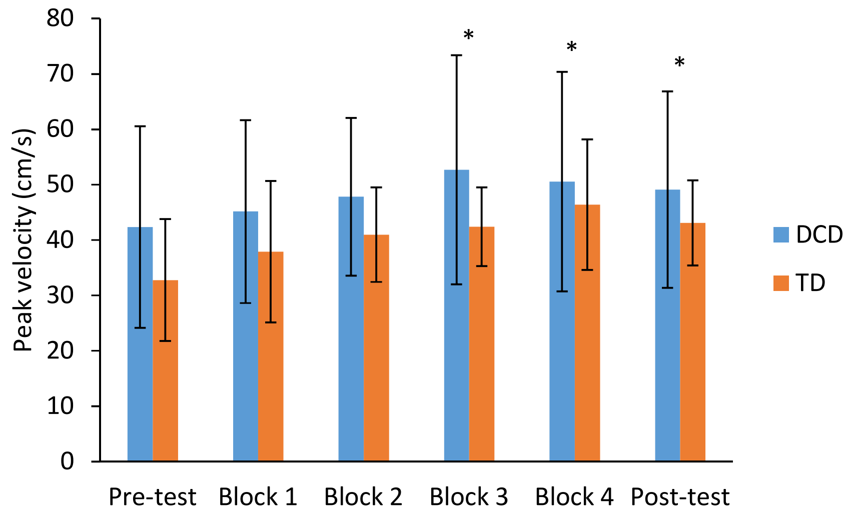


Figure 15. Mean peak velocity for DCD and TD groups at pre-test, block 1, block 2, block 3, block 4, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test ($p < .05$).

Time to peak acceleration

A significant main effect for time, $F(1.84, 33.12) = 67.65$ $p < .001$, $\eta_p^2 = .79$, was found indicating that the time to peak acceleration for participants was significantly faster at post-test ($M = 0.45$, $SD = 0.15$) than at pre-test ($M = 1.58$, $SD = 0.60$). Pairwise comparisons showed that a significant improvement occurred from pre-test to block 1 ($p < .001$), from block 1 to block 2 ($p < .001$), and block 2 to block 3 ($p < .05$). From block 3 no further significant improvements were made (all $p > .05$) and performance remained at the same level.

A significant main effect for group was also found, $F(1,18) = 5.41$, $p = .03$, $\eta_p^2 = .23$, indicating that the time to peak acceleration of participants in the DCD group was significantly slower than that of the TD group at pre-test, during training, and at post-test. However, no significant interaction was found, $F(1.84, 33.12) = 1.33$, $p = .27$, $\eta_p^2 = .07$ (see Figure 16).

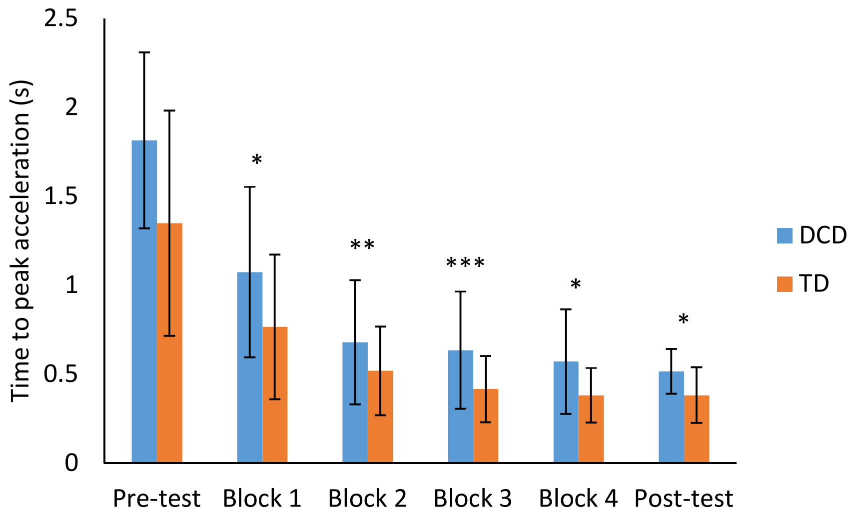


Figure 16. Time to peak acceleration for DCD and TD groups at pre-test, block 1, block 2, block 3, block 4, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test (p < .001); ** indicates a significant difference from block 1 (p < .001); *** indicates a significant difference from block 2 (p < .05).

A 2 (Group: AOMI; Control) x 6 (Time: Pre-test; block 1; block 2; block 3; block 4; post-test) ANOVA performed on the standard deviations of the time to peak acceleration data revealed a significant main effect for time, $F(2.05, 36.89) = 34.35$, $p < .001$, $\eta_p^2 = .66$, indicating that variability was significantly lower at post-test (M = 1.65, SD = 0.73) than pre-test (M = 0.52, SD = 0.23). Pairwise comparisons showed that a significant improvement occurred from pre-test to block 1 (p < .001) and from block 1 to block 2 (p < .001). From block 2 no further significant improvements were made (all p > .05) and performance remained at the same level. However, no significant main effect for group, $F(1,18) = .21$, $p = .65$, $\eta_p^2 = .01$, or interaction, $F(2.05, 36.89) = .26$, $p = .78$, $\eta_p^2 = .01$ was found (see Figure 17).

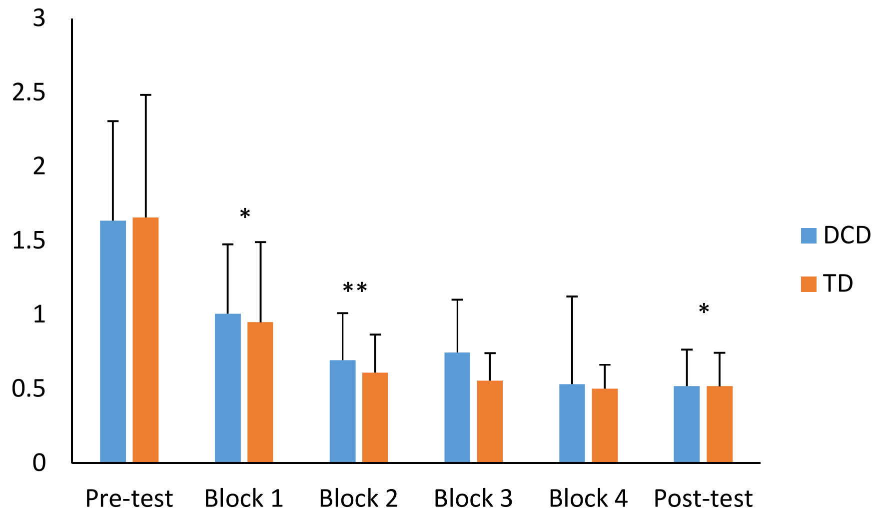


Figure 17. Standard deviations of time to peak acceleration for DCD and TD groups at pre-test, block 1, block 2, block 3, block 4, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test ($p < .001$); ** indicates a significant difference from block 1 ($p < .001$).

Time to peak velocity

A significant main effect for time, $F(1.69, 30.41) = 73.41$, $p < .001$, $\eta_p^2 = .80$, was found indicating that the time to peak velocity for participants was significantly faster at post-test ($M = 0.75$, $SD = 0.16$) than at pre-test ($M = 2.29$ $SD = 0.73$). Pairwise comparisons showed that a significant improvement occurred from pre-test to block 1 ($p < .001$), from block 1 to block 2 ($p < .001$), and block 2 to block 3 ($p < .05$). From block 3 no further significant improvements were made (all $p > .05$) and performance remained at the same level. However, no significant main effect for group, $F(1,18) = .44$, $p = .52$, $\eta_p^2 = .02$, or interaction was found, $F(1.69, 30.41) = .11$, $p = .87$, $\eta_p^2 = .01$ (see Figure 18).

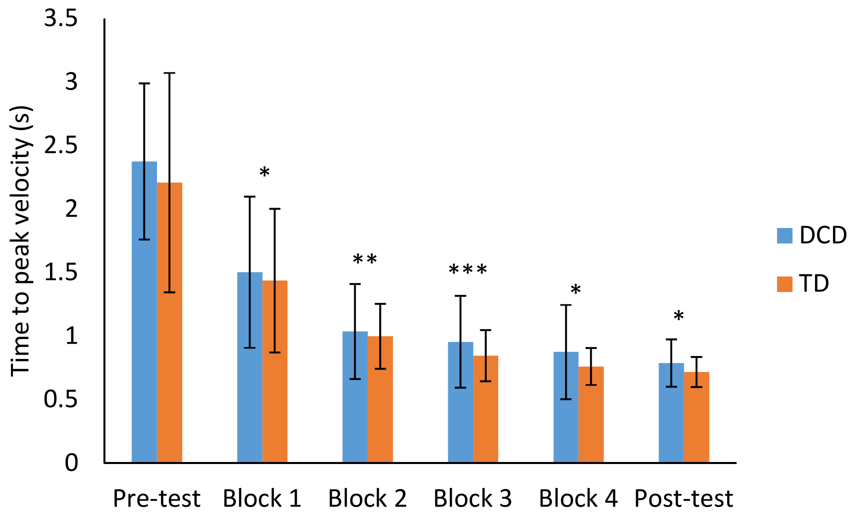


Figure 18. Time to peak velocity for DCD and TD groups at pre-test, block 1, block 2, block 3, block 4, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test (p < .001); ** indicates a significant difference from block 1 (p < .001); *** indicates a significant difference from block 2 (p < .05).

After-effects analyses

Gaze control

The results of the 2 (Group: DCD; TD) x 2 (Time: pre-test; post-test) repeated measures ANOVA indicated no significant interaction, $F(1,18) = .578$, $p = .46$, $\eta_p^2 = .03$ or significant main effects for time, $F(1,18) = .153$, $p = .70$, $\eta_p^2 = .01$ or group, $F(1,18) = .236$, $p = .63$, $\eta_p^2 = .01$.

Completion time

No significant interaction for completion time was found, $F(1,18) = .242$, $p = .63$, $\eta_p^2 = .01$. In addition, no significant main effect of time, $F(1,18) = .026$, $p = .87$, $\eta_p^2 = .001$ or group, $F(1,18) = 2.33$, $p = .14$, $\eta_p^2 = .11$ was found.

Path length

No significant interaction for total path length was found, $F(1,18) = 1.13$, $p = .30$, $\eta_p^2 = .06$ but a significant main effect for time was revealed, $F(1,18) = 15.68$, $p = .001$, $\eta_p^2 = .47$ with total path lengths significantly longer for both groups at post-test (*M* = 249.26, *SD* = 52.83) than pre-test (*M* = 199.32, *SD* = 13.83). No main effect for group was found, $F(1,18) = .003$, $p = .96$, $\eta_p^2 = .001$.

RMSE

No significant interaction for RMSE was found, $F(1,18) = .97$, $p = .34$, $\eta_p^2 = .05$ but a significant main effect for time was found, $F(1,18) = 5.17$, $p = .04$, $\eta_p^2 = .22$ with RMSE significantly higher for both groups at post-test (*M* = 110.91, *SD* = 21.46) than pre-test (*M* = 98.02, *SD* = 9.20). No main effect for group was found, $F(1,18) = .140$, $p = .71$, $\eta_p^2 = .01$.

Peak a*cceleration*

No significant interaction was found for peak acceleration, $F(1,18) = .33$, $p = .57$, $\eta_p^2 = .02$ nor any main effects for time, $F(1,18) = 1.44$, $p = .24$, $\eta_p^2 = .07$, or group, $F(1,18) = 1.22$, $p = .28$, $\eta_p^2 = .06$.

Peak velocity

No significant interaction was found for peak velocity, $F(1,18) = .002$, $p = .96$, $\eta_p^2 = .001$ and no effect for time, $F(1,18) = .46$, $p = .50$, $\eta_p^2 = .02$, or group, $F(1,18) = 1.62$, $p = .22$, $\eta_p^2 = .08$.

Discussion

The aim of this study was to compare task performance and gaze behaviour of children with DCD and TD controls as they adapted to a novel visuomotor task. Analysis of the completion time, RMSE, total path length, peak acceleration, peak velocity, and gaze control dependent variables revealed no significant differences between children with DCD and their TD peers when performing the novel visuomotor task. Although these results are not supportive of the hypotheses, they may provide support for the findings from previous research that have also reported comparable levels of performance for children with and without DCD in tasks of lower complexity. In a comparison of DCD and age-matched TD children performing a reciprocal aiming task under discrete and cyclic conditions, Smits-Engelsman et al. (2003) found that both of their experimental groups did not differ in terms of response time and performed in a conventional manner according to Fitts' Law. They did find, however, that whilst DCD children produced minimal errors on the discrete aiming task, they made significantly more errors when performing the more complex cyclic task, in addition to producing faster endpoint velocities. Kagerer et al. (2004) found limited differences between DCD and TD children during exposure to a visuomotor rotation task that also extended to a lack of significant after-effects. In a follow up study examining the effect of abrupt and gradual exposure to visuomotor rotations, Kagerer et al. (2006) also found no significant differences between groups during exposure to the adaptation. In another visuomotor adaptation study, Cantin et al. (2007) found that children with DCD were able to learn and adapt to the constraints of a throwing task despite being more variable and less accurate than TD children. Furthermore, Cantin et al. (2014) also found no significant difference in performance between children with DCD and their TD peers using a simple visuomotor task but did identify differences when analysing performance on tasks of increasing complexity.

As previous research has described children with DCD as having a deficit in predictive control (Debrabant et al., 2013; Wilson et al., 2013; Sumner et al., 2018), it is of interest that both groups in this study performed on a similar level and adapted at a similar rate. Task complexity may therefore explain the lack of significant differences in performance observed in the present study. Using an interceptive task computer game, Candler and Meeuwsen (2002) identified a significant relationship between task complexity and implicit learning. The ability of children with DCD to learn effectively through implicit means has also been found for more complex tasks (Mombarg et al. 2013). Taken together, this evidence emphasises that, despite children with DCD being described as having a motor learning deficit (Schoemaker et al., 2015) and finding the acquisition of new skills difficult (Lejeune et al., 2016), task complexity and learning types are important factors. The novel visuomotor task used in this study was deemed complex in terms of requiring participants to produce forward estimates of cursor position in relation to target locations. The 180º x-axis reversal was intended to produce a scenario that created an initial over reliance on visual feedback whilst sensorimotor mapping rules were learned and developed. While this initial disruption to eye-hand coordination did occur, it would appear that the level of task complexity was not high enough to elicit behavioural differences such as those reported by other studies (e.g. Candler and Meeuwsen, 2002; Cantin et al., 2014). This is of interest as the novel visuomotor task described in the present study would seem to have at least an equal, if not higher, index of difficulty than the intermediate task utilised by Cantin et al. (2014) which required participants to guide a computerised spaceship towards planets using a joystick. Furthermore, the average age of the children with DCD in their study was 10.7 years, which is similar to the mean age of 9.7 years in the present study. The task used by Cantin et al. (2014) task did not incorporate any elements of visuomotor rotation and only manipulated the parameters of movement whereas the novel visuomotor task used in the current study required participants to adapt to new sensorimotor constraints. Taken together, these findings from the existing literature in this area would suggest that insufficient task complexity may be central to the lack of between groups differences recorded in this current study.

Incorporating physical practice into training in this study may also be a potential explanation for the quick and effective adaptation observed in both groups in this experiment as it could have allowed the sensorimotor mapping rules concerning the visuomotor workspace to be developed using sensorimotor feedback. If physical practice is to be used in a training study alongside observational learning techniques in order to elicit unintentional after-effects (Ong and Hodges, 2012) then a novel visuomotor task with a higher index of difficulty will have to be used.

The lack of any significant difference between groups in terms of eye-gaze behaviour underlines the importance of the relationship between task completion time and target locking score. The results of Study 1 describe how higher target locking scores were accurate predictors of faster task completion times and the same association has been identified here in so much as effective eye gaze behaviour facilitates optimal performance. In this study, participants in both groups were able to switch gaze strategies at a similar rate. Specifically, participants began with a bottom-up strategy, in which vision was used to supervise cursor movement, before shifting to a top-down control strategy where vision was employed in a proactive manner to lead movement of the cursor to the target. This is encouraging in terms of providing further evidence that children with DCD can acquire effective eye-gaze behaviours through training (Miles et al., 2015; Wood et al., 2017), and in a manner similar to that of TD children. This evidence also contributes to the existing body of literature suggesting that the characteristic movement impairments associated with DCD are not the result of specific deficits in low-level oculomotor processes (Sumner et al., 2018). Interventions that facilitate the acquisition of this optimised visuomotor behaviour could therefore prove to be beneficial for the acquisition of novel motor skills in children with DCD. Previous studies, however, have identified differences in gaze behaviour despite similar levels of task performance (Langaas et al., 1998). As target locking score is a ratio measure of fixation durations on different areas of interest, it does lack granularity compared to the techniques used in previous studies such as those comparing smooth pursuit performance of children with and without DCD (Langaas et al., 1998; Robert et al., 2014; Sumner et al., 2018). Furthermore, the eye tracking equipment used in this study samples at a rate of 60 Hz, which makes it unsuitable for the analysis of high-speed eye movements such as saccades, which have previously been used to identify differences in higher order oculomotor processes of children with and without DCD (Sumner et al., 2018).

Analysis of the baseline trials before and after the adaptation training yielded mixed results in identifying the presence of any unintentional after-effects. During the baseline pre-test, the DCD group produced slightly slower completion times, larger amounts of error, and longer paths than those of their TD peers. This does not appear to have hindered their ability to adapt to this particular task as analysis of the pre-test and post-test trials baseline trials also provides some indication of unintentional after-effects resulting from the adaptation training. Both the DCD and TD groups produced longer paths with increased error on the baseline post-test compared to the baseline pre-test which suggests both groups were affected by having to adapt to the visuomotor rotation. This appears to have had no significant impact on task completion time, however, suggesting the presence of one or more compensatory strategies. Overall, the results of the analysis for the presence of after-effects illustrate some influence of the adaptation training upon the internal modelling process for both groups that warrants further investigation.

In conclusion, the results from this study indicate that the novel visuomotor task used in this experiment may have lacked a level of task complexity sufficient to elicit significant differences in performance between children with and without DCD. Subsequently, this particular visuomotor task may therefore not be suitable for use in a training study that incorporates observational learning techniques and physical practice. The findings from this study, however, do contribute to the body of existing literature in this area querying the assertion that children with DCD cannot learn new motor skills at the same rate as their TD peers (e.g. Kagerer et al., 2004; Cantin et al., 2014). Furthermore, this study also provides further support for recent research that has identified the considerable effect of task complexity upon motor control and motor skill acquisition in children with DCD that can be used to inform the design of future studies in the area. The development of a more complex visuomotor task is discussed in the following chapter.

5. Study 3: The development of a novel and complex visuomotor task

Introduction

The findings discussed in Chapter 4 suggested that the novel visuomotor task used was not complex enough to reveal significant differences in performance between children with and without DCD. Specifically, although task performance and eye-hand coordination were initially affected, adequate adaptation occurred quickly (after 10 trials) for both groups of children. A slower rate of adaptation is desired for experimental purposes, especially if the task is to be used to measure performance in an intervention study (e.g., Ong and Hodges, 2012). If adaptation occurs too rapidly, it is difficult to assess how much can be ascribed to the intervention or how much has simply happened as the result of natural adaptive processes. With a more complex task, it would be possible to observe the natural rate of adaptation and the potential effects of an intervention.

A visuomotor task with a higher degree of complexity may have revealed significant between group differences in performance in Chapter 4. Task difficulty has previously been shown to affect the motor planning of children with DCD (Wilmut and Byrne, 2014; Adams et al., 2017) and their ability to perform motor imagery tasks, such as mental rotation (Williams et al., 2008; Noten et al., 2014; Reynolds et al., 2015). The difficulty of a task is also a factor for consideration when comparing visuomotor performance of children with and without the condition. For example, Chang and Yu (2010) compared the handwriting performance of young, Chinese speaking children both with and without DCD and found that, in terms of movement time, the performance of children with DCD was modulated by task complexity. Specifically, children with DCD used faster stroke velocities than their TD peers when writing simple Chinese characters that incorporated fewer strokes and turning points. In contrast, when writing complex Chinese characters that required a higher number of strokes and turns, the children with DCD produced slower stroke velocities. Cantin et al. (2014) also examined task difficulty as a factor in the performance of children with and without DCD and did so using a computer-based task, in which the goal was to guide a shuttle to a planet and land upon it. Task difficulty was manipulated by using three control schemes of differing complexity to guide the shuttle. The simple control scheme used a computer mouse with default settings to guide the shuttle and the intermediate control scheme used the same directional inputs but replaced the mouse with a joystick. The complex control scheme incorporated a novel controller very similar to that used by Sailer et al. (2005), in which forces and torques applied along the longitudinal axis of the device were used to control movement. They concluded that the initial visuomotor task performance of children with DCD was as fast and accurate as that of their TD peers on the simple and intermediate tasks but they were significantly slower and less accurate on the complex task. Furthermore, performance on the complex task was modulated by an interaction between motor ability and task difficulty. This suggests that both the simple and intermediate tasks were not difficult enough to differentiate between children with and without DCD. Although Cantin et al. (2014) considered the control scheme used for the intermediate task to be more complex than that used in the simple task, they only modified the parametric features of the interactive tool resulting in the visuomotor mapping rules required to control the shuttle remaining the same and thereby not adding a suitable level of additional complexity.

In order to produce a novel task of sufficient complexity for use with children with DCD, a new visuomotor rotation that affects movement on both axes may be suitable (Kagerer et al., 2004; 2006; Sailer et al., 2005). This may also produce characteristic movement patterns that can be replicated in an AO stimulus. For example, Roby-Brami and Burnod (1995) identified the emergence of spiralling cursor trajectories when using a computer mouse with a geometrical transformation applied. They concluded that these patterns of movement may evolve as the result of an adaptive process of online correction and similar spiralling or curved trajectories have been recorded in subsequent visuomotor adaptation research (e.g. Buch et al., 2003; Contreras-Vidal and Buch, 2003). Any such patterns of movement that may be produced during adaptation to the visual perturbation incorporated in a novel task may therefore provide the basis for suitable visual stimuli in a subsequent training intervention. With this in mind, it is desirable to test the efficacy of a new task with adults, as they are capable of verbally reporting detailed feedback regarding specific learning strategies and overall task difficulty.

Another design consideration for an updated novel visuomotor task is its potential for use as a measure of performance in an AO training intervention. In order to be suitable for use in an intervention, it is necessary to be able to use the task to generate visual stimuli that reflected skilled task performance. In the context of AOMI it is desirable to produce visual stimuli to be observed from a 1PP. Mental simulation from this perspective has been used in numerous studies due to the increased visual congruence between the observed action and physical performance (Holmes and Collins, 2001). There also is a substantial body of evidence supporting the use of AO stimuli delivered from a 1PP in visuomotor adaptation paradigms (Ong and Hodges, 2012; Lim et al., 2014; Lei et al., 2016). Previous visuomotor adaptation studies with DCD children have used novel visuomotor rotations of up to 60^{o} (Kagerer et al., 2004; 2006) and have found they have more difficulty adapting to gradual rotations of 10^{o} (Kagerer et al., 2006). When producing a video of a model performing gradual 10^{o} visuomotor transformations, however, in which the model's hand is also part of the visuospatial workspace, it is highly likely that cursor movements would be obscured by hand movements. This would likely impair the tracking of eye movements when gaze is directed toward the cursor during training.

An additional design concern for an updated novel visuomotor task is the need to address the potential confound of a sequence learning aspect. Task completion times may be affected by how effectively participants are able to learn the order of sequentially presented targets, rather than the speed and accuracy of their movements. In addition to this, performance may also be mediated by the efficiency of each participants' visual search in identifying the next target location. As sequence learning and visual search performance are not central to the research questions addressed in this thesis, these aspects must be considered as confounding variables and desirable to avoid.

There were two aims for this study: 1) to test the suitability of a novel visuomotor task in adults with a view to subsequently using it in an intervention study with DCD children; and 2) to identify specific movement characteristics that facilitate task performance that may then be used to support the development of an appropriate AOMI training stimulus. Based on the findings discussed in Chapter 4 and the literature described above, the new visuomotor task needed to meet three main design considerations: 1) the new task should feature a higher level of complexity; 2) it should not require a significant sequence learning aspect; and 3) it should be suitable for use in a 1PP AO intervention.

Methods

Participants

Thirty participants (15 male and 15 female; age *M* = 24.33, *SD* = 3.66 years) with normal or corrected-to-normal vision, volunteered to take part in the experiment. All participants were right-handed as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971) (see Appendix A). Participants gave their written informed consent prior to taking part and the experimental procedures were granted ethical approval by the local university ethics committee. Pilot testing was also performed with one 10-year old male TD child to check that the task was not overly difficult or frustrating to perform for younger participants.

Task

Participants performed an experimental task that was a further extension of the adapted virtual radial Fitt's task described in Chapters 3 and 4. For this new task, a 90^o counter-clockwise visual feedback rotation was used that resulted in stylus movements along the x-axis producing equivalent cursor movements along the y-axis and vice versa. This rotation affects both axes of movement and during pilot testing participants verbally reported the new 90^o visuomotor rotation to be harder to adapt to than the 180^o x-axis reversal used in the original task (Completion time for the 1st trial of the original task: 91.98 seconds; new task: 116.69 seconds). Learning the sensorimotor mapping rules for this particular rotation therefore was expected to take a longer period of visuomotor workspace exploration during which participants would seek to acquire the structural features of the task (Sailer et al., 2005).

In a similar manner to the experiments described in Chapters 3 and 4, the goal of the task was to use a stylus to guide a cursor out from a central home square to a yellow highlighted target square and then back to the central square (see Figure 19). Six targets were presented sequentially from left to right with the next target becoming highlighted each time the cursor returned to the central square. Based on a similar design used by Heremans et al. (2011), all the target positions were visible throughout the task in an arc radiating out at a distance of 170mm from the central square (see Figure 14). All six targets being successfully hit and the cursor returning to the central square represented one full trial of the task.

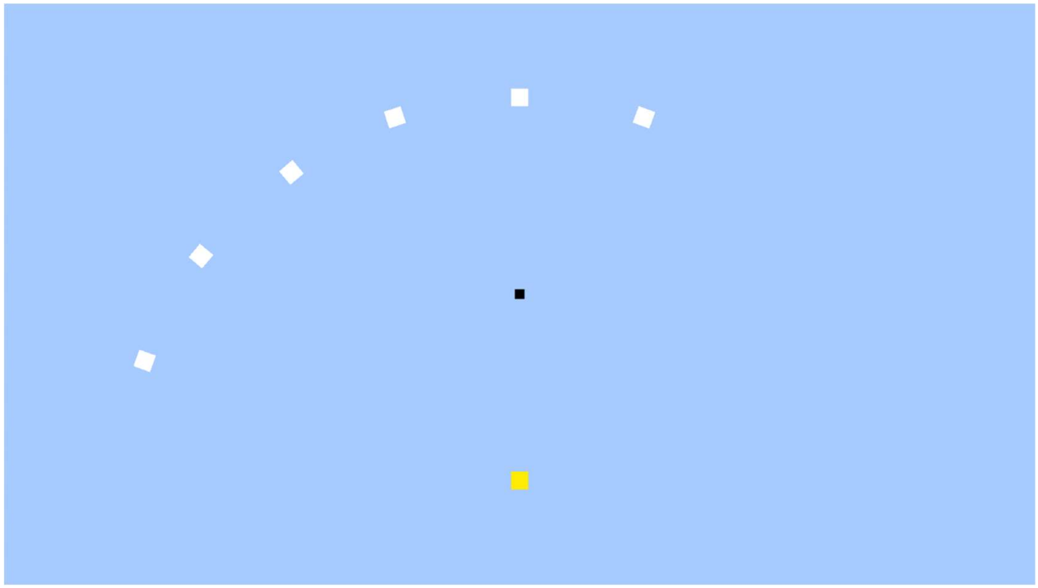


Figure 19. Diagram of the screen presentation of the experimental task.

Apparatus

Testing was performed using the same touchscreen monitor described in Chapter 3. The Unity3D game engine (Unity Technologies, San Francisco, CA) was used to produce and present the experimental task. This software was also used to collect data on the position of the cursor in both the x and y axes at a sampling rate of 80 Hz and record onset and termination of timing for the task.

Participants' eye movements were monitored using ETG 2w eye tracking glasses and iView ETG 2.7 software (SMI, Teltow, Germany) using the same procedure described in Chapter 3.

Procedure

Testing

All participants performed a familiarisation trial that consisted of guiding the cursor to hit three targets under the constraints of the 90º rotation. Following this, participants were then fitted with eye tracking glasses and performed a three-point calibration. Following calibration, participants immediately began the training intervention and gaze behaviour was recorded throughout.

Training protocol

Each participant performed five blocks of 10 trials of the experimental task. At the end of each block, participants were given a five-minute rest during which they completed sections of an in-house questionnaire designed to record information related to performance of the task (see Appendix C). Participants were asked to rate on a 7-item Likert scale the extent to which they were trying to perform the task as quickly and accurately as possible. During the rest period, participants were also asked to describe in their own words what they were trying to do and any strategies or techniques they were using in order to complete the task.

Measures

Performance

For each trial, total path length (cm), and RMSE (cm), were calculated using the same methods outlined in Chapter 4. Completion time was calculated as the time taken in seconds to hit all six outboard targets and return to the central starting square. RMSE was used as a measure of deviation from an ideal straight path between two points.

Gaze control

Analysis of the eye tracking data for each odd numbered trial (1 – 49, 25 trials in total) was performed using the same BeGaze 3.7 software (SMI, Teltow, Germany) as described in Chapter 3. This number of trials was selected for analysis based on time considerations and is consistent with other research in this area (e.g., Vine and Wilson, 2010; Vine et al., 2013). Targets were defined as the target and home squares. Fixations were defined as gaze dispersed over less than 3^{o} of visual angle for a minimum of 80 ms and a target locking measure was calculated using the methods described in Chapter 3.

Data analysis

Performance was quantified on a trial-by-trial basis for completion time, total path length, and RMSE for each participant. Target locking scores were calculated for each odd-numbered trial for all participants. Mean values for each dependent variable on each trial were also calculated. Paired samples t-tests were performed to compare the mean values for completion time, total path length, and RMSE on each trial to the mean value of the final three trials. For target locking score, paired t-tests were performed to compare the mean value of each trial to the 49th trial which was the final trial used in analysis. This method was chosen in order to identify a point of adaptation to the task at which no further significant differences in performance across the various dependent variables occurred.

Results

Performance

Completion time

Paired samples t-tests performed to compare the mean completion times for each trial in comparison to the average of the final three trials (*M* = 19.41s, *SD* = 5.58) revealed that improvements in completion time plateaued at trial 39 after which no further significant performance improvements were made, (*M* = 20.82, *SD* = 8.11) , t (29) = 1.62 , *p* = .12 (see Figure 20).

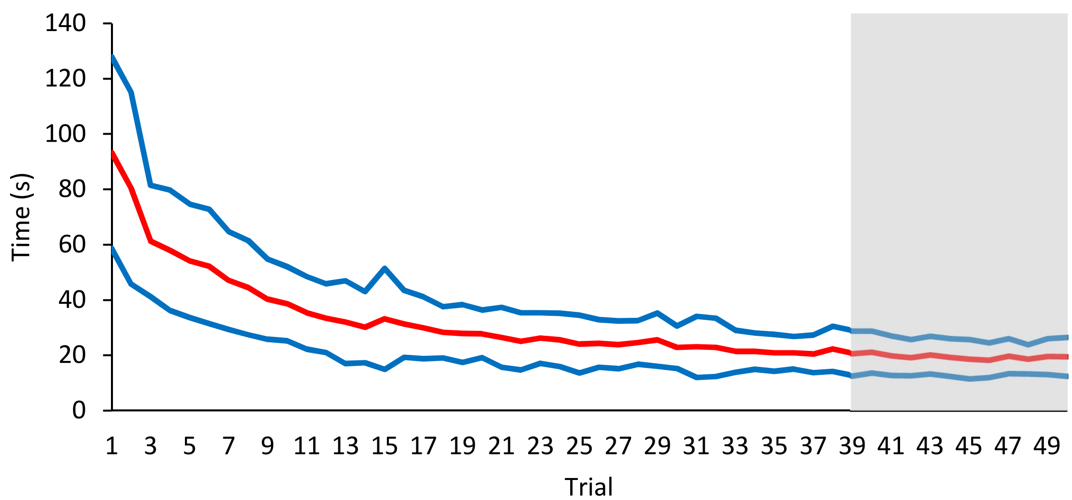


Figure 20. Red line indicates mean values per trial for completion time. Blue lines indicate SD. Shaded area indicates plateau.

Gaze control

The results of the paired samples t-tests performed on the mean target locking score data identified that improvements in target locking score in comparison to the 49th trial (*M* =

50.53, *SD* = 32.26) plateaued at trial 31 (*M* = 43.00, *SD* = 33.15) , t (28) = -1.57 , *p* = .127 after which no further significant improvements were made (see Figure 21).

Further analysis of the target locking data reveals that during the 50 trials, 77% of participants recorded target locking scores over 50% indicating a full target locking strategy (Wilson et al., 2011). Of the seven who did not record a score over 50%, three did score over 40%. The remaining four participants' highest target locking scores ranged between 3.13% and 25%. Of these participants, two were male and two female. Overall, there was a distinct pattern of higher target locking scores for participants with faster completion times with some exceptions. All seven participants whose highest target locking score was less than 50% were in the bottom eleven performers in terms of fastest completion time. One of these slower performers, however, did record a highest target locking score of 97.33%. Overall, the data are indicative of a relationship between higher target locking scores and faster task performance.

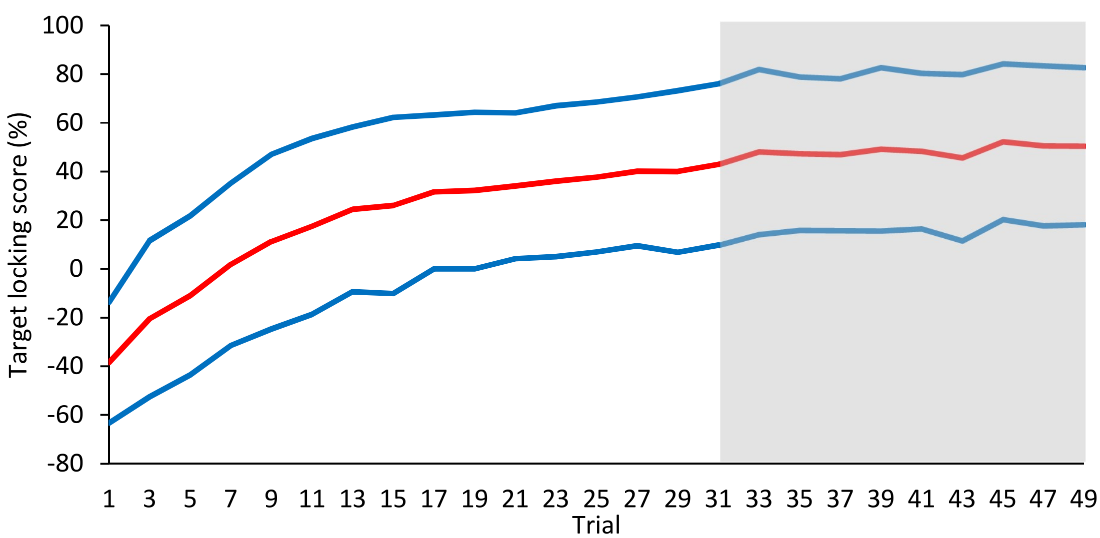


Figure 21. Red line indicates mean values per trial for target locking score. Blue lines indicate SD. Shaded area indicates plateau.

Total path length

The results of the paired samples t-tests performed to compare the mean total path length for each trial in comparison to the average of the last three trials (*M* =266.73, *SD* = 36.91) showed that significant improvements in the reduction of total path length plateaued at trial 21, (*M* = 270.85, *SD* = 49.32), t(29) = .53, *p* = .60 (see Figure 22).

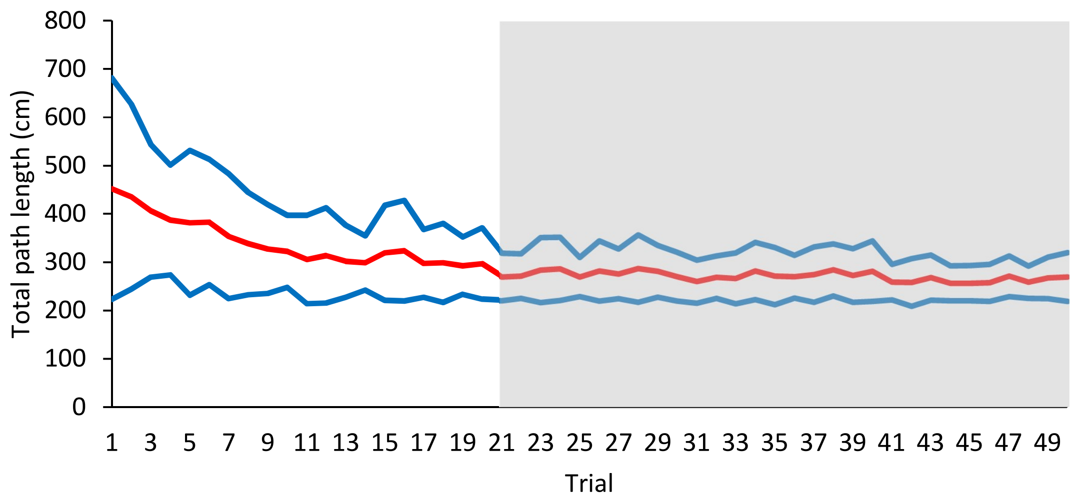


Figure 22. Red line indicates mean values per trial for total path length. Blue lines indicate SD. Shaded area indicates plateau.

RMSE

Paired samples t-tests performed to compare the mean RMSE for each trial to the average of the final three trials (*M* = 103.55, *SD* = 39.74) indicated that significant improvements in the reduction in RMSE plateaued at trial 21 (*M* = 107.37, *SD* = 55.53), t(29) = .56, *p* = .58 (see Figure 23).

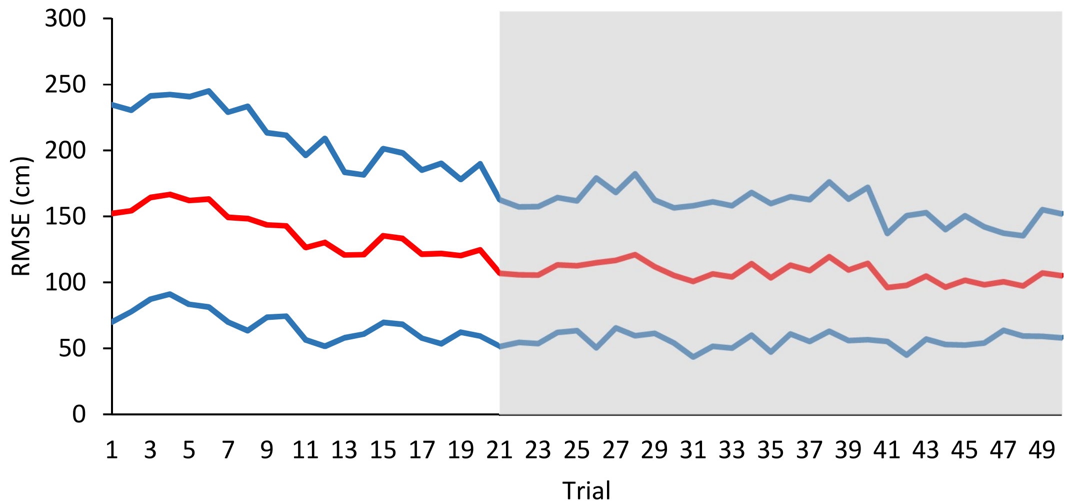


Figure 23. Red line indicates mean values per trial for RMSE. Blue lines indicate SD. Shaded area indicates plateau.

Movement patterns during initial trials

Plots of the cursor paths for all 50 trials for each of the 30 participants were produced using Matlab 2017b (MathWorks Inc, Natick, MA). Visual inspection of these plots reveals the presence of distinct movement patterns during the initial five trials that can be categorised into three groups: **angular**, **direct**, and **looping**. Due to the visuomotor rotation, each plot is rotated by 90^{o} and the axes are labelled to represent this.

Angular

This pattern was characterised by relatively straight vertical and horizontal lines in which the cursor is directed straight up until level with a target and then directed horizontally. The return path is either a reverse of this pattern or a downward movement of the cursor until level with the home target. Errors were often corrected by reversing back along the previous path using the same types of perpendicular movements (see Figure 24).

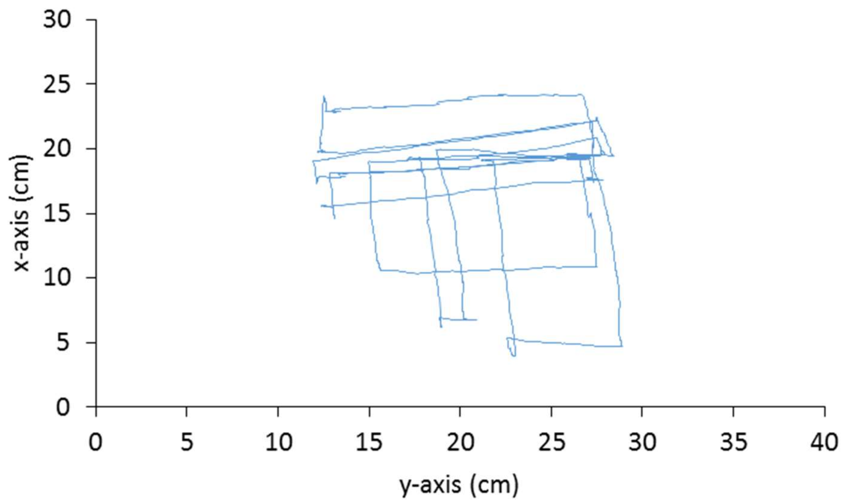


Figure 24. Plot of the cursor path for participant 1, trial 1.

Direct

In this movement pattern, the cursor path appeared to be moved directly towards each target at the cost of movement speed. Although the path was direct it was also accompanied by multiple, small, jittery movements as the cursor was moved in small increments and the course was constantly corrected (see Figure 25).

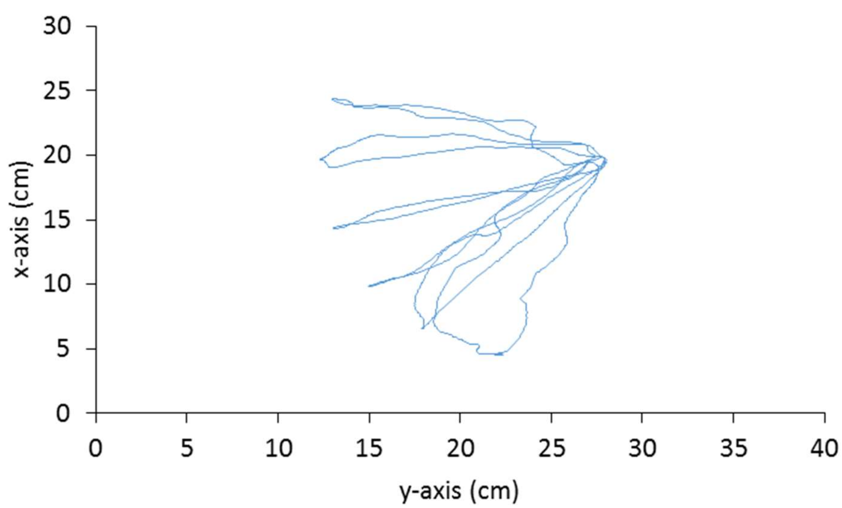


Figure 25. Plot of the cursor path for participant 28, trial 1.

Looping

This movement pattern was characterised by curved paths that passed directly through targets in large circles or spiral paths. These paths were long but were performed swiftly. Error corrections in this pattern manifested as smaller loops or spirals that continued along the original movement vector and reset the cursor position to a location approximate to that just prior to the error (see Figure 26).

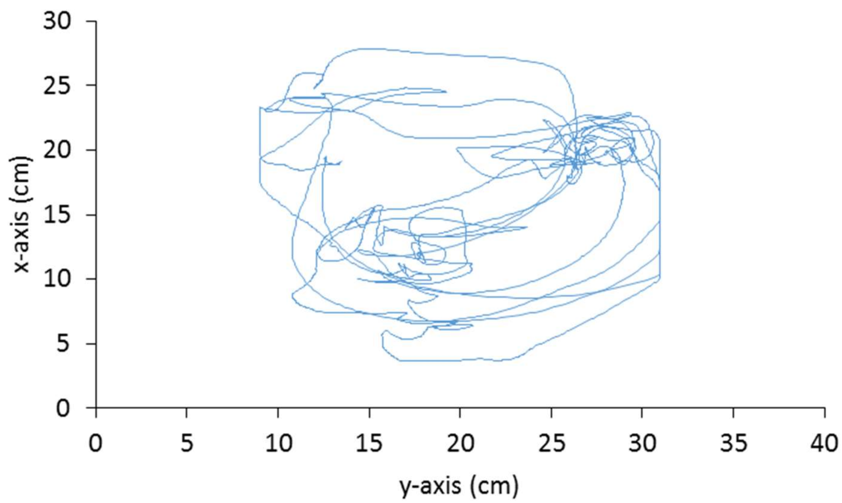


Figure 26. Plot of the cursor path for participant 2, trial 1.

Out of the 30 participants, 14 started by using the Angular movement pattern, eight used the Direct pattern, and 8 began with the Looping pattern. Over the duration of the training period, most participants abandoned the Angular and Direct patterns in favour of the Looping movement. Of the 14 participants who began with an Angular movement strategy, only five persisted with its use after the first seven trials and none of the eight participants who initially used the Direct strategy continued with it beyond trial five. During the 50 trials of training, 28 of the 30 participants eventually adopted the Looping strategy at some point.

Movement pattern progressions

As training progressed most participants adopted the Looping pattern within seven trials. This form of movement typically evolved gradually into one of two patterns with the majority of participants' fastest trials displaying these characteristics. These patterns may be indicative of progression through skill acquisition and skill refinement stages similar to those outlined by Sailer et al. (2005).

Direct and straight

This movement pattern was characterised by 'flattened loop' paths that formed almost direct straight lines to and from each target resulting in a 'hairpin' shape. In this pattern, errors were often still corrected by much smaller swift loop movements (see Figure 27).

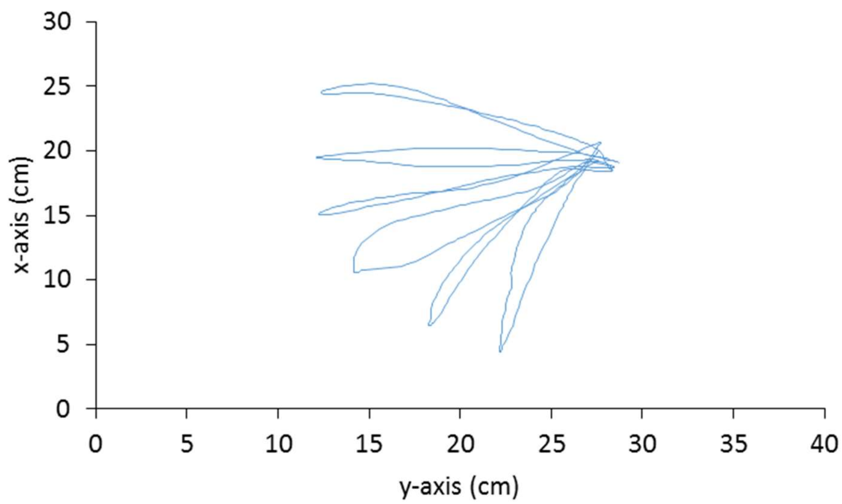


Figure 27. Plot of the cursor path for participant 15, trial 49.

Looping continuation

This pattern was characterised by large loops with long paths that were executed at a higher speed than earlier loops. In this pattern also, errors were still corrected using smaller swift loop movements (see Figure 28).

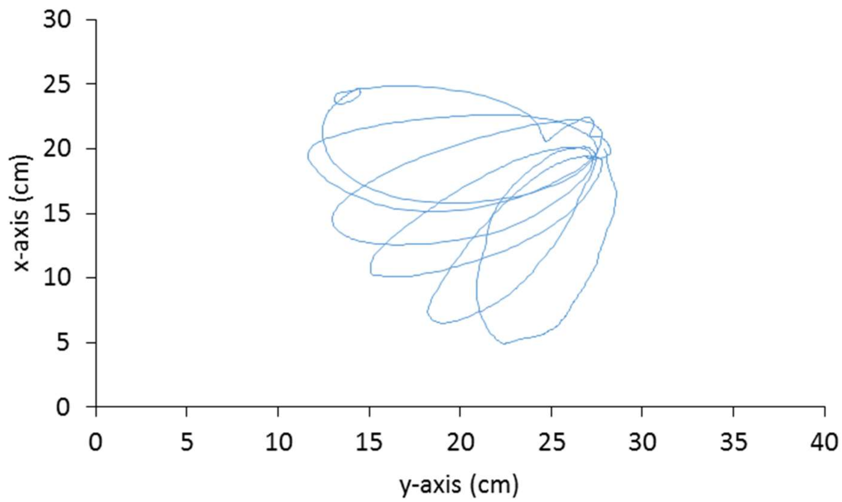


Figure 28. Plot of the cursor path for participant 18, trial 45.

Visual inspection of the cursor path plots for each participant's fastest trial revealed that 19 of the images exhibited the Looping continuation pattern, nine showed the Direct and straight pattern and two still showed Angular patterns.

Four participants were slower than others in adopting the Looping strategy and persisted with the Angular pattern until trial 35, 40, 44, and 50 respectively. Three of the four participants that persisted with the Angular pattern were the three worst performers in terms of completion time and only one of the four recorded a highest TL score over 50%. The majority of participants with faster completion times that started with the Angular strategy had abandoned the pattern after seven trials. In contrast, however, one of the top seven fastest performers persisted with the Angular pattern until trial 15 and one of the four slowest performers abandoned the strategy within five trials.

This provides a strong indication that using the Looping pattern and its subsequent refinement was the most effective strategy for completing the task as quickly as possible (see Figure 29). Similar looping patterns have been observed in other studies and may be the result of rapid online correction (Roby-Brami and Burnod, 1995; Buch et al., 2003; Contreras-Vidal and Buch, 2003).

Participant 23

Trial 1	Trial 11	Trial 21	Trial 31	Trial 41
114.92 s	24.34 s	17.15 s	17.32 s	15.52 s

Participant 22

Trial 1	Trial 11	Trial 21	Trial 31	Trial 41
159.61 s	56.59 s	61.05 s	65.22 s	40.72 s

Figure 29. Cursor paths and respective completion times in seconds produced by two participants during training (plots are rotated by 90^{o}). Participant 23 used the Looping strategy in trial 1, participant 22 used the Angular strategy.

Discussion

The aim of this study was to develop a novel visuomotor task with a higher level of task difficulty that would take longer for participants to adapt to and potentially provide a useful training stimulus for an AOMI intervention for children with DCD. Data analysis revealed that completion times plateaued after 39 trials whilst target locking scores did so after 31 trials. Total path length and RMSE were found to plateau after trial 21. Furthermore, analysis of the cursor paths for each trial revealed the manifestation and evolution of distinct movement patterns that facilitated optimal task performance.

The point of optimal movement strategy selection appears to precede the peak for target locking score, which in turn leads peak task completion time. During early trials in which the novel visuomotor constraints of the workspace were being explored through sensorimotor feedback, gaze was likely being used to provide visual feedback of the cursor's movements in relation to hand movement (Sailer et al., 2005). Once a movement pattern that yielded preferred performance results was settled upon, attentional resources may have been required less for ongoing supervision of cursor movement. Through a combination of visual and kinaesthetic feedback, an internalised model of the visuospatial space may have been developed and appropriate movements based on the parameters of the visuospatial environment were selected (Land et al., 2009). The coupling between eye and hand movements, in which gaze leads the hand, steadily improved as gaze may no longer have been required primarily for feedback but instead could be directed to targets and peak task performance was then attained. Analysis of the target locking data indicated that mean target locking scores reached a plateau at trial 31, a few trials before the same occurred for completion time at trial 39, after which point 80% of participants produced their fastest task completion time. Target locking scores plateauing just before completion time could be interpreted as evidence of when the optimal gaze strategy or ratio of target to cursor fixation duration was acquired. At this point, peripheral vision may have provided sufficient information to further refine hand movement control (Sailer et al., 2005). The combined results of the first two studies in this thesis illustrate that improvements in target locking are a reliable predictor of decreases in task completion time and therefore support the need for techniques that may improve the rate at which effective gaze is acquired during novel motor skill learning. Furthermore, the findings of the current study may suggest that if a participant was provided with visual cues supporting the early adoption of the Looping strategy prior to performing this particular novel visuomotor task then this could facilitate the earlier acquisition of optimal proactive eye movements and subsequently enhance task performance.

Task completion time and target locking score both reaching a plateau of performance improvement following trial 39 indicates that the visuomotor task used in the current study requires a longer period of exposure before adaptation occurs, compared to the 10 trials needed in Chapter 4. Participants required on average over 90 seconds to complete the first trial and 24 of the 30 participants produced their fastest task completion time during the final 10 trials of training. This new visuomotor task may have taken longer to adapt to than the task used in Chapter 4 because of the relationship between cursor and hand movement being much less obvious. In the experiments described in Chapters 3 and 4, cursor movement along the x-axis was able to be mapped directly to hand movements in the opposite direction and subsequently used to provide forward estimates of cursor position. In this study, the relationship between cursor and hand movement was less explicit and required a much longer period of exploration before sensorimotor mapping rules could be developed effectively (Sailer et al., 2005). The verbal reports collected from several participants following each block of ten trials indicated that the first ten-trial phase of training was often used to try to understand the relationship between hand and cursor movement (as outlined below):

> *'I was trying to be systematic at first.' (Participant (P) 21)*
>
> *'My first go was a practice. I wanted to work out how it responded.' (P25)*
>
> *'I'm taking my time. I'm trying to think about what to do when changing direction. Trying to figure out what the other directions are.' (P5)*
>
> *'I tried using the first few seconds to work out the movement.' (P11)*
>
> *'When I get nearer the squares I try to work out which way I have to go.' (P15)*
>
> *'I tried to work out the pattern and curved trajectories seemed to work better.' (P18)*

Partial evidence of this can be seen in the RMSE and total path length findings as the participants explored the structural features of the task using a variety of movement strategies before refining their visuomotor map of the novel workspace. RMSE and total path length both reaching a plateau at trial 21 could be evidence of participants abandoning earlier exploratory movement patterns and committing to a single strategy for producing the best possible completion times, which in this case, appeared to be the Looping continuation strategy. Visual inspection of the cursor paths for each trial for each participant showed that this type of movement was not actually selected by most participants and instead, the majority employed longer looping or spiralling paths. Both RMSE and total path length scores were therefore unlikely to reach a particularly low threshold but instead plateau at a point of movement pattern optimisation. Visual inspection of the cursor paths for each trial revealed that all but five participants in the current study began incorporating Looping movements within the first seven trials and so this plateau may be indicative of a point at which other experimental or exploratory strategies were abandoned and an optimised movement pattern was fully adopted.

An aim of this study was to identify specific patterns of movement that were adopted by participants to facilitate performance. Three distinct patterns were observed during the initial training trials (Angular, Looping, and Direct), which were then refined as training progressed. Sailer et al. (2005) identified that as participants learned to adapt to a novel visuomotor task they progressed through exploratory, skill acquisition, and skill refinement stages. The presence of three distinct movement strategies during the initial trials may be evidence of the exploratory stage in which participants attempted to establish a relationship between motor commands and their sensory consequences. Of the three initial patterns, only the Looping strategy was later adopted by almost every participant and furthermore, refinements of this pattern also produced the best results in terms of task completion time. This selection and refinement process may indicate progression through skill acquisition and refinement stages in which gaze becomes proactive as the result of learning spatially congruent eye and hand motor commands (Sailer et al., 2005).

The success of the Looping movement pattern may have been because it placed an emphasis on an external focus of attention, which has been previously shown to be beneficial during early skill acquisition (Wulf et al., 2010a; Wulf et al., 2010b). Participants who used the Looping strategy described a process of not thinking about the process behind their movements (*'Trying not to think about it. I'm watching the cursor to see what it does next, I'm not really trying to figure it out' (P6); 'I guess I'm trying to look more at the square and trust that my hand is going to get the cursor into position' (P13)*).

The verbal feedback collected from participants who used the Angular strategy indicated that their adaptation process also tended to involve a significant verbal component in an attempt to explicitly commit the visuomotor rotation rules to memory (*'I kept trying to remind myself left is up, right is down…' (P16); 'I'm giving myself a reminder of the directions each time at the start.' (P17)*). This may have placed heavier demands on cognitive resources, as evidenced by an increased reliance on vision to monitor cursor movements. Using vision in a supervisory capacity has previously been suggested to represent conscious movement control (Land et al., 1999). There is an indication of this in the presence of perpendicular 90^{o} cursor paths in which cursor movement along one axis may have been more easily understood in relation to hand movement as participants used their movements to try and directly map the rules of the workspace to their own motor input. Each of these components could be indicative of an internal focus of attention, resulting in attempts at conscious control that constrained the motor system (Wulf et al., 2001). As a potential consequence of constantly referring to a set of explicitly created visuomotor rules, participants using this strategy may have resorted to bottom-up visual processing in which attentional resources were devoted to regularly checking the position and state of the cursor in relation to the targets, disrupting movement automaticity (Wulf et al., 2001). When errors were made using the Angular strategy, the visuomotor map may have had to be explicitly consulted before the appropriate corrective movement could be selected and executed. In contrast, when errors were made by those utilising the Looping strategy, a quick loop was performed to return the cursor to its previous position before the erroneous movement was made and another attempt was executed. By correcting errors in this way, participants may have adopted an external focus of attention and were able to remove the explicit component of associating cursor movement with that of the hand and instead focused mainly on the cursor's trajectory and endpoints. Future research using EEG techniques could be performed to further explore the comparative cognitive workloads of these movement strategies and their associated error correction models.

By potentially adopting an external focus of attention, participants may have implicitly been able to learn the rules governing the visuomotor workspace and update their internal model (*'Drawing circles is helping but I'm not sure why! I don't know the rule yet.' (P9)*). In turn, this may have allowed the use of a top-down form of visual processing in which attentional resources were directed more towards target locations, facilitating movement automaticity and faster task performance (Wulf et al., 2001; Zachry et al., 2005). There is some indication of this in participants refining the Looping strategy into the Looping continuation pattern that more accurately intersected target locations with fewer errors. Furthermore, some participants refined this pattern even further into a direct and straight pattern incorporating almost straight lines between targets, which could potentially be indicative of a high level of adaptation.

In summary, the aims of this study were to: 1) develop the complex novel visuomotor task used in Chapters 3 and 4 into a more complex and challenging version; 2) identify movement characteristics that could be used to support the development of an appropriate AOMI training stimulus. By incorporating a visuomotor rotation that could not immediately be mapped to hand movements, this new task required more than 30 trials before task performance plateaued and therefore would appear to be suitably complex enough for use in an intervention study with DCD children (Cantin et al., 2014). Furthermore, the manifestation of a specific pattern of movement adopted by the majority of participants could provide the basis of an observational learning stimulus that induces an external focus of attention and facilitates motor learning. The examination of an AOMI intervention for children with DCD incorporating this novel visuomotor task is discussed in the following chapter.

6. Study 4: Combined action observation and motor imagery improves eye-hand coordination in children with DCD

Introduction

A number of therapeutic approaches exist for the treatment of DCD, such as neuromotor task training (Ferguson et al., 2013), cognitive orientation to daily occupational performance (CO-OP) (Barnhart et al., 2003), quiet eye (QE) training (Miles et al., 2015; Wood et al., 2017), and MI training (Wilson et al., 2002; 2016). Neuromotor task training features a task-oriented approach, drawing upon motor learning theory, in which therapists use cognitive strategies (such as reducing fear, increasing motivation, and improving motor control processes through parameter setting) to address motor problems (Ferguson et al., 2013). In a similar fashion, CO-OP draws on cognitive-behavioural methods to establish a top-down problem-solving system for skill acquisition. Using this technique, children are encouraged to identify how to approach a movement task, plan its implementation, and subsequently reflect upon their performance (Barnhart et al., 2003). In contrast, QE training adopts a process-oriented approach that uses a measure of optimal visual control, termed quiet eye (Vickers, 1996; 2007), to improve visuomotor skills by instructing children with DCD where to direct their gaze during performance of a motor task. This method has been shown to improve catching technique in children with DCD (Miles et al., 2015). Furthermore, this type of training, when administered in group-based settings, has also been demonstrated to positively impact parents' perceptions of their children's motor ability and other psychosocial aspects such as confidence, social skills, and engagement in physical activity (Wood et al., 2017).

Another intervention that has been shown to help children with DCD is MI training. MI is the process of mentally rehearsing an action with the absence of any overt physical movement (Jeannerod, 2006). While MI training has been shown to be an effective intervention for producing positive behavioural outcomes related to DCD (e.g., Wilson et al., 2002; 2016), very few studies exploring the use of this particular technique exist and none have incorporated any specific process measures related to eye-hand coordination. This may be in part due to a considerable body of research that associates DCD with a diminished ability to perform imagery in the form of mental rotation tasks (Wilson et al., 2004; Williams et al., 2008; Deconinck et al., 2009; Noten et al., 2014).

Deficits in MI ability can be seen as evidence of the IMD hypothesis. This states that the motor control issues associated with DCD are the result of impaired predictive motor control stemming from disrupted cognitive representations of movement (Wilson et al., 2013). Although impaired imagery ability characteristics are also associated with a decreased potential to benefit from MI training (Robin et al., 2007), there is evidence to support the use of such interventions for children with DCD (Wilson et al., 2002; 2016; Adams et al., 2017).

AO has also been shown to provide a positive contribution to motor skill performance in populations with similar neurodevelopmental disorders, such as cerebral palsy (Buccino et al., 2012; 2018; Sgandurra et al., 2013). Taken together these findings are encouraging and would seem to provide a rationale for the use of mental simulation processes in the functional rehabilitation of children with movement disorders. Interestingly, despite each of the studies conducted by Wilson et al. (2002; 2016) incorporating AO followed by MI practice into their respective training protocols, no study has yet examined the use of AO and concurrent MI for training motor skills in children with DCD.

The findings from Chapter 3 indicated that AOMI was an effective AO condition for facilitating a shift to a proactive pattern of eye-hand coordination that enhanced task performance. The aim of this experiment therefore was to examine the effects of an AOMI training intervention on eye-hand coordination and visuomotor adaptation on children with DCD. To achieve this aim, the task performance and eye gaze behaviour of two groups of children with DCD were recorded as they trained on the novel visuomotor task described in Chapter 5. Previous research in this area with DCD children has produced equivocal results but each has identified deficits in predictive motor control and a reliance on slower feedback control, resulting in slower task performance, increased jerk, and poor perceptual-motor coupling (Kagerer et al., 2004; 2006). Several studies have indicated that observational learning can facilitate adaptation to novel visuomotor rotations in typical populations (Mattar and Gribble, 2005; Ong and Hodges, 2010; Ong et al., 2012; Lim et al., 2014; Lei et al., 2016) but none has attempted to do so with children with DCD.

I hypothesised that AOMI training would produce a significant improvement in visuomotor adaptation in terms of task performance. I also hypothesised that this performance improvement would be supported by the development of a pattern of optimised eye gaze behaviour in which attention is directed to the next intended target as opposed to being focused on the movement of the cursor. It was also predicted that AOMI training would produce significant after-effects for completion time, path length, RMSE, and target locking score when participants repeated the task in a normal visuomotor environment.

Methods

Participants

Twenty children aged 7 to 11 years with confirmed or suspected DCD participated in this study (13 male, 7 female; age *M* = 9.0, *SD* = 1.45 years). The number of participants recruited was selected to be comparable to that of similar studies of visuomotor adaptation and DCD (Kagerer et al., 2004; 2006). Each child had normal or corrected-to-normal vision. Participants were recruited through local dyspraxia and DCD support groups. Potential participants were screened using the DCDQ (Wilson et al., 2007) (see Appendix B). Participants with potential DCD were invited to a testing session if they scored within the recommended range of 15-55 on this questionnaire, did not attend a specialist school or have a formal diagnosis of learning difficulties or ADHD, and did not suffer from any other general medical condition known to affect sensorimotor function (e.g., cerebral palsy, hemiplegia, or muscular dystrophy). Parents and children provided written informed consent and assent respectively prior to taking part and the experimental procedures were granted ethical approval by the local ethics committee.

At the start of the laboratory session participants first completed the MABC-2 (Henderson et al., 2007) in order to provide a quantitative assessment of each child’s motor skills as outlined in Chapter 4. Only children who scored at or below the 5th percentile on the MABC-2 were asked to take part in the study as previous research has suggested MI training can produce greater performance improvements for those with more severe DCD symptoms (Wilson et al., 2016).

Task

The 90° visuomotor task described in the method section of Chapter 5 was used in this experiment (see Figure 19 in Chapter 5).

Apparatus

Testing was performed using the same touchscreen monitor described in Chapter 3. The Unity3D (Unity Technologies, San Francisco, CA) software used to present the experimental task was also used to collect data on the position of the cursor in both the x and y axes at a sampling rate of 80 Hz and record onset and termination of timing for the task.

The same SMI ETG 2w eye tracking glasses and iView ETG 2.7 software (SMI, Teltow, Germany) used in each of the previous studies was also used in this experiment (see Chapter 3). As in Chapter 4, the eye-tracking equipment was calibrated in this study using a 1-point calibration prior to each physical trial. Eye-tracking data were recorded throughout each physical trial of the pre-test baseline, pre-test, training, post-test and post-test baseline phases of the experiment.

Procedure

Familiarisation

All participants performed two practice trials of the task, with no visuomotor rotation applied, to familiarise them with the visual characteristics and goal of the task. At this point participants were then fitted with the eye-tracking glasses and performed the calibration procedure.

Pre-test baseline

Following familiarisation, participants performed three pre-test baseline trials of the task with no visuomotor rotation applied. Participants were instructed to perform the task as quickly and accurately as possible on each trial.

Pre-test

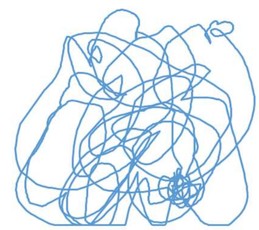
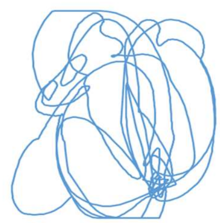
Once participants had completed their practice trials, they then performed one trial of the task with the 90° visuomotor rotation applied. Prior to starting this trial, participants were informed that, although the task looked the same and still had the same goal, the cursor would move differently. Each participant was given a maximum of three minutes to hit all of the presented targets. If all the targets had not been hit during this time, 180 seconds was recorded as the trial completion time along with the number of targets successfully hit. Of the 20 participants, 14 reached the 180 second limit on the pre-test (M = 164.85, SD = 26.61). The three-minute maximum allowed for some control over the amount of exposure participants had to the novel visuomotor environment prior to training. This rule also applied to each physical practice trial throughout the training phase. Immediately after completing the baseline test, participants started the training intervention to which they had been randomly assigned.

Training interventions

AOMI group. Participants in the AOMI group (six male, four female; age M = 9.0, SD = 1.56 years) performed MI of executing the task as they watched a series of videos of a novice performer completing the same visuomotor task. The video series consisted of three videos recorded at different stages of the novices' learning experience as they performed 50 trials of the task as per the method outlined in Chapter 5. These stages were determined based on the number of trials completed by the novice performer and were identified as: Early (trials 1 to 10), Mid (trials 11 to 30), and Late (trials 31 to 50). Each video was selected to represent the natural progression of looping movements described in Chapter 5 as the novice performer became more accomplished at the task. This strategy yielded the best results for task performance and target locking score in Chapter 5 and MI theory has suggested that MI should reflect a learner's level of experience (Holmes and Collins, 2001) whilst visuomotor adaptation studies using observational learning have also used videos which show progressive changes in performance (Lei et al., 2016). Each video was filmed from the same 1PP using a static camera mounted at head height and showed only the touchscreen monitor and the novice performer's hand moving the stylus over the screen in order to guide the cursor to each target (see Figure 30). At the start of each video, a MI script was presented in written form on the screen along with a recorded narration. This script was slightly different for each video in order to reflect the adaptations made by the novice performer as their training progressed (see Table 2).

Table 2.

AOMI instructions and plotted paths of the observed cursor movement for each training stage.

Stage	Instructions	Plotted cursor path
Early	"I am watching the video on the screen. The hand in the video is mine and I am making the movements that I see. I can feel myself holding the pen and I can feel my arm and hand moving the cursor to the yellow squares"	
Mid	"I am watching the video on the screen. The hand in the video is mine and I am making the movements that I see. I can feel myself holding the pen and I can feel my arm and hand moving the cursor in circles towards the yellow squares"	
Late	"I am watching the video on the screen. The hand in the video is mine and I am making the movements that I see. My movements are steady and accurate. I can feel myself holding the pen and I can feel my arm and hand moving the cursor in oval patterns towards the yellow squares"	

After every AOMI trial, participants then immediately performed a physical practice trial as previous research has suggested that observational learning alone is not enough to update an internal model of the visuomotor environment and at least some amount of physical practice is required (Ong and Hodges, 2010; 2012; Lim et al., 2014; Lei et al., 2016).

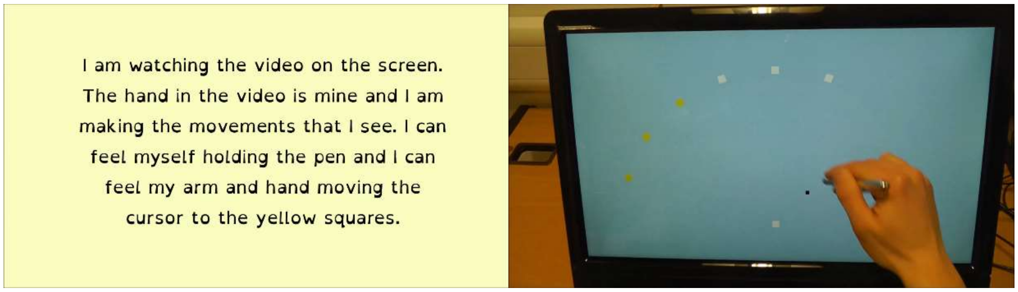


Figure 30. Left hand image shows MI instructions for the Early stage presented prior to the AO stimulus. Right hand image shows a frame from the Early stage video.

Training was split into three blocks of seven AOMI and immediate physical practice trials, with each block using a different AOMI video (see Figure 31). Rest periods were given after every block and the eye-tracking equipment was recalibrated before the start of each trial.

Control group. Participants in the control group (seven male, three female; age *M* = 9.0, *SD* = 1.41 years) watched 42 second clips of a nature documentary (Buccino et al., 2012) followed by an immediate physical practice trial. The duration of video clips was chosen in order to represent a total time that was equivalent to the total of the AOMI videos. These trials were also divided into three blocks of seven video and immediate physical practice trials and in total, participants in this group physically performed 21 trials of the task (see Figure 31). Rest periods were also given after every block and the eye-tracking equipment was recalibrated before the start of each trial.

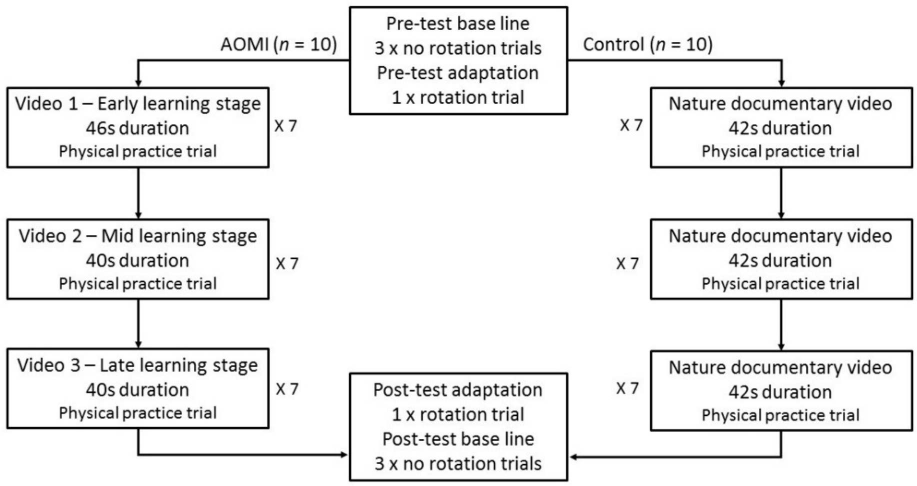


Figure 31. Flow diagram outlining testing procedures and intervention schedule for both the AOMI and control groups.

Post-test

Each participant completed a final rotation trial as a post-test.

Post-test baseline

Following completion of the post-test, participants immediately performed three trials of the task with no visuomotor rotation as outlined in the baseline pre-test in order to assess the presence of any after-effects. After this was completed, participants and their parents were debriefed and thanked for their participation.

Measures

Performance

For each trial, total path length (cm), peak acceleration (cm/s^2), and peak velocity (cm/s) were calculated using the same methods described in Chapter 4. Completion time was calculated as the time taken in seconds to hit all six outboard targets and return to the central starting square.

Gaze control

Each baseline, pre-test, and post-test trial for each participant were analysed using the same BeGaze 3.7 software (SMI, Teltow, Germany) described in Chapter 3. In addition, the 1st, 3rd, 5th, and 7th trials from each training block were also analysed. This number of trials were selected for analysis based on time considerations and is consistent with similar research in this area (e.g., Vine and Wilson, 2010; Vine et al., 2013). Targets were defined as the six outboard target squares and the central home square. Fixations were defined as gaze dispersed over less than 3^{o} of visual angle for a minimum of 80 ms and a target locking measure was calculated using the methods described in Chapter 3.

Data analysis

Preliminary analyses

As preliminary analyses, participants' pre-test performance data was analysed using independent sample t-tests to check for any pre-test differences between groups for completion time, mean total path length, mean peak acceleration, mean peak velocity, and gaze control.

Main analyses

For the main analyses of the data, 2 (Group: AOMI, control) x 5 (Time: Pre-test, Block 1, Block 2, Block 3, Post-test) ANOVAs were performed on participants' completion time, mean total path length, mean peak acceleration, mean peak velocity, time to peak acceleration, time to peak velocity, and gaze control data.

To assess the presence of after-effects following the adaptation training, 2 (Group: AOMI, control) x 2 (Baseline pre-test, baseline post-test) ANOVAs were conducted using the mean value of the three average pre-test baseline trials and the first post-test baseline trial (Kagerer et al., 2006). Where sphericity was violated, Greenhouse-Geisser corrections were used. All significant effects are reported at an alpha value of 0.05. Effect sizes are reported as partial eta squared (ηp^2).

Results

Preliminary analyses

The results of the independent sample t-tests revealed no significant differences at pre-test for completion time (t(18) = -.39, p = .70), mean total path length (t(17) = -.53, p = .61), mean peak acceleration (t(18) = .28, p = .78), mean peak velocity (t(18) = .06, p = .95) or gaze control (t(17) = .91, p = .38). Furthermore, no significant differences were found for the mean age of participants between groups (t(18) = .001, p = 1.00). These analyses indicated that all groups were of the same level of performance at pre-test.

Main analyses

Due to the data for completion time, mean total path length, and mean peak acceleration and velocity not meeting the equality of variances assumption, these variables were log transformed for use in the following data analyses.

Performance

Completion time

A significant effect for time, $F(2.49, 44.87) = 147.86$, $p < .001$, $\eta_p^2 = 0.89$, and group, $F(1,18) = 11.26$, $p = .004$, $\eta_p^2 = 0.39$, indicated that both groups completed the task significantly faster at post-test compared to pre-test. A significant interaction, $F(2.49, 44.87) = 3.55$, $p = .03$, $\eta_p^2 = 0.16$, was found for completion time, indicating that the AOMI group was the faster of the two groups at post-test. Independent sample t-tests revealed that the AOMI group produced significantly faster completion times than the control group at block 2 (p = .003), block 3 (p = .011) and post-test (p = .008) (see Figure 32). Figure 33 visually illustrates an example of the difference in completion times and cursor paths between the two groups throughout the study. Each of these example participants used a movement strategy that was characteristic of those used by other members of their group. The use of curved, looping movements in this case appears to be associated with faster task completion.

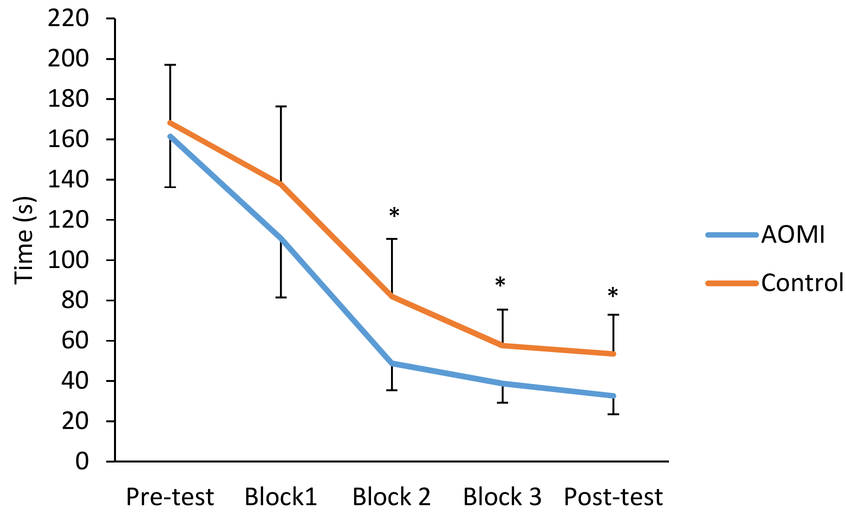


Figure 32. Mean completion times for AOMI and control groups at pre-test, block 1, block 2, block 3, and post-test. Error bars indicate SD. * indicates significant difference between groups ($p < .01$).

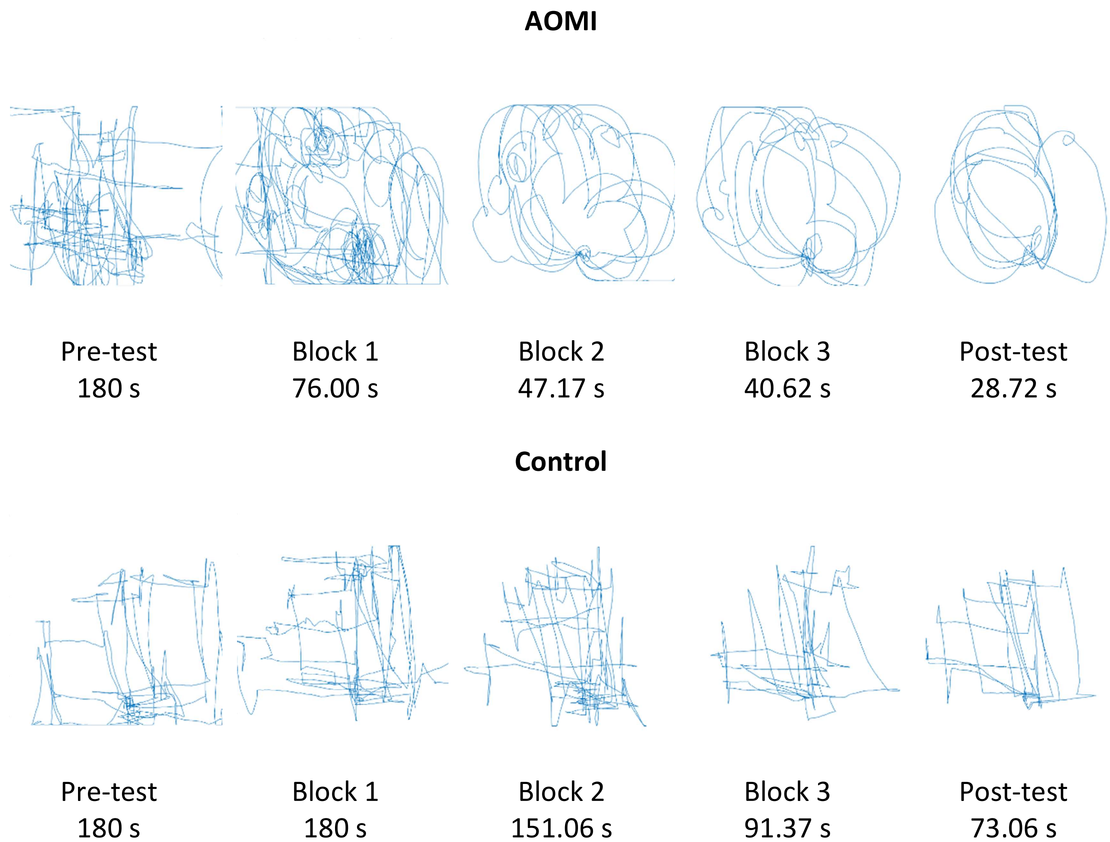


Figure 33. Cursor paths and respective completion times in seconds produced by two participants during the AOMI and control training interventions.

Total path length

Data for one participant in the AOMI group were removed prior to analysis as their total path length at pre-test was 7.8 times longer than the mean of the group as the result of a technical issue with the touchscreen and stylus. A significant effect for time, $F(1.94, 33.01) = 12.53$, $p < .001$, $\eta_p^2 = 0.42$, was found for mean total path length, which indicates that both groups produced shorter paths as training progressed. No significant main effect for group, $F(1, 17) = 3.91$, $p = .06$, $\eta_p^2 = .19$ or interaction, $F(1.94, 33.01) = 2.65$, $p = .09$, $\eta_p^2 = .13$ was found (see Figure 34).

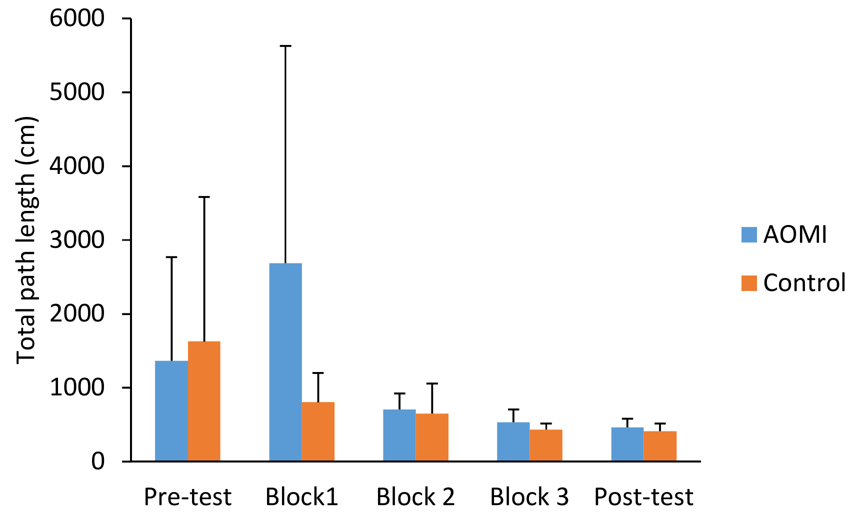


Figure 34. Mean total path length for AOMI and control groups at pre-test, block 1, block 2, block 3, and post-test. Error bars indicate SD.

Mean peak acceleration

A significant main effect for time, $F(1.54, 27.81) = 7.24$, $p < .001$, $\eta_p^2 = .29$, was found indicating that participants in both groups produced significantly lower peak accelerations at post-test ($M = 809.82$, $SD = 316.53$) than at pre-test ($M = 1405.84$, $SD = 728.70$). Pairwise comparisons showed that a significant improvement occurred from pre-test to block 2 ($p = .02$) and pre-test to block 3 ($p = .01$). However, no significant main effect for group, $F(1,18) = 1.45$, $p = .24$, $\eta_p^2 = .07$, or interaction, $F(1.54, 27.81) = 1.20$, $p = .30$, $\eta_p^2 = .06$, was found (see Figure 35).

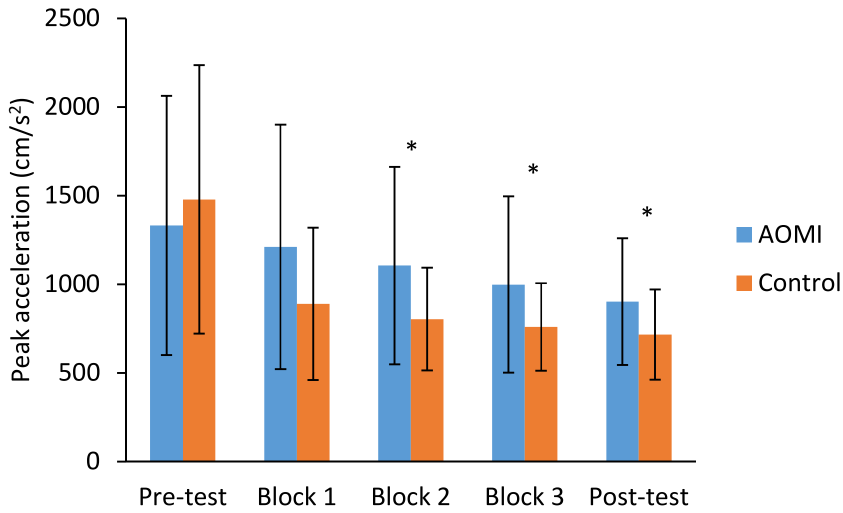


Figure 35. Mean peak acceleration for AOMI and control groups at pre-test, block 1, block 2, block 3, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test ($p < .05$).

Mean peak velocity

A significant main effect for time, $F(1.66, 29.80) = 5.31$, $p = .01$, $\eta_p^2 = .23$, was found indicating that participants in both groups produced significantly lower peak velocities at post-test ($M = 49.33$, $SD = 11.56$) than at pre-test ($M = 70.45$, $SD = 28.46$). Pairwise comparisons showed that a significant improvement occurred from pre-test to block 2 ($p = .04$) and pre-test to block 3 ($p = .02$). However, no significant main effect for group, $F(1,18) = 2.94$, $p = .10$, $\eta_p^2 = .14$, or interaction, $F(1.66, 29.80) = 1.08$, $p = .34$, $\eta_p^2 = .06$ was found (see Figure 36).

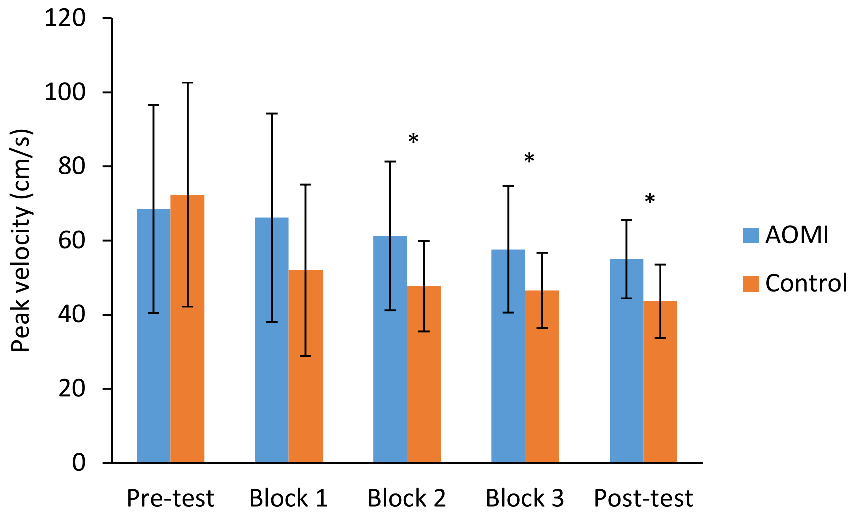


Figure 36. Mean peak velocity for AOMI and control groups at pre-test, block 1, block 2, block 3, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test (p < .05).

Time to peak acceleration

A significant main effect for time, $F(1.15, 20.67) = 9.03$, $p = .005$, $\eta_p^2 = .33$, was found indicating that participants in both groups produced reached peak acceleration significantly faster at post-test (M = 1.40, SD = 0.63) than at pre-test (M = 29.19, SD = 37.32). Pairwise comparisons showed that a significant improvement occurred from block 1 to block 2 (p = .03). However, no significant main effect for group, $F(1,18) = .003$, $p = .96$, $\eta_p^2 = .001$, or interaction, $F(1.15, 20.67) = 1.11$, $p = .31$, $\eta_p^2 = .06$ was found (see Figure 37).

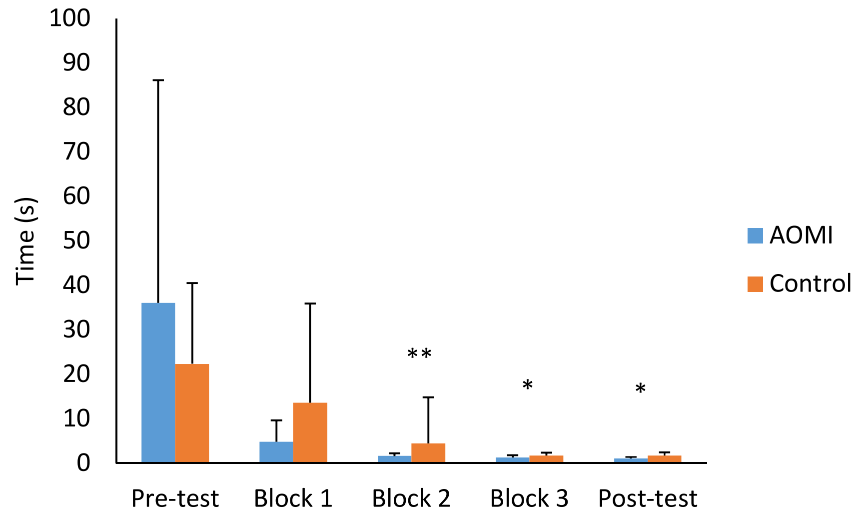


Figure 37. Time to peak acceleration for AOMI and control groups at pre-test, block 1, block 2, block 3, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test ($p < .05$); ** indicates a significant difference from block 1 ($p < .05$).

A 2 (Group: AOMI; Control) x 5 (Time: Pre-test; block 1; block 2; block 3; post-test) ANOVA performed on the standard deviations of the time to peak acceleration data revealed a significant main effect for time, $F(1.19, 13.08) = 10.84$, $p = .004$, $\eta_p^2 = .50$, indicating that variability of both groups was significantly lower at post-test ($M = 1.06$, $SD = 0.73$) than pre-test ($M = 11.97$, $SD = 10.43$). Pairwise comparisons revealed that a significant improvement occurred from block 1 to block 2 ($p = .03$) and block 2 to block 3 ($p = .03$). However, no significant main effect for group, $F(1,11) = .30$, $p = .59$, $\eta_p^2 = .03$, or interaction, $F(1.19, 13.08) = .05$, $p = .87$, $\eta_p^2 = .004$ was found (see Figure 38).

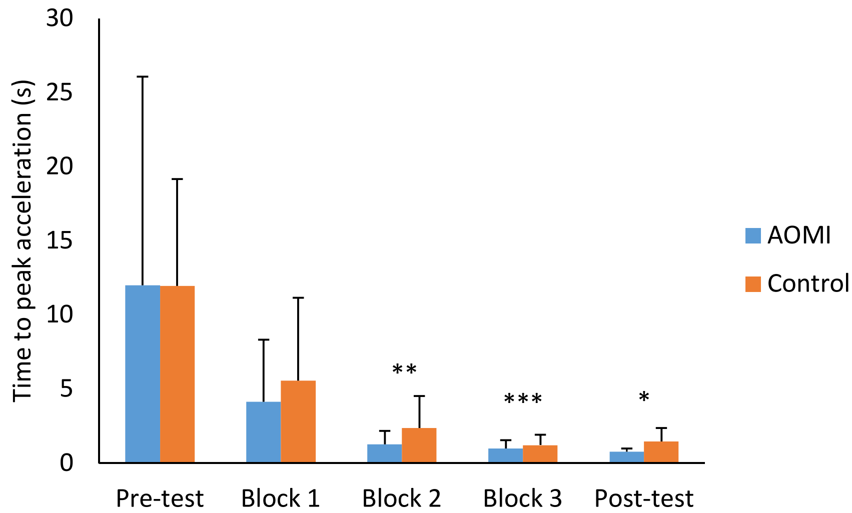


Figure 38. Standard deviations for time to peak acceleration for AOMI and control groups at pre-test, block 1, block 2, block 3, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test (p < .05); ** indicates a significant difference from block 1 (p < .05); *** indicates a significant difference from block 2 (p < .05).

Time to peak velocity

A significant main effect for time, $F(1.01, 19.79) = 9.27$, $p = .005$, $\eta_p^2 = .34$, was found indicating that participants in both groups reached peak velocity significantly faster at post-test ($M = 1.27$, $SD = 0.64$) than pre-test ($M = 28.89$, $SD = 37.16$). Pairwise comparisons revealed a significant improvement from block 1 to block 2 ($p = .01$). However, no significant main effect for group, $F(1,18) = .08$, $p = .78$, $\eta_p^2 = .004$, or interaction, $F(1.01, 19.79) = .27$, $p = .63$, $\eta_p^2 = .01$ was found (see Figure 39).

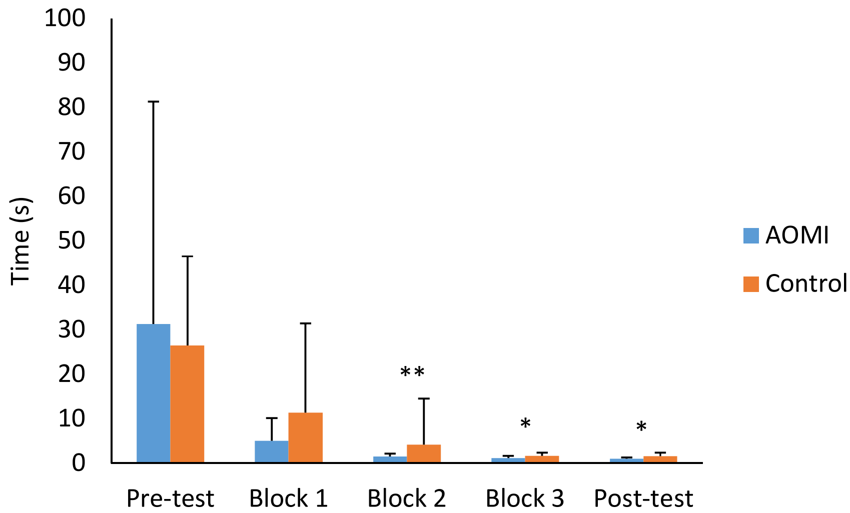


Figure 39. Time to peak velocity for AOMI and control groups at pre-test, block 1, block 2, block 3, and post-test. Error bars indicate SD. * indicates a significant difference from pre-test ($p < .05$); ** indicates a significant difference from block 1 ($p < .01$).

Gaze control

A significant effect for time, $F(2.04, 34.7) = 99.82$, $p < .001$, $\eta_p^2 = 0.85$, and a significant effect for group, $F(1,17) = 19.48$, $p < .001$, $\eta_p^2 = 0.53$, was found. A significant interaction was revealed, $F(2.04, 34.7) = 3.50$, $p = .04$, $\eta_p^2 = .17$ for target locking score. Independent samples t-tests revealed no significant difference between groups at pre-test ($p = .38$) but did indicate that the AOMI group had a significantly greater target locking score at block1 ($p < .001$), block 2 ($p < .001$), block 3 ($p = .005$) and post-test ($p = .03$). One participant in the AOMI group refused to wear the eye tracking glasses during testing but did otherwise complete all other aspects of the procedure (see Figure 40).

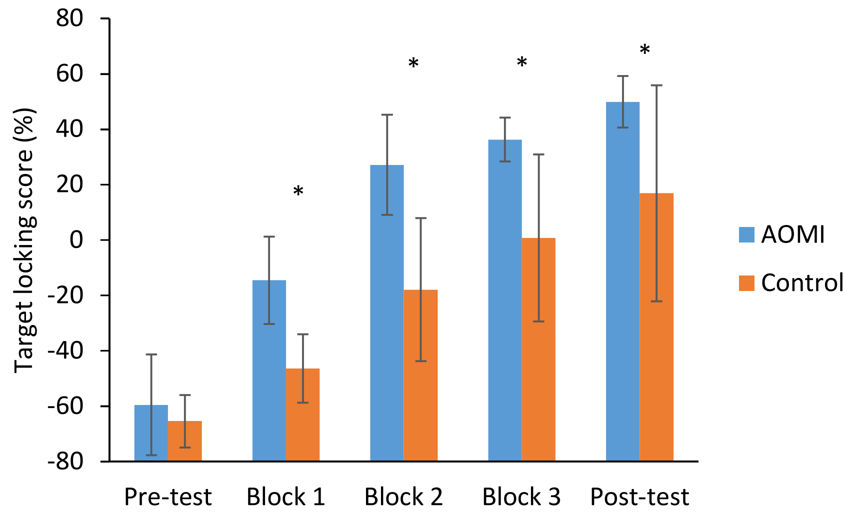


Figure 40. Mean target locking scores for AOMI and control groups at pre-test, block 1, block 2, block 3, and post-test. Error bars indicate SD. * indicates a significant difference between groups indicated ($p < .05$).

After-effects

No significant main effects or interactions were found between groups (See Tables 3 and 4).

Table 3. Mean scores for completion time, total path length, first path length, first path RMSE, and target locking score.

	AOMI		Control	
	Pre	Post	Pre	Post
Completion time (seconds)	14.66 (5.90)	17.04 (5.31)	14.49 (4.82)	17.27 (6.78)
Total path length (mm)	2749.55 (171.05)	3262.23 (1035.77)	2866.35 (246.44)	2884.36 (672.84)
First path length (mm)	265.76 (65.16)	338.28 (122.90)	254.82 (49.99)	270.23 (56.05)
First path RMSE (mm)	9.81 (0.55)	12.09 (4.05)	10.45 (2.84)	10.94 (2.99)
Target locking score (%)	64.01 (23.01)	61.61 (31. 50)	62.34 (17.98)	55.40 (22.47)

Table 4. 2 (Group: AOMI, control) x 2 (Time: pre-test, post-test) repeated measures ANOVA results for completion time, total path length, first path length, first path RMSE, and target locking score.

		df	*F*	*p*
Completion time				
	Time	1	2.42	.14
	Group	1	.00	.99
	Interaction	1	.01	.90
Total path length				
	Time	1	2.14	.16
	Group	1	.36	.56
	Interaction	1	1.86	.19
First path length				
	Time	1	3.38	.08
	Group	1	2.29	.15
	Interaction	1	1.43	.29
First path RMSE				
	Time	1	2.89	.10
	Group	1	.06	.80
	Interaction	1	1.21	.29
Target locking score				
	Time	1	.46	.50
	Group	1	.21	.65
	Interaction	1	.11	.74

Discussion

This study aimed to examine the effects of an AOMI training intervention on eye-hand coordination and visuomotor adaptation of children with DCD. Analysis of the data indicates that the AOMI training group produced a significant improvement in task performance at post-test, as measured by task completion time, in addition to demonstrating a significantly higher target locking score at post-test compared to the control group. Analysis of the total path length and peak acceleration and velocity variables indicated no significant differences between the two groups in terms of their movement kinematics.

The findings of this study support the existing literature that indicate mental simulation processes can be used to facilitate motor learning for children with DCD (Wilson et al., 2002; 2006; Adams et al., 2017) and extend the research in this area by providing preliminary evidence that AOMI training is also effective in this clinical population. AOMI has been proposed as a novel method for delivering mental simulation interventions (Vogt et al., 2013; Eaves et al., 2016) and the present study represents the first attempt to provide evidence of the efficacy of this technique for use with DCD. Furthermore, this study is the first to use gaze metrics to assess how AOMI affects the development of eye-hand coordination in the DCD population. The novel finding that AOMI training produces significant improvements in gaze control for children with DCD supports the existing literature describing the positive behavioural outcomes associated with the training of gaze in this population (Miles et al., 2015; Wood et al., 2017). These findings may be encouraging for applied practitioners and occupational therapists as they may indicate that a training programme incorporating AOMI and physical practice may contribute positively to performance improvements in children with DCD.

One possible explanation for the significant improvements in performance and eye gaze behaviour resulting from AOMI training could relate to the implicit learning of skilled eye movements. According to Vickers (2011), acquiring the most optimal spatial information subsequently allows for the optimal organisation of the neural structures underlying the action, which is characterised by early fixations of long durations on critical external locations, such as targets. The target locking data for this study show that at post-test the AOMI group were utilising a more efficient gaze strategy in which attention was directed more towards targets than the movement of the cursor. This could be indicative of increased top-down attentional control being exhibited by the AOMI group allowing for a more efficient dissemination of task relevant information to the motor control system. Previous research has described how during an early exploratory stage of skill learning eye-gaze initially performs a supervisory role. In this role, gaze is used for monitoring effector movement and administering online control whilst sensorimotor mapping rules are discovered (Sailer et al., 2005). As learning progresses and sensorimotor maps are developed during a distinct skill acquisition stage of learning, gaze slowly switches to a feedforward resource in which fixations are directed toward targets of interaction well ahead of hand movement. This allows the most optimal visuospatial position information to be conveyed to the motor control system and ensure accurate movements (Sailer et al., 2005; Land, 2009; Vine et al., 2013). In this experiment, AOMI training may have formed an environment that supported the development of a feedforward eye-gaze strategy that then supported movement refinement. This finding is supported by the results from Chapter 3, which showed a non-significant trend towards a higher target locking score for the AOMI training group in comparison to the AO and PO groups, even in the absence of physical practice. In this manner, AOMI training may provide similar benefits for children with DCD to those of QE training (Miles et al., 2015; Wood et al., 2017) albeit without the use of explicit instructions directing eye movement.

In Chapter 3, the inclusion of kinaesthetic imagery was discussed as potentially being central to the development of more proactive eye movements in the AOMI group. MI has been shown to access the forward model in order to predict the sensory outcomes of actions (Kilteni et al., 2018). This in turn leads to an internalised process of movement simulation in which the comparison of anticipated and simulated sensory consequences of the motor act provides an error signal that is used to improve motor performance (Ridderinkhof and Brass, 2015). By actively imaging the kinaesthetic components of the task in this study, participants in the AOMI group may have produced afferent proprioceptive feedback that was used to form, and subsequently adapt, the internal model of the novel visuomotor environment when combined with sensorimotor feedback derived from physical practice. By simulating somatosensory feedback, kinaesthetic imagery may have supported the development of sensorimotor maps during the skill acquisition stage and allowed attention to be deployed as a feedforward resource (Sailer et al., 2005; Land et al., 2009). Recent research, however, has found children with DCD to have lower kinaesthetic imagery ability than their typically developing peers (Fuchs and Cacola, 2018). This diminished capacity to use kinaesthetic imagery may be reflective of an impaired egocentric representation of space in children with DCD and it remains to be seen if providing an AO stimulus alongside kinaesthetic imagery during AOMI may restore some of this capability specifically.

The changes in eye gaze behaviour and task performance observed in this study could also be explained in a different, albeit closely related, way. It is possible that the effective formation and subsequent ongoing update of the internal model through AOMI processes may have improved predictive control and subsequently gaze was required less and less for the ongoing supervision of movement. Anticipatory eye movements have previously been shown to be both the result, and cause of, faster task performance (Foerster and Schneider, 2015) and as the novel visuomotor parameters of the task were learned, less time may have been required for visual intake of the cursor position relative to movement direction.

Observing and imaging the looping movements used by the model to complete the task may have provided participants in the AOMI group with a framework for implicitly learning skilled hand and eye movements. Using a QE training intervention with DCD children with the intention of improving throwing and catching skills, Wood et al. (2017) suggested that a more implicit learning environment, that did not place emphasis on explicit movement instructions, may have been of particular importance. Previous research has also suggested that visuomotor adaptation may involve implicit and explicit components of motor learning (Lei et al., 2016). AOMI training may have provided participants with both aspects whilst the control group had to undergo a different process of trying to learn the task. Furthermore, Candler et al. (2002) have also suggested how implicit learning may be beneficial for children with DCD when learning new skills, and this intervention may offer a similar effect.

Although significant differences between the AOMI and control groups were found for task completion time and gaze control, no further kinematic differences were identified. This may be indicative of the heterogeneous nature of DCD potentially inducing high movement variability and individualised motor control solutions. Previous research has described children with DCD exhibiting variable levels of movement across a variety of motor skills (Kagerer et al., 2004; Smits-Engelsman et al., 2008; 2013) that may be the result of individuals adopting different compensatory strategies based on their own unique movement limitations. Adoption of such strategies in this experiment may provide some explanation for the lack of group differences in terms of peak acceleration and velocity, despite the AOMI group's significant improvements in performance. Wade and Kazeck (2016) proposed that a dynamical systems approach that describes the complex interactions between many different subsystems in the body, current task and environment is necessary in order to understand more comprehensively how children with DCD adapt. Understanding the constraints of the individual with DCD would also facilitate the development of interventions tailored to their specific needs.

The results of this study only partially support the hypotheses as no significant unintentional after-effects were found following adaptation training for either group. Effective adaptation to visuomotor rotation is typically attributed to updating the internal model, evidence of which is quantified through the appearance of unintentional after-effects when the performer repeats the experimental task in a normal visuospatial environment (Kagerer et al., 2004; 2006). The coordination impairments associated with DCD are often ascribed to an underlying deficit in the ability to form and update internal models of movement (Wilson et al., 2013) so evidence of AOMI facilitating this process would have been desirable. Although the current experiment revealed direct learning effects, no after-effects were observed. Nevertheless, there is evidence from previous visuomotor adaptation studies that suggests the internal model may be updated even in the absence of after-effects. In a visuomotor adaptation study in which participants had to adapt to a 30^{o} visual rotation, first with one arm and then the other, Wang and Lei (2015) observed inter-limb transfer of direct learning effects but not the presence of after-effects. Furthermore, they found evidence of after-effects when the same limb was tested in a different workspace. These findings suggest that internal models may be formed and updated (as shown by the presence of after-effects when the same limb was tested in a different workspace) but that adaptation of the internal model does not necessarily always produce after-effects (as evidenced by the lack of after-effects when the second limb was tested). This finding is consistent with those of other studies that have also found no after-effects as a result of successful visuomotor adaptation following observational learning (Ong and Hodges, 2010; Lei et al., 2016). The extent to which AOMI facilitates the formation and subsequent updating of the internal model in children with DCD, however, is unclear. The task performance and eye gaze results from this study would suggest that, at the very least, the process is faster in comparison to learning by trial and error and is indicative of increased predictive control and subsequent better movement planning. In comparison to TD children, Kagerer et al. (2004) previously demonstrated that children with DCD utilise shorter, jerkier movements during visuomotor adaptation that they suggested were indicative of a deficit in planning resulting from impaired predictive control linked to cerebellar deficiencies often implicated in theories as to the underlying cause of DCD (Wilson et al., 2013). It is reasonable therefore to surmise that the direct learning effects observed in the current experiment may provide preliminary evidence of the formation and ongoing update of an internal model in children with DCD.

In this study, AOMI training may have provided a framework for motor learning in which children with DCD were shown an optimal way to perform the task that they could then apply to their own physical practice. The AOMI stimulus used in this experiment was designed to show a specific movement pattern that could be imitated in order to facilitate successful skill performance. It is clear from the results that the AOMI group successfully integrated visuospatial information from the AOMI training into their own physical practice and make performance improvements whereas the control group had to do so through trial and error and their progress was slower. The AOMI training stimulus may therefore have imparted initial sensorimotor mapping information that would otherwise have had to be derived through an early exploratory stage of skill learning (Sailer et al., 2005). Essentially, by being shown an effective way to complete the task the AOMI training group were able to assimilate information about movement and quickly use it in combination with physical practice to refine their own movement patterns. Participants in the control group had to achieve this through exploration of the visuomotor workspace and appear to have done so with reduced effectiveness. The control group also produced performance improvements but the slower rate at which they did so could be viewed as evidence of an impaired ability to learn from feedback and explore alternatives, with participants choosing to persist with a less effective learning strategy rather than experimenting with other approaches (Biotteau et al., 2016). What is apparent is that when provided with useful movement pattern information, the AOMI training group were able to utilise their physical practice trials more effectively. This may point towards the AOMI group imitating the video and applying it to their own practice, but previous research has described an impaired capacity for children with DCD to imitate and mirror novel gestures, which is thought to be linked to deficits in the hMNS (Reynolds et al., 2017). It is possible that these deficits may be related to perspective. Whilst Wilson et al. (2002; 2016) utilised both internal and external perspectives in addition to AO components to demonstrate the effectiveness of MI training, children with DCD have previously been shown to display impairments in performing mental imagery from a 1PP (Adams et al, 2014). By observing model performance from a 1PP whilst also engaging in concurrent MI from a matching perspective, AOMI may have lessened the impact of this impairment and allowed the hMNS to be employed in a more effective way.

Despite the encouraging results found in this study, there are some limitations to the current study. The absence of significant after-effects could be due to a lack of sensitivity in the measures used to detect them, for example, due to a limitation of the software used to design the task, no measure of initial directional error was employed in this study. As described above, several other studies also report a lack of after-effects following visuomotor adaptation through observational learning so this may not be the sole cause. It is also difficult to say with certainty the extent to which participants engaged in MI. The imagery ability of participants was not assessed prior to testing but all participants in the AOMI group were asked throughout their intervention if they were trying to imagine the movements they were observing and if they were finding it difficult to do so. Each participant reported engaging in the MI process but it is difficult to know to what extent. A benefit of using AOMI is that, due to the video stimulus providing all the necessary visual and audio components of the movement that it is to be imaged, only kinaesthetic elements of the movement need to be generated by the participant. Finally, this study employed a relatively small sample size and therefore the results deserve to be interpreted with some caution as other studies investigating motor imagery training for the DCD population have tested larger samples (Wilson et al., 2016; Adams et al., 2017). However, these studies did not recruit children from the MABC-2 5th percentile and the present study did use the same sample size as other DCD visuomotor adaptation studies (Kagerer et al., 2004; 2006).

In conclusion, children with DCD were shown to benefit from an AOMI training intervention as they completed the experimental significantly faster at post-test than the control group and employed a full target locking strategy. AOMI training therefore may facilitate the acquisition of more effective eye gaze behaviours and allow for the implicit learning of complex movement patterns that can then be refined through physical practice.

7. Summary, implications and conclusions

The overarching aim of this thesis was to examine the effects of AOMI on eye-hand coordination in children with DCD. This chapter will discuss the conclusions from each study and how they meet each of the aims outlined at the start of the thesis.

The first aim of this thesis was to examine the effect of AOMI training, in comparison to other AO conditions, upon eye-hand coordination during the performance of a novel visuomotor task. In Chapter 3, it was found that although physical practice produced the greatest improvements in task performance and target locking score, the use of AOMI instructions resulted in a statistically significant increase in comparison to the control group, but no such improvements were found following active or passive observation. Furthermore, increases in proactive gaze behaviour were found to be a reliable predictor of faster task performance. This suggests that AOMI may be an effective condition for facilitating the acquisition of skilled eye movements that facilitate optimal task performance in this context. This was the first study to empirically test the effects of different AO conditions on both performance and gaze behaviour and the findings have important theoretical and applied implications. AOMI is different from other AO techniques in that it includes MI, particularly kinaesthetic imagery, which may allow the more extensive development of the internal model in a manner more analogous to that experienced in physical practice. During AOMI, kinaesthetic imagery may have provided simulated sensorimotor feedback that was used to update the internal model. This may have resulted in a task-specific motor representation that also encoded visuomotor commands supporting movement planning which manifested as proactive eye movements. This finding provides support for the simulation hypothesis (Jeannerod, 2001; 2006) and suggests that implicitly encoding skilled eye movements through AOMI can aid task performance.

The second aim was to explore how eye-hand coordination develops during visuomotor adaptation for children with and without DCD. Previous studies have identified differences in gaze behaviour in these two populations and this study was the first to attempt to do so during visuomotor adaptation. The results from Chapter 4 demonstrated no significant differences in task performance or eye-hand coordination between DCD children and their TD peers. These findings are supportive of other studies that have found the performance of children with and without DCD to be comparable when performing tasks of simple to moderate complexity (e.g. Cantin et al., 2014). Furthermore, these findings are also indicative of children with DCD being equally as adept as typically developing children at performing skilled eye movements in certain contexts. This is also further evidence to support the ability of children with DCD to learn new tasks at a similar rate to their TD peers, which suggests the IMD may be modulated by task complexity and attentional constraints. In order to achieve the aim of exploring the use of an AOMI training intervention with DCD children, a new visuomotor task with a higher index of difficulty needed to be developed and this was one of the aims of Chapter 5.

In Chapter 5, the findings of Chapter 4 were drawn upon to develop a novel visuomotor task with a higher level of complexity that would a longer period of adaptation training with a view to subsequently using it in an intervention study with DCD children. An additional aim of this study was to identify specific patterns of movement that facilitated task performance, which could be used to inform the design of an AOMI intervention for children with DCD. The results of this study demonstrated the successful development of a new task as indexed through task performance and eye-hand coordination measures. Furthermore, analysis of the cursor paths created by each participant identified a specific looping pattern of movement that was employed by each of the top performers in terms of fastest completion times and highest target locking scores. Based on the verbal feedback from participants, this pattern may have promoted an external focus of attention that facilitated early skill acquisition and expedited improvements in performance. Other participants appeared to adopt a strategy with more of an internal attentional focus and an increased dependence on working memory that yielded a slower rate of improvement. These findings determined that the new task would be suitable for use as a performance measure with a DCD population and that the looping pattern, which emerged during physical practice, would be appropriate to form the basis of an AOMI training intervention.

The aim of the fourth study was to explore the effects of an AOMI training intervention on the development of eye-hand coordination during visuomotor adaptation in children with DCD. The results of this study found that AOMI training produced significant improvements in task performance and gaze behaviour in comparison to a control intervention. These findings indicate that AOMI training could be used to implicitly train the acquisition of skilled eye movements which facilitate performance and subsequently enable more effective adaptation of the internal model. Furthermore, these results indicate that whilst children with DCD may struggle to adapt an internal model based on their own physical practice, they can do so adequately when simulating a more effective movement strategy. This was the first study to examine the use of an AOMI training intervention with DCD and demonstrate its benefits and feasibility for use with this population. In addition, this study was the first to include gaze metrics in the assessment of the effects of mental simulation on visuomotor adaptation in DCD populations. The results of this study provide evidence to support the IMD hypothesis but extend the findings of the body of literature in this area by demonstrating that children with DCD can acquire a complex set of sensorimotor mapping rules through a combination of AOMI and physical practice. By engaging in MI during AO of a skilled performer, children with DCD may be better able to develop the internal model in order to more accurately predict sensory outcomes that align with the observed consequences produced by the actor, as opposed to incongruent outcomes produced during their own physical practice. By updating their own internal model based on the simulated re-enactment of the actor's skilled performance, children with DCD may therefore be able to engage in physical practice more effectively and use more accurate actual sensory feedback to update the internal model.

Taken together, the findings from this series of studies provide further evidence of the efficacy of motor learning interventions that target internal modelling for children with DCD. Furthermore, these findings may help to explain the mechanisms that underpin the performance benefits of AOMI.

Practical implications

Previous research has identified simulation training as an efficacious technique for improving motor functionality in children with DCD (Wilson et al., 2002; 2016; Adams et al., 2017) and this series of studies has provided useful behavioural evidence of the efficacy of AOMI in this population. This additional evidence for the practical benefits associated with techniques that target the ability of children with DCD to perform internal modelling may have potential applications for improving their performance of activities of daily living. For children with DCD, everyday tasks such as buttoning up clothes and using utensils can be difficult and enabling the skilled execution of these activities is a highly desirable outcome for both children and their parents (Dunford et al., 2005; Summers et al., 2008). Learning to ride a bike is often cited as a desirable motor task to learn for children with DCD (Mandich et al., 2003) and achieving this goal could enable additional desired outcomes such as increasing physical activity and participation in leisure activities with peers. These behaviours may then have long-term benefits to physical and mental health that are often a cause of concern regarding children with DCD.

Recent research has demonstrated how suboptimal gaze behaviours for throwing and catching can be improved using QE training (Miles et al., 2015; Wood et al., 2017). The findings of this thesis offer additional support for the application of interventions that foster the development of optimal eye movements in the DCD population. Researchers and practitioners may find task specific advantages to using either QE or AOMI training that would yield the best results for improvements in eye-hand coordination across a variety of domains. Future research should examine the benefits of AOMI training in other tasks.

As mental simulation processes have been shown to promote neuroplastic change in cortical motor areas, even in the absence of physical practice (Ertelt et al., 2007; Buccino et al., 2014), the initial findings described in this thesis imply that AOMI could be particularly useful in rehabilitation settings where physical practice is difficult or impossible, such as for post-stroke hemiparetic patients. AOMI has previously been shown to produce increased activity in neural areas associated with movement compared to AO or MI performed in isolation (Taube et al., 2015) and has been found to be effective in restoring aspects of motor function as part of a post-stroke rehabilitation programme (Sun et al., 2016). The impact that learning to perform activities of daily living may have on the quality of life for those in similar atypical populations is considerable and AOMI may allow the use of relatively low-cost, mobile training interventions that can be performed in occupational therapy settings or at home (Bek et al., 2016). Studies with post-stroke patients have demonstrated that both home-based MI and AO interventions can be used to provide a motivational aspect to rehabilitation and subsequently generate positive affects in psychological well-being and motor function (Chatterton et al., 2008; Dunsky et al., 2008; Ewan et al., 2010). It is hoped that the findings of this series of studies can be extended to further clinical populations such as Parkinson's disease patients, amputees learning to use prostheses, and spinal cord injury patients.

Theoretical implications

The findings from this series of studies offer additional support for the IMD hypothesis (Wilson et al., 2013; Adams et al., 2014), which suggests that impairments in coordinated movements experienced by children with DCD arise from diminished predictive control. In order to adapt the internal model, the predicted sensory outcomes of a movement must be compared to the actual sensory consequences of the movement (Wolpert, 1997). By making this comparison, an error signal is generated which is then used to modulate future movements affording rapid online correction. Chapter 6 described a study in which two groups of children with DCD trained on a novel visuomotor task using different training programmes, AOMI and control. Whereas the AOMI group adopted an effective movement pattern that facilitated skill acquisition, most control group participants persisted with a less effective movement strategy typical in children with DCD (Biotteau et al., 2016) but still improved as a result of training. It is possible that this persistence with a less effective strategy placed a large emphasis on bottom up attentional control in which movement of the cursor had to be closely monitored. This much slower rate of improvement and persistence with a relatively ineffective strategy would suggest that for children with DCD, physical practice alone is not enough to facilitate adaptation of the internal model in this context. The novel contribution of this study is that it would appear to suggest that AOMI can be used to improve this process, resulting in reductions in task completion time and the acquisition of skilled gaze behaviours that lead hand movement to targets.

The internal modelling of children with DCD, however, could be influenced by itself. In DCD, if the feedforward model used to predict the outcome of a movement is not well defined, then the subsequent error signals produced by a comparison to sensory consequences are also likely to be highly variable (Kagerer et al., 2004). Subsequently, these variable error signals may be of diminished use in providing the accurate feedback needed to fine-tune online movement corrections (Wolpert, 1997). This provides an explanation as to why children with DCD are still able to learn new motor tasks, albeit at a slower rate (Kagerer et al., 2006; Brookes et al., 2007). Alternatively, it may be that highly variable movements provide less accurate sensory feedback in comparison to the predicted sensory feedback thereby producing an inaccurate error signal to update the internal model, which results in a less well-defined motor representation. In either case, a poorly defined internal model is central to the production of the highly variable movements that characterise DCD.

AOMI may therefore facilitate motor control by providing simulated sensory outcomes that are less variable than actual sensory feedback. During AOMI, the internal model is compared with the predicted sensory outcomes of a simulated action. This simulation may align more closely with the anticipated consequences of the action and produce a more accurate error signal. The caveat of this potential explanation is that simulated actions do not produce actual sensory feedback but research has shown that kinaesthetic MI uses the internal model in order to predict the sensory consequences of imagined movements (Kilteni et al., 2018) and produces increased cortical motor activity compared to visual MI (Stinear et al., 2006). This suggests that although mental simulation has previously been described as impaired in children with DCD, it may be that this impairment is partially task-specific and simulation processes can still be used to enhance predictive control in this population. In Chapter 6, the skilled eye movements produced by the AOMI group may be indicative of a level of predictive control that is significantly greater than that of the control group. By facilitating the effective adaptation of the internal model and expediting the acquisition of complex sensorimotor mapping rules, AOMI may have promoted top-down attentional control as evidenced by eye movements that were significantly more target-focused than those of the control group.

In Chapter 4, it was found that children with and without DCD performed comparably on a task of moderate difficulty which also provides support for recent findings indicating that the ability of children with DCD to make use of feedforward estimates is modulated by task complexity (Cantin et al., 2014; Noten et al., 2014; Reynolds et al., 2015). In this particular case, children with DCD were able to adapt quickly to an 180^{o} visuomotor rotation. This may be of interest to DCD researchers wishing to test the IMD hypothesis as the sufficient level of task complexity required may be quite specific to the types of skill being assessed. Cantin et al. (2014) used visuomotor tasks of differing complexities to identify differences between children with and without DCD and although the novel control scheme required to perform the visuomotor task in Chapter 4 was deemed complex enough to find similar effects, this ultimately was not the case. Although researchers should consider tasks of high complexity when examining visuomotor performance in DCD, they should also take into account the potential for frustration or loss of attention if task demands are too high and success seemingly unattainable. Increasingly, studies in this area should aim to use paradigms that employ activities of daily life. Although task demands in these contexts may be more challenging to manipulate experimentally, they are ecologically valid and can still provide the basis for complex tasks.

MI training, with an element of video modelling, has previously been shown to an effective method for improving motor function in children with DCD (Wilson et al., 2002; 2016) but very few studies have expanded on these findings. In this thesis, AOMI has been found to be an efficacious technique for enhancing performance of a novel visuomotor task. AOMI offers a number of benefits compared to MI, such as controlling for the visual and timing components of the simulated action and allowing more attention to directed towards imagining the kinaesthetic sensations associated with the action. I hope that by identifying the benefits of using this technique with the DCD population, further research will explore its use with other clinical populations such as stroke, and cerebral palsy.

Limitations

The first limitation of this series of studies is the relatively small sample size used for each comparison group. In other studies from the DCD literature examining visuomotor coordination, many have selected samples sizes of seven to twelve participants (e.g. Kagerer et al., 2004; 2006; Wilmut et al., 2006; Zwicker et al., 2010). The two MI training studies conducted by Wilson et al. in 2002 and 2016, however, employed group sizes of 18 and 12 participants respectively. Although the sample size used in this series of studies is smaller than those utilised by Wilson et al. in their studies it is important to note the inclusion criteria chosen for each study. Wilson et al. (2002) included participants who scored at or below the 50th percentile on the MABC-2 test and noted that 11 children were below the 15th percentile whilst their replication study used the criteria of the 10th percentile (Wilson et al., 2016). In this thesis, only children who scored at or below the 5th percentile on the MABC-2 test were included in data analysis. According to the MABC-2 scoring criteria, scores beneath the 15th percentile are indicative of a potential motor impairment which is worthy of further observation and assessment, whereas scores below the 5th percentile suggest the child has a serious motor problem. In fact, only children below the 5th percentile should be diagnosed with DCD (Leeds Consensus Statement, 2006) and this is a significant limitation of previous work in this area. The more stringent criterion for inclusion was selected in order to provide a more representative sample of the DCD population (Smits-Engelsman et al., 2015). Naturally, this approach limits the extent of recruitment, especially when the additional diagnostic criteria of DCD are considered alongside no formal diagnoses of attentional disorders (American Psychological Association, 2013). Future research should certainly seek to recruit larger groups who score at or below the 5th percentile as efficacious interventions for this subset of the DCD population may well prove fruitful for those with less pronounced coordinative difficulties.

Another limitation of this series of studies is a lack of further comparisons of children with and without DCD performing the more complex visuomotor task (see Chapter 6). Whilst this was regrettably not possible due to time considerations, the additional comparison of a TD control group would have provided a baseline measure of typical performance (Debrabant et al., 2013; Sumner et al., 2018). It would have been of interest to compare this baseline measure to the two DCD groups and examine the extent to which AOMI enhances performance and this may provide a fruitful avenue for further research.

Although the touchscreen interface used in this series of studies allowed for cursor paths to be analysed, children with DCD have specific movement characteristics, such as shorter, jerkier movements, that were not possible to extract from the kinematic data collected. Data of this nature may have provided a rich source of discussion when considering the implications of AOMI training upon eye-hand coordination. By using motion capture methods, such as Vicon, it would have been possible to gather three-dimensional data of each participant's movement kinematics (Wilmut et al., 2013). The reflective markers used by the infrared cameras of the Vicon 3D motion capture system to track movements, however, may have proved distracting or uncomfortable for children with DCD. Recent studies have emerged proposing the use of Microsoft Kinect 3D motion tracking systems integrated with eye-tracking technology that may allow future research in this area to conducted more easily (Li et al., 2018).

In addition to the extra kinematic analyses, a qualitative component exploring how participants engaged in the AOMI process may have also been enlightening. Data of this type will be necessary in order to inform the design of future interventions and numerous studies emphasise the importance of personalising mental simulation stimuli (Holmes et al., 2001; Williams et al., 2011; Cooley et al., 2013) so it is regrettable that more detailed qualitative information was not gathered on this occasion.

Future directions

This series of studies has highlighted the potential for the use of AOMI as a technique to assist motor learning and subsequently there a number of exciting directions for future research into its application. A useful direction for future research would be to extend the findings of this series of studies to use with functional tasks, such as activities of daily living and sports. As sport settings provide such a diverse range of novel skills, there exists already a substantial body of research regarding the application of mental simulation processes in this domain (see Holmes and Calmels (2008) for a review) but few studies have examined the use of AOMI. Marshall and Wright (2016) conducted one such study and compared AOMI training and layered stimulus response training (LSRT) for improving novice golf putting performance. They found that AOMI training did not significantly improve performance although this was partially attributed to a lack of personalisation in the AOMI stimulus. In contrast, a recent study by Romano-Smith et al. (2018) demonstrated that six weeks of AOMI training produced significantly greater improvements in dart-throwing performance than either AO or MI used in isolation. Interestingly in this study, Romano-Smith and colleagues found that both AO and MI performed concurrently and in patterns of AO followed consecutively by MI produced significantly greater benefits to performance than AO. This evidence suggests that AOMI may be an efficacious technique for improving aiming skills regardless of the manner in which the two simulation states are combined. The comparative lack of research in this area illustrates a need for AOMI training to be researched across a number of sport tasks to explore its benefits and limitations in motor learning contexts. Imagery has previously been shown to offer additional benefits for sports performers, such as enhancing self-efficacy (Jones et al., 2002; Nordin and Cumming, 2005) and motivation (Martin and Hall, 1995; Cumming et al., 2002), which extend beyond the mastery of motor skills and the effects of AOMI on these factors should also be investigated.

A further avenue for future research regarding AOMI is to identify optimal delivery techniques. This series of studies employed MI instructions with kinaesthetic imagery propositions that placed an emphasis on the feelings and sensations associated with executing the action being observed. Manipulating the number of kinaesthetic propositions used alongside the same AO stimulus would provide a useful insight into the precise contribution of MI to the apparent benefits of AOMI. The structure of interventions also needs to be examined as both concurrent AOMI and alternate performance of AO and MI have been shown to produce positive behavioural outcomes (Sun et al., 2016; Romano-Smith et al., 2018) and certain types of approach may benefit specific populations.

An alternative delivery technique for MI that could potentially be incorporated into an AOMI training programme is layered stimulus response training (LSRT: Williams et al., 2013). Using this method, an image including only the most easily generated components is gradually developed and enriched by adding layers of stimulus and response propositions that are meaningful to the imager. These layers are selected by the imager based on their own reflection of how clear and vivid their image is. This process results in a highly personalised and individually meaningful imagery script that has been shown to enhance task performance (Williams et al., 2013; Marshall and Wright, 2016). Using this technique as part of an AOMI training programme it would be possible to include alongside an AO stimulus user-generated MI scripts that may be more effective due to their personalised nature. Whilst this layering process was tentatively explored in this thesis (see Chapter 6), the layers used were derived by the experimenter and were the same for each participant. It remains to be seen how effective an AOMI approach incorporating LSRT may be when used with children with DCD or other populations.

In order to optimise the way in which AOMI instructions are delivered, imagery ability must also be considered as the capability of an individual to perform MI has previously been demonstrated to modulate the effectiveness of training programmes (Robin et al., 2007). A recent study examining the imagery ability characteristics of children with DCD, in comparison to their typically developing peers, found that kinaesthetic imagery ability and MI accuracy were significantly lower for those with DCD (Fuchs and Cacola, 2018). This finding suggests imagery ability may not only be a mediating factor for the effectiveness of mental simulation interventions for children with DCD but may also underpin their coordination impairments by impairing their ability to predict the sensory consequences of actions. The findings of this thesis, however, suggest that children with DCD are capable of engaging in AOMI and benefiting from it. If imagery ability characteristics also mediate the effectiveness of kinaesthetic imagery during AOMI then this is an important consideration for researchers and practitioners and an avenue of research worthy of further exploration. As AOMI provides several benefits over performing MI in isolation it may even have the potential to facilitate or improve imagery ability characteristics (Ono et al., 2018). Currently, there are tests for the assessment of imagery ability characteristics but none for AO or AOMI ability. As MI appears to comprise a set of skills that can be improved with training (Cumming and Williams, 2012) it would appear intuitive that the ability to perform AO, and by extension AOMI, may be modifiable through practice and this needs to be addressed in research. This line of enquiry could prove to highly beneficial to researchers and practitioners across all domains.

An additional avenue of AOMI research concerns how both AO and MI are performed simultaneously. A recent conceptualisation of this process, termed dual-action simulation (Vogt et al., 2013; Eaves et al., 2016), suggests that concurrent sensorimotor streams for AO and MI, which are either competing with one another or merging depending on context, may allow for an imagined and observed action to be represented simultaneously. Eaves et al. (2016) have therefore proposed that concurrent AO and MI may place an increased burden on cognitive resources that could impact supervisory control and preclude the use of AOMI with certain populations. Romano-Smith et al. (2018), however, recently suggested that concurrent AOMI might actually serve to reduce the demands on working memory that other simulation states, such as MI or alternate AO and MI, may require. This is an important point of consideration as working memory has been demonstrated to be impaired in several clinical populations, such as children with DCD (Alloway, 2007; 2011), the elderly (Schott, 2012), stroke patients (Constantinidis and Klingberg, 2016), and Parkinson’s disease patients (Lewis et al., 2003). Future research seeking to assess the demands placed on working memory during AOMI interventions in these populations is certainly welcomed.

Although this series of studies has provided preliminary evidence as to the efficacy of AOMI as a technique for use with DCD children and produced additional support for the IMD hypothesis, the precise causation of DCD remains unknown. Whilst it would appear increasingly probable that the motor impairments characteristic of DCD are rooted in a diminished capacity to utilise feedforward mechanisms (Adams et al., 2014), and that this is also linked to the functions of the hMNS (Reynolds et al., 2015), some aspects of DCD are not adequately explained by the IMD hypothesis. As evidenced in this series of studies and others, task complexity has a mediating effect on task performance in children with DCD, with only tasks of higher complexity being able to identify issues in predictive control (Candler and Meeuwsen, 2002; Cantin et al., 2014). At present, the IMD hypothesis does not offer an explanation as to why task demands affect the way in which the internal model is accessed for action planning. The fact that children with DCD are clearly able to learn and perform many skills in a comparable manner to their TD peers may suggest that motor control is not globally impaired in DCD and instead may only be affected by high complexity tasks. Future research should consider manipulating task complexity and seek to identify the extent to which specific motor systems, such as the oculomotor system, are affected by task demands in order to isolate the specific impact of this variable.

Alongside the specific aetiology of the coordinative deficits that characterise DCD, the heterogeneous nature of this population and subsequent high variability across individuals in the extent of their motor control impairments is also poorly understood (Kaplan et al., 1998; King et al., 2011). Researchers may wish to attempt to stratify experimental designs in accordance with subscale scores from the MABC-2 and parent accounts of their child's motor ability. Whilst studies of this type would be challenging to execute with sufficient statistical power, smaller samples or case studies could still provide insight into how common individual differences manifest within DCD and should not be ignored.

A further challenge associated with the heterogeneity of children with DCD is the means of diagnosis. One common means of diagnosis is a motor ability examination conducted by an occupational therapist. Such an examination may typically require a child to perform the MABC-2 test and these results are then considered alongside parental interviews and questionnaires. Such methods are clearly merited but may be biased by the subjective nature of some of the test criteria. Objective quantitative methods that would enable the early identification of DCD should be of interest to future researchers and the visuomotor adaptation task used in this series of studies may have potential as a tool for this purpose, particularly in combination with the collection of gaze metrics. Previous studies have identified developmental differences in smooth pursuit in children with DCD (Robert et al., 2014) and have proposed that gaze metrics may be of use as diagnostic criteria for the early identification of DCD (Langaas et al., 1998). By using a task similar to that used in this series of studies, it may be possible to develop a diagnostic test that quantifies visuomotor performance alongside gaze behaviour. Such a test could be mobile and used alongside other motor ability tests when assessing a child. Furthermore, if effective, a test such as this may be able to be applied earlier in child development, enabling early identification of the disorder and subsequently, earlier access to additional learning resources in educational settings.

Conclusion

This thesis has addressed gaps in the current literature concerning how AOMI may be used to improve aspects of eye-hand coordination for children with DCD and in neurotypical populations. It was found that AOMI training facilitated the development of proactive eye movements that enhanced task performance. Furthermore, these improvements were greater than those resulting from a control intervention, whereas both active and passive observation interventions did not produce improvements. It was also found that children with DCD perform comparably to their TD peers on a visuomotor task of moderate complexity and that proactive eye movements developed at the same rate for both groups. When performing a more complex task, it was found that children with DCD benefit from receiving AOMI training as it may enhance their ability to utilise an internal model for the planning and coordination of actions. In summary, this series of studies has demonstrated that by engaging in the use of AOMI, individuals with and without DCD may be able to recruit the internal model to predict the sensory outcomes of a simulated action and develop proactive eye movements that facilitate the performance of coordinated actions.

References

Adams, I. L., Lust, J. M., Wilson, P. H. and Steenbergen, B. (2014). 'Compromised Motor Control in children with DCD: a deficit in the internal model? - A systematic review.' *Neuroscience and Biobehavioral Reviews*, 47, pp. 225-244.

DOI: http://dx.doi.org/10.1016/j.neubiorev.2014.08.011

Adams, I. L., Lust, J. M., Wilson, P. H. and Steenbergen, B. (2017). 'Testing predictive control of movement in children with developmental coordination disorder using converging operations.' *British Journal of Psychology*, 108(1), pp. 73-90. DOI:10.1111/bjop.12183

Alloway, T. P. (2007). 'Working memory, reading and mathematical skills in children with developmental coordination disorder.' *Journal of Experimental Child Psychology*, 96(1), pp. 20-36. DOI: https://doi.org/10.1016/j.jecp.2006.07.002

Alloway, T. P. (2011). 'A comparison of working memory profiles in children with ADHD and DCD.' *Child Neuropsychology*, 17(5), pp. 483-494.

DOI: https://doi.org/10.1080/09297049.2011.553590

Altschuler, E. L., Vankov, A., Hubbard, E. M., Roberts, E., Ramachandran, V. S. and Pineda, J. A. (2000). 'Mu wave blocking by observation of movement and its possible use as a tool to study theory of other minds.' Paper presented at: *The 30th Annual Meeting of the Society for Neuroscience,* New Orleans, LA, USA, 4th-9th November.

Altschuler, E. L., Vankov, A., Wang, V., Ramachandran, V. S. and Pineda, J. A. (1998). 'Person see, person do: Human cortical electrophysiological correlates of monkey see monkey do cells?' *Journal of Cognitive Neuroscience*, 10, pp. 91-91.

American Psychiatric Association. (2013) *Diagnostic and statistical manual of mental disorders (DSM-5®).* Washington, DC: American Psychiatric Publishing.

Andersen, R. A., Snyder, L. H., Bradley, D. C. and Xing, J. (1997). 'Multimodal representation of space in the posterior parietal cortex and its use in planning movements.' *Annual Review of Neuroscience*, 20(1), pp. 303-330.

Anguera, J. A., Reuter-Lorenz, P. A., Willingham, D. T. and Seidler, R. D. (2010). 'Contributions of spatial working memory to visuomotor learning.' *Journal of Cognitive Neuroscience*, 22(9), pp. 1917-1930. DOI: https://doi.org/10.1162/jocn.2009.21351

Ashford, D., Bennett, S. J. and Davids, K. (2006). 'Observational modeling effects for movement dynamics and movement outcome measures across differing task constraints: a meta-analysis.' *Journal of Motor Behavior*, 38(3), pp. 185-205.

DOI: https://doi.org/10.3200/JMBR.38.3.185-205

Astill, S. and Utley, A. (2006). 'Two-handed catching in children with developmental coordination disorder.' *Motor Control*, 10(2), pp. 109-124. DOI: https://doi.org/10.1123/mcj.10.2.109

Barnhart, R. C., Davenport, M. J., Epps, S. B. and Nordquist, V. M. (2003). 'Developmental coordination disorder.' *Physical Therapy*, 83(8), pp. 722-731.

DOI: https://doi.org/10.1093/ptj/83.8.722

Bart, O., Jarus, T., Erez, Y. and Rosenberg, L. (2011). 'How do young children with DCD participate and enjoy daily activities?' *Research in Developmental Disabilities*, 32(4), pp. 1317-1322. DOI: 10.1016/j.ridd.2011.01.039

Bek, J., Poliakoff, E., Marshall, H., Trueman, S. and Gowen, E. (2016). 'Enhancing voluntary imitation through attention and motor imagery.' *Experimental Brain Research*, 234(7), pp. 1819-1828. DOI: https://doi.org/10.1007/s00221-016-4570-3.

Bekkering, H., Adam, J. J., van den Aarssen, A., Kingma, H. and Whiting, H. J. (1995). 'Interference between saccadic eye and goal-directed hand movements.' *Experimental Brain Research*, 106(3), pp. 475-484.

Bellelli, G., Buccino, G., Bernardini, B., Padovani, A. and Trabucchi, M. (2010). 'Action observation treatment improves recovery of postsurgical orthopedic patients: evidence for a top-down effect?' *Archives of Physical Medicine and Rehabilitation*, 91(10), pp. 1489-1494. DOI: https://doi.org/10.1016/j.apmr.2010.07.013

Biotteau, M., Chaix, Y., Blais, M., Tallet, J., Péran, P. and Albaret, J. M. (2016). 'Neural signature of DCD: a critical review of MRI neuroimaging studies.' *Frontiers in Neurology*, 7(227), pp. 1-9. DOI: 10.1007/s40474-016-0084-8

Biotteau, M., Chaix, Y. and Albaret, J. M. (2016). 'What do we really know about motor learning in children with Developmental Coordination Disorder?' *Current Developmental Disorders Reports*, 3(2), pp. 152-160.

Braun, S., Beurskens, A., Kleynen, M., Schols, J. and Wade, D. (2011). 'Rehabilitation with mental practice has similar effects on mobility as rehabilitation with relaxation in people with Parkinson's disease: a multicentre randomised trial.' *Journal of Physiotherapy,* 57(1), pp. 27-34. DOI: https://doi.org/10.1016/S1836-9553(11)70004-2

Brookes, R. L., Nicolson, R. I. and Fawcett, A. J. (2007). 'Prisms throw light on developmental disorders.' *Neuropsychologia*, 45(8), pp. 1921-1930.

DOI: 10.1016/j.neuropsychologia.2006.11.019

Brown, D. K., Barton, J. L. and Gladwell, V. F. (2013). 'Viewing nature scenes positively affects recovery of autonomic function following acute-mental stress.' *Environmental Science and Technology*, 47(11), pp. 5562-5569. DOI: 10.1021/es305019p

Brunelli, S., Morone, G., Iosa, M., Ciotti, C., De Giorgi, R., Foti, C. and Traballesi, M. (2015). 'Efficacy of progressive muscle relaxation, mental imagery and phantom exercise training on phantom limb: a randomized controlled trial.' *Archives of Physical Medicine and Rehabilitation*, 96(2), pp. 181-187. DOI: https://doi.org/10.1016/j.apmr.2014.09.035

Buccino, G. (2014). 'Action observation treatment: a novel tool in neurorehabilitation.' *Philosophical Transactions of the Royal Society B*, 369(1644), pp. 20130185. DOI: 10.1098/rstb.2013.0185

Buccino, G., Arisi, D., Gough, P., Aprile, D., Ferri, C., Serotti, L., Tiberti, A. and Fazzi, E. (2012). 'Improving upper limb motor functions through action observation treatment: a pilot study in children with cerebral palsy.' *Developmental Medicine* *and Child Neurology*, 54(9), pp. 822-828. DOI: https://doi.org/10.1111/j.1469-8749.2012.04334.x

Buccino, G., Binkofski, F., Fink, G. R., Fadiga, L., Fogassi, L., Gallese, V., Seitz, R. J., Zilles, K., Rizzolatti, G. and Freund, H. J. (2001). 'Action observation activates premotor and parietal areas in a somatotopic manner: an fMRI study.' *European Journal of Neuroscience*, 13(2), pp. 400-404. DOI: https://doi.org/10.1111/j.1460-9568.2001.01385.x

Buccino, G., Molinaro, A., Ambrosi, C., Arisi, D., Mascaro, L., Pinardi, C., Rossi, A., Gasparotti, R., Fazzi, E. and Galli, J. (2018). 'Action Observation Treatment Improves Upper Limb Motor Functions in Children with Cerebral Palsy: A Combined Clinical and Brain Imaging Study.' *Neural Plasticity*, 2018, pp. 1-11. DOI: https://doi.org/10.1155/2018/4843985

Buch, E. R., Young, S. and Contreras-Vidal, J. L. (2003). 'Visuomotor adaptation in normal aging.' *Learning and Memory*, 10(1), pp. 55-63. DOI: 10.1101/lm.50303

Buneo, C. A. and Andersen, R. A. (2006). 'The posterior parietal cortex: sensorimotor interface for the planning and online control of visually guided movements.' *Neuropsychologia*, 44(13), pp. 2594-2606. DOI: https://doi.org/10.1016/j.neuropsychologia.2005.10.011

Cairney, J., Hay, J. A., Faught, B. E. and Hawes, R. (2005). 'Developmental coordination disorder and overweight and obesity in children aged 9–14 years.' *International Journal of Obesity*, 29(4), pp. 369-372.

Cairney, J. and Veldhuizen, S. (2013). 'Is developmental coordination disorder a fundamental cause of inactivity and poor health-related fitness in children?' *Developmental Medicine and Child Neurology*, 55, pp. 55-58.

Calvo-Merino, B., Glaser, D. E., Grèzes, J., Passingham, R. E. and Haggard, P. (2004). 'Action observation and acquired motor skills: an FMRI study with expert dancers.' *Cerebral Cortex*, 15(8), pp. 1243-1249. DOI: https://doi.org/10.1093/cercor/bhi007.

Calvo-Merino, B., Grèzes, J., Glaser, D. E., Passingham, R. E. and Haggard, P. (2006). 'Seeing or doing? Influence of visual and motor familiarity in action observation.' *Current Biology*, 16(19), pp. 1905-1910. DOI: https://doi.org/10.1016/j.cub.2006.07.065

Campbell, W. N., Missiuna, C. and Vaillancourt, T. (2012). 'Peer victimization and depression in children with and without motor coordination difficulties.' *Psychology in the Schools*, 49(4), pp. 328-341. DOI: 10.1002/pits.21600

Candler, C. and Meeuwsen, H. (2002). 'Implicit learning in children with and without developmental coordination disorder.' *American Journal of Occupational Therapy*, 56(4), pp. 429-435.

Cantin, N., Polatajko, H. J., Thach, W. T. and Jaglal, S. (2007). 'Developmental coordination disorder: exploration of a cerebellar hypothesis.' *Human Movement Science*, 26(3), pp. 491-509. DOI:10.1016/j.humov.2007.03.004

Cantin, N., Ryan, J. and Polatajko, H. J. (2014). 'Impact of task difficulty and motor ability on visual-motor task performance of children with and without developmental coordination disorder.' *Human Movement Science*, 34, pp. 217-232.

DOI: http://dx.doi.org/10.1016/j.humov.2014.02.006

Caramazza, A., Anzellotti, S., Strnad, L. and Lingnau, A. (2014). 'Embodied cognition and mirror neurons: a critical assessment.' *Annual Review of Neuroscience*, 37, pp. 1-15. DOI: https://doi.org/10.1146/annurev-neuro-071013-013950

Caspers, S., Zilles, K., Laird, A. R. and Eickhoff, S. B. (2010). 'ALE meta-analysis of action observation and imitation in the human brain.' *Neuroimage*, 50(3), pp. 1148-1167. DOI: https://doi.org/10.1016/j.neuroimage.2009.12.112.

Chan, A. H. and Hoffmann, E. R. (2017). 'Subjective estimation of task time and task difficulty of simple movement tasks.' *Journal of Motor Behavior*, 49(2), pp. 185-199. DOI: https://doi.org/10.1080/00222895.2016.1169984

Chang, S. H. and Yu, N. Y. (2010). 'Characterization of Motor Control in handwriting difficulties in children with or without developmental coordination disorder.' *Developmental Medicine and Child Neurology*, 52(3), pp. 244-250. DOI: https://doi.org/10.1111/j.1469-8749.2009.03478.x

Chen, I. C., Tsai, P. L., Hsu, Y. W., Ma, H. I. and Lai, H. A. (2013). 'Everyday memory in children with developmental coordination disorder.' *Research in Developmental Disabilities*, 34(1), pp. 687-694. DOI: http://dx.doi.org/10.1016/j.ridd.2012.09.012

Cochin, S., Barthelemy, C., Lejeune, B., Roux, S. and Martineau, J. (1998). 'Perception of motion and qEEG activity in human adults.' *Electroencephalography and Clinical Neurophysiology*, 107(4), pp. 287-295. DOI: http://doi.org/10.1016/S0013-4694(98)00071-6

Cochin, S., Barthelemy, C., Roux, S. and Martineau, J. (1999). 'Observation and execution of movement: similarities demonstrated by quantified electroencephalography.' *European Journal of Neuroscience*, 11(5), pp. 1839-1842. DOI: https://doi.org/10.1046/j.1460-9568.1999.00598.x

Cohen, Y. E. and Andersen, R. A. (2002). 'A common reference frame for movement plans in the posterior parietal cortex.' *Nature Reviews Neuroscience*, 3(7), pp. 553-562.

Collet, C., Di Rienzo, F., Hoyek, N. and Guillot, A. (2013). 'Autonomic nervous system correlates in movement observation and motor imagery.' *Frontiers in Human Neuroscience*, 7, pp. 1-17. DOI: 10.3389/fnhum.2013.00415

Constantinidis, C. and Klingberg, T. (2016). 'The neuroscience of working memory capacity and training.' *Nature Reviews Neuroscience*, 17(7), pp. 438-449. DOI: https://doi.org/10.1038/nrn.2016.43

Contreras-Vidal, J. L. and Buch, E. R. (2003). 'Effects of Parkinson's disease on visuomotor adaptation.' *Experimental Brain Research*, 150(1), pp. 25-32.

Cooley, S. J., Williams, S. E., Burns, V. E. and Cumming, J. (2013). 'Methodological variations in guided imagery interventions using movement imagery scripts in sport: A systematic review.' *Journal of Imagery Research in Sport and Physical Activity*, 8(1), pp. 13-34. DOI: https://doi.org/10.1515/jirspa-2012-0005

Cumming, J., Hall, C., Harwood, C. and Gammage, K. (2002). 'Motivational orientations and imagery use: A goal profiling analysis.' *Journal of Sports Sciences*, 20(2), pp. 127-136. DOI: https://doi.org/10.1080/026404102317200837

Cumming, J. and Ramsey, R. (2009). 'Imagery interventions in sport.' *In* Mellalieu, S.D. and Hanton, S. (ed.) *Advances in Applied Sport Psychology: A Review*, London: Routledge, pp. 5-36.

Cumming, J. and Williams, S. E. (2012). 'The role of imagery in performance.' *In* Murphy, S. M. (ed.) *Handbook of Sport and Performance Psychology*, Oxford: Oxford University Press, pp. 213-232.

Cusack, W. F., Thach, S., Patterson, R., Acker, D., Kistenberg, R. S. and Wheaton, L. A. (2016). 'Enhanced neurobehavioral outcomes of action observation prosthesis training.' *Neurorehabilitation and Neural Repair*, 30(6), pp. 573-582. DOI: https://doi.org/10.1177/1545968315606992

Debrabant, J., Gheysen, F., Caeyenberghs, K., Van Waelvelde, H. and Vingerhoets, G. (2013). 'Neural underpinnings of impaired predictive motor timing in children with Developmental Coordination Disorder.' *Research in Developmental Disabilities*, 34(5), pp. 1478-1487. DOI: http://dx.doi.org/10.1016/j.ridd.2013.02.008

Decety, J., Jeannerod, M., Germain, M. and Pastene, J. (1991). 'Vegetative response during imagined movement is proportional to mental effort.' *Behavioural Brain Research*, 42(1), pp. 1-5.

Deconinck, F. J., De Clercq, D., Savelsbergh, G. J., Van Coster, R., Oostra, A., Dewitte, G. and Lenoir, M. (2006). 'Differences in gait between children with and without developmental coordination disorder.' *Motor Control*, 10(2), pp. 125-142. DOI: https://doi.org/10.1123/mcj.10.2.125

Deconinck, F. J., Spitaels, L., Fias, W. and Lenoir, M. (2009). 'Is developmental coordination disorder a motor imagery deficit?' *Journal of Clinical and Experimental Neuropsychology*, 31(6), pp. 720-730. DOI: https://doi.org/10.1080/13803390802484805

Desmurget, M. and Grafton, S. (2000). 'Forward modeling allows feedback control for fast reaching movements.' *Trends in Cognitive Sciences*, 4(11), pp. 423-431. DOI: https://doi.org/10.1016/S1364-6613(00)01537-0

Dewey, D., Kaplan, B. J., Crawford, S. G. and Wilson, B. N. (2002). 'Developmental coordination disorder: associated problems in attention, learning and psychosocial adjustment.' *Human Movement Science*, 21(5-6), pp. 905-918. DOI: doi:10.1016/S0167-9457(02)00163-X

Dewey, D., Wilson, B. N. and Missiuna, C. (2001). 'Developmental coordination disorder: what is it.' *In* Missiuna, C. (ed.) *Children with Developmental Coordination Disorder: Strategies for Success*, New York: Routledge, pp. 5-27.

Dickstein, R., Dunsky, A. and Marcovitz, E. (2004). 'Motor imagery for gait rehabilitation in post-stroke hemiparesis.' *Physical Therapy*, 84(12), pp. 1167-1177. DOI: https://doi.org/10.1093/ptj/84.12.1167

Di Pellegrino, G., Fadiga, L., Fogassi, L., Gallese, V. and Rizzolatti, G. (1992). 'Understanding motor events: a neurophysiological study.' *Experimental Brain Research*, 91(1), pp. 176-180.

Dunford, C., Missiuna, C., Street, E. and Sibert, J. (2005). 'Children's perceptions of the impact of developmental coordination disorder on activities of daily living.' *British Journal of Occupational Therapy*, 68(5), pp. 207-214.

DOI: https://doi.org/10.1177/030802260506800504

Dunsky, A., Dickstein, R., Ariav, C., Deutsch, J. and Marcovitz, E. (2006). 'Motor imagery practice in gait rehabilitation of chronic post-stroke hemiparesis: four case studies.' *International Journal of Rehabilitation Research*, 29(4), pp. 351-356. DOI: 10.1097/MRR.0b013e328010f559

Dunsky, A., Dickstein, R., Marcovitz, E., Levy, S. and Deutsch, J. (2008). 'Home-based motor imagery training for gait rehabilitation of people with chronic poststroke hemiparesis.' *Archives of Physical Medicine and Rehabilitation*, 89(8), pp. 1580-1588. DOI: https://doi.org/10.1016/j.apmr.2007.12.039

Eaves, D. L., Riach, M., Holmes, P. S. and Wright, D. J. (2016). 'Motor imagery during action observation: a brief review of evidence, theory and future research opportunities.' *Frontiers in Neuroscience*, 10(514), pp. 1-10. DOI: https://doi.org/10.3389/fnins.2016.00514

Elliott, D., Hansen, S., Grierson, L. E., Lyons, J., Bennett, S. J. and Hayes, S. J. (2010). 'Goal-directed aiming: two components but multiple processes.' *Psychological Bulletin*, 136(6), pp. 1023-1044.

Ertelt, D., Small, S., Solodkin, A., Dettmers, C., McNamara, A., Binkofski, F. and Buccino, G. (2007). 'Action observation has a positive impact on rehabilitation of motor deficits after stroke.' *Neuroimage*, 36, pp. T164-T173.

DOI: https://doi.org/10.1016/j.neuroimage.2007.03.043

Ewan, L. M., Kinmond, K. and Holmes, P. S. (2010). 'An observation-based intervention for stroke rehabilitation: experiences of eight individuals affected by stroke.' *Disability and Rehabilitation*, 32(25), pp. 2097-2106.

DOI: https://doi.org/10.3109/09638288.2010.481345

Fabbri-Destro, M. and Rizzolatti, G. (2008). 'Mirror neurons and mirror systems in monkeys and humans.' *Physiology*, 23(3), pp. 171-179. DOI: https://doi.org/10.1152/physiol.00004.2008

Fadiga, L., Fogassi, L., Pavesi, G. and Rizzolatti, G. (1995). 'Motor facilitation during action observation: a magnetic stimulation study.' *Journal of Neurophysiology*, 73(6), pp. 2608-2611. DOI: https://doi.org/10.1152/jn.1995.73.6.2608

Ferguson, G. D., Jelsma, D., Jelsma, J. and Smits-Engelsman, B. C. M. (2013). 'The efficacy of two task-orientated interventions for children with Developmental Coordination Disorder: Neuromotor Task Training and Nintendo Wii Fit training.' *Research in Developmental Disabilities*, 34(9), pp. 2449-2461. DOI: https://doi.org/10.1016/j.ridd.2013.05.007

Filimon, F., Nelson, J. D., Hagler, D. J. and Sereno, M. I. (2007). 'Human cortical representations for reaching: mirror neurons for execution, observation and imagery.' *Neuroimage*, 37(4), pp. 1315-1328. DOI: https://doi.org/10.1093/cercor/bhu110.

Fitts, P. M. (1954). 'The information capacity of the human motor system in controlling the amplitude of movement.' *Journal of Experimental Psychology*, 47(6), pp. 381-391. DOI: http://dx.doi.org/10.1037/h0055392

Flanagan, J. R. and Johansson, R. S. (2003). 'Action plans used in action observation.' *Nature*, 424(6950), pp. 769-771.

Flanagan, J. R., Rotman, G., Reichelt, A. F. and Johansson, R. S. (2013). 'The role of observers' gaze behaviour when watching object manipulation tasks: predicting and evaluating the consequences of action.' *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, 368(1628), pp. 20130063. DOI: 10.1098/rstb.2013.0063

Forster, K. I. and Forster, J. C. (2003). 'DMDX: A Windows display program with millisecond accuracy.' *Behavior Research Methods*, 35(1), pp. 116-124.

Foerster, R. M. and Schneider, W. X. (2015). 'Anticipatory eye movements in sensorimotor actions: on the role of guiding fixations during learning.' *Cognitive Processing*, 16(1), pp. 227-231.

Franceschini, M., Ceravolo, M. G., Agosti, M., Cavallini, P., Bonassi, S., Dall'Armi, V., Massucci, M., Schifini, F. and Sale, P. (2012). 'Clinical relevance of action observation in upper-limb stroke rehabilitation: a possible role in recovery of functional dexterity. A randomized clinical trial.' *Neurorehabilitation and Neural Repair*, 26(5), pp. 456-462. DOI: https://doi.org/10.1177/1545968311427406

Frank, C., Land, W. M. and Schack, T. (2016). 'Perceptual-cognitive changes during motor learning: The influence of mental and physical practice on mental representation, gaze behavior and performance of a complex action.' *Frontiers in Psychology*, 6(1981), pp. 1-14. DOI: https://doi.org/10.3389/fpsyg.2015.01981

Fuchs, C. T. and Caçola, P. (2018). 'Differences in accuracy and vividness of motor imagery in children with and without Developmental Coordination Disorder.' *Human*

Movement Science, 60, pp. 234-241. DOI: https://doi.org/10.1016/j.humov.2018.06.015

Gallese, V., Fadiga, L., Fogassi, L. and Rizzolatti, G. (1996). ‘Action recognition in the premotor cortex.’ *Brain*, 119(2), pp. 593-609. DOI: https://doi.org/10.1093/brain/119.2.593

Geuze, R. H. (2005). ‘Postural control in children with developmental coordination disorder.’ *Neural Plasticity*, 12(2-3), pp. 183-196.

Geuze, R. H. (2007). ‘Characteristics of DCD: on problems and prognosis.’ *In* Geuze, R. H. (ed.) *Developmental Coordination Disorder: A Review of Current Approaches*, Marseille: Solal Editeurs, pp. 9-25.

Gheysen, F., Van Waelvelde, H. and Fias, W. (2011). ‘Impaired visuo-motor sequence learning in Developmental Coordination Disorder.’ *Research in Developmental Disabilities*, 32(2), pp. 749-756. DOI: https://doi.org/10.1016/j.ridd.2010.11.005

Gilger, J. W. and Kaplan, B. J. (2001). ‘Atypical brain development: a conceptual framework for understanding developmental learning disabilities.’ *Developmental Neuropsychology*, 20(2), pp. 465-481. DOI: https://doi.org/10.1207/S15326942DN2002_2

Glazebrook, C. M., Elliott, D. and Lyons, J. (2006). ‘A kinematic analysis of how young adults with and without autism plan and control goal-directed movements.’ *Motor Control*, 10(3), pp. 244-264. DOI: https://doi.org/10.1123/mcj.10.3.244

Gonsalves, L., Campbell, A., Jensen, L. and Straker, L. (2015). ‘Children with developmental coordination disorder play active virtual reality games differently than children with typical development.’ *Physical Therapy*, 95(3), pp. 360-368.

DOI: https://doi.org/10.2522/ptj.20140116

Guillot, A. and Collet, C. (2005). ‘Duration of mentally simulated movement: a review.’ *Journal of Motor Behavior*, 37(1), pp. 10-20. DOI: https://doi.org/10.3200/JMBR.37.1.10-20

Hammond, J., Jones, V., Hill, E. L., Green, D. and Male, I. (2014). 'An investigation of the impact of regular use of the Wii F it to improve motor and psychosocial outcomes in children with movement difficulties: a pilot study.' *Child: Care, Health and Development*, 40(2), pp. 165-175. DOI: https://doi.org/10.1111/cch.12029

Hardwick, R. M., Caspers, S., Eickhoff, S. B. and Swinnen, S. P. (2018). 'Neural Correlates of Action: Comparing Meta-Analyses of Imagery, Observation and Execution.' *Neuroscience and Biobehavioral Reviews*, 94, pp. 31-44. DOI: https://doi.org/10.1016/j.neubiorev.2018.08.003

Hayhoe, M. M., Shrivastava, A., Mruczek, R. and Pelz, J. B. (2003). 'Visual memory and motor planning in a natural task.' *Journal of Vision*, 3(1), pp. 49-63. DOI:10.1167/3.1.6

Hebb, D. O. (1949) *The Organization of Behavior: A Neuropsychological Theory*. New York: Wiley.

Henderson, J. M. (2003). 'Human gaze control during real-world scene perception.' *Trends in Cognitive Sciences*, 7(11), pp. 498-504. DOI: https://doi.org/10.1016/j.tics.2003.09.006

Henderson, S. E. and Sugden, D. A. (1992). *'Movement assessment battery for children.'* London: The Psychological Corporation.

Henderson, S. E., Sugden, D. A. and Barnett, A. L. (2007). '*Movement assessment battery for children-2 second edition.'* London: The Psychological Corporation

Hendrix, C. G., Prins, M. R. and Dekkers, H. (2014). 'Developmental coordination disorder and overweight and obesity in children: a systematic review.' *Obesity Reviews*, 15(5), pp. 408-423. DOI: https://doi.org/10.1111/obr.12137

Heremans, E., Helsen, W. F. and Feys, P. (2008). 'The eyes as a mirror of our thoughts: quantification of motor imagery of goal-directed movements through eye movement registration.' *Behavioural Brain Research*, 187(2), pp. 351-360. DOI: https://doi.org/10.1016/j.bbr.2007.09.028

Heremans, E., Smits-Engelsman, B., Caeyenberghs, K., Vercruysse, S., Nieuwboer, A., Feys, P. and Helsen, W. F. (2011). ‘Keeping an eye on imagery: the role of eye movements during motor imagery training.’ *Neuroscience*, 195, pp. 37-44.

DOI: https://doi.org/10.1016/j.neuroscience.2011.07.030

Hétu, S., Grégoire, M., Saimpont, A., Coll, M. P., Eugène, F., Michon, P. E. and Jackson, P. L. (2013). ‘The neural network of motor imagery: an ALE meta-analysis.’ *Neuroscience and Biobehavioral Reviews*, 37(5), pp. 930-949.

DOI: https://doi.org/10.1016/j.neubiorev.2013.03.017.

Holmes, P. S. and Collins, D. J. (2001). ‘The PETTLEP approach to motor imagery: A functional equivalence model for sport psychologists.’ *Journal of Applied Sport Psychology*, 13(1), pp. 60-83. DOI: https://doi.org/10.1080/10413200109339004

Holmes, P. S. and Calmels, C. (2008). ‘A neuroscientific review of imagery and observation use in sport.’ *Journal of Motor Behavior*, 40(5), pp. 433-445.

DOI: https://doi.org/10.3200/JMBR.40.5.433-445

Horn, R. R., Williams, A. M., Hayes, S. J., Hodges, N. J. and Scott, M. A. (2007). ‘Demonstration as a rate enhancer to changes in coordination during early skill acquisition.’ *Journal of Sports Sciences*, 25(5), pp. 599-614. DOI: https://doi.org/10.1080/02640410600947165

Hyde, C. and Wilson, P. H. (2011). ‘Dissecting online control in Developmental Coordination Disorder: a kinematic analysis of double-step reaching.’ *Brain and Cognition*, 75(3), pp. 232-241. DOI: https://doi.org/10.1016/j.bandc.2010.12.004

Hyde, C. E. and Wilson, P. H. (2013). ‘Impaired online control in children with developmental coordination disorder reflects developmental immaturity.’ *Developmental Neuropsychology*, 38(2), pp. 81-97. DOI: https://doi.org/10.1080/87565641.2012.718820

Imamizu, H., Miyauchi, S., Tamada, T., Sasaki, Y., Takino, R., Putz, B., Yoshioka, T. and Kawato, M. (2000). ‘Human cerebellar activity reflecting an acquired internal model of a new tool.’ *Nature*, 403(6766), pp. 192-195.

Imamizu, H., Kuroda, T., Miyauchi, S., Yoshioka, T. and Kawato, M. (2003). 'Modular organization of internal models of tools in the human cerebellum.' *Proceedings of the National Academy of Sciences*, 100(9), pp. 5461-5466. DOI: https://doi.org/10.1073/pnas.0835746100

Ito, M. (2008). 'Control of mental activities by internal models in the cerebellum.' *Nature Reviews Neuroscience*, 9(4), 304-313.

Ivry, R. B. and Keele, S. W. (1989). 'Timing functions of the cerebellum.' *Journal of Cognitive Neuroscience*, 1(2), pp. 136-152.

Ivry, R. B. (2003). 'Cerebellar involvement in clumsiness and other developmental disorders.' *Neural Plasticity*, 10(1-2), pp. 141-153.

DOI: http://dx.doi.org/10.1155/NP.2003.141

Jarus, T., Lourie-Gelberg, Y., Engel-Yeger, B. and Bart, O. (2011). 'Participation patterns of school-aged children with and without DCD.' *Research in Developmental Disabilities*, 32(4), pp. 1323-1331. DOI: https://doi.org/10.1016/j.ridd.2011.01.033

Jeannerod, M. (2001). 'Neural simulation of action: a unifying mechanism for motor cognition.' *Neuroimage*, 14(1), pp. S103-S109.

DOI: https://doi.org/10.1006/nimg.2001.0832.

Jeannerod, M. (2006). '*Motor cognition: What actions tell the self*.' Oxford: Oxford University Press.

Johnston, L. M., Burns, Y. R., Brauer, S. G. and Richardson, C. A. (2002). 'Differences in postural control and movement performance during goal directed reaching in children with developmental coordination disorder.' *Human Movement Science*, 21(5-6), pp. 583-601. DOI: https://doi.org/10.1016/S0167-9457(02)00153-7

Jones, M. V., Mace, R. D., Bray, S. R., MacRae, A. W. and Stockbridge, C. (2002). 'The impact of motivational imagery on the emotional state and self-efficacy levels of novice climbers.' *Journal of Sport Behaviour*, 25(1), pp. 57-73.

Kagerer, F. A., Bo, J., Contreras-Vidal, J. L. and Clark, J. E. (2004). 'Visuomotor adaptation in children with developmental coordination disorder.' *Motor Control*, 8(4), pp. 450-460. DOI: https://doi.org/10.1123/mcj.8.4.450

Kagerer, F. A., Contreras-Vidal, J. L., Bo, J. and Clark, J. E. (2006). 'Abrupt, but not gradual visuomotor distortion facilitates adaptation in children with developmental coordination disorder.' *Human Movement Science*, 25(4-5), pp. 622-633. DOI: https://doi.org/10.1016/j.humov.2006.06.003

Kaplan, B. J., Wilson, B. N., Dewey, D. and Crawford, S. G. (1998). 'DCD may not be a discrete disorder.' *Human Movement Science*, 17(4-5), pp. 471-490. DOI: https://doi.org/10.1016/S0167-9457(98)00010-4

Kashiwagi, M., Iwaki, S., Narumi, Y., Tamai, H. and Suzuki, S. (2009). 'Parietal dysfunction in developmental coordination disorder: a functional MRI study.' *Neuroreport*, 20(15), pp. 1319-1324. DOI: 10.1097/WNR.0b013e32832f4d87

Keele, S. W. (1968). 'Movement control in skilled motor performance.' *Psychological Bulletin*, 70(6, Pt. 1), pp. 387-403.

Kilteni, K andersson, B. J., Houborg, C and Ehrsson, H. H. (2018) 'Motor imagery involves predicting the sensory consequences of the imagined movement.' *Nature Communications,* 9(1617), pp. 1-52. DOI: 10.1038/s41467-018-03989-0

King, B. R., Harring, J. R., Oliveira, M. A. and Clark, J. E. (2011). 'Statistically characterizing intra-and inter-individual variability in children with Developmental Coordination Disorder.' *Research in Developmental Disabilities*, 32(4), pp. 1388-1398. DOI: https://doi.org/10.1016/j.ridd.2010.12.043

Krakauer, J. W., Ghilardi, M. F. and Ghez, C. (1999). 'Independent learning of internal models for kinematic and dynamic control of reaching.' *Nature Neuroscience*, 2(11), pp. 1026-1031

Land, M. F. (1999). 'Motion and vision: why animals move their eyes.' *Journal of Comparative Physiology A*, 185(4), pp. 341-352.

Land, M. F. (2009). 'Vision, eye movements and natural behavior.' *Visual Neuroscience*, 26(1), pp. 51-62. DOI: https://doi.org/10.1017/S0952523808080899

Lang, P. J. (1979). 'A bio-informational theory of emotional imagery.' *Psychophysiology*, 16(6), pp. 495-512. DOI: https://doi.org/10.1111/j.1469-8986.1979.tb01511.x

Langaas, T., Mon-Williams, M., Wann, J. P., Pascal, E. and Thompson, C. (1998). 'Eye movements, prematurity and developmental co-ordination disorder.' *Vision Research*, 38(12), pp. 1817-1826. DOI: https://doi.org/10.1016/S0042-6989(97)00399-4

Larson, T., Lundström, S., Nilsson, T., Selinus, E. N., Råstam, M., Lichtenstein, P., Gumpert, C. H., Anckarsater, H. and Kerekes, N. (2013). 'Predictive properties of the A-TAC inventory when screening for childhood-onset neurodevelopmental problems in a population-based sample.' *BMC Psychiatry*, 13(233), pp. 1-11. DOI: https://doi.org/10.1186/1471-244X-13-233

Leeds Consensus Statement. (2006) *Leeds Consensus Statement: Developmental Coordination Disorder as a Specific Learning Difficulty*. University of Leeds, Leeds, UK.

Lei, Y., Bao, S. and Wang, J. (2016). 'The combined effects of action observation and passive proprioceptive training on adaptive motor learning.' *Neuroscience*, 331, pp. 91-98. DOI: https://doi.org/10.1016/j.neuroscience.2016.06.011

Lejeune, C., Catale, C., Willems, S. and Meulemans, T. (2013). 'Intact procedural motor sequence learning in developmental coordination disorder.' *Research in Developmental Disabilities*, 34(6), pp. 1974-1981. DOI: https://doi.org/10.1016/j.ridd.2013.03.017

Lejeune, C., Wansard, M., Geurten, M. and Meulemans, T. (2016). 'Procedural learning, consolidation and transfer of a new skill in Developmental Coordination Disorder.' *Child Neuropsychology*, 22(2), pp. 143-154.DOI: https://doi.org/10.1080/09297049.2014.988608

Lewis, S. J., Cools, R., Robbins, T. W., Dove, A., Barker, R. A. and Owen, A. M. (2003). 'Using executive heterogeneity to explore the nature of working memory deficits in

Parkinson's disease.' *Neuropsychologia*, 41(6), pp. 645-654. DOI: https://doi.org/10.1016/S0028-3932(02)00257-9

Li, S., Li, B., Zhang, S., Fu, H., Lo, W. L., Yu, J., Sit, C. H. P. and Li, R. (2017). 'A markerless visual-motor tracking system for behavior monitoring in DCD assessment.' *In* Asia-Pacific Signal and Information Processing Association Annual Summit and Conference (APSIPA ASC), Aloft Kuala Lumpur Sentral, 12th -15th December 2017, pp. 774-777.

Liberman, L., Ratzon, N. and Bart, O. (2013). 'The profile of performance skills and emotional factors in the context of participation among young children with Developmental Coordination Disorder.' *Research in Developmental Disabilities*, 34(1), pp. 87-94. DOI: https://doi.org/10.1016/j.ridd.2012.07.019

Licari, M. K., Billington, J., Reid, S. L., Wann, J. P., Elliott, C. M., Winsor, A. M., Robins, E., Thornton, A.L., Jones, R. and Bynevelt, M. (2015). 'Cortical functioning in children with developmental coordination disorder: a motor overflow study.' *Experimental Brain Research*, 233(6), pp. 1703-1710. DOI: 10.1007/s00221-015-4243-7

Lim, S. B., Larssen, B. C. and Hodges, N. J. (2014). 'Manipulating visual–motor experience to probe for observation-induced after-effects in adaptation learning.' *Experimental Brain Research*, 232(3), pp. 789-802.

Liu, K. P., Chan, C. C., Lee, T. M. and Hui-Chan, C. W. (2004). 'Mental imagery for promoting relearning for people after stroke: A randomized controlled trial.' *Archives of Physical Medicine and Rehabilitation*, 85(9), pp. 1403-1408.

DOI: https://doi.org/10.1016/j.apmr.2003.12.035

Mackenzie, S. J., Getchell, N., Deutsch, K., Wilms-Floet, A., Clark, J. E. and Whitall, J. (2008). 'Multi-limb coordination and rhythmic variability under varying sensory availability conditions in children with DCD.' *Human Movement Science*, 27(2), pp. 256-269. DOI: https://doi.org/10.1016/j.humov.2008.02.010

Mak, M. K. (2010). 'Reaching and grasping a moving target is impaired in children with developmental coordination disorder.' *Pediatric Physical Therapy*, 22(4), pp. 384-391. DOI: doi: 10.1097/PEP.0b013e3181f9d885

Mandich, A. D., Polatajko, H. J. and Rodger, S. (2003). 'Rites of passage: Understanding participation of children with developmental coordination disorder.' *Human Movement Science*, 22(4-5), pp. 583-595. DOI: https://doi.org/10.1016/j.humov.2003.09.011

Marshall, B. and Wright, D. J. (2016). 'Layered Stimulus Response Training versus Combined Action Observation and Imagery: Effects on Golf Putting Performance and Imagery Ability Characteristics.' *Journal of Imagery Research in Sport and Physical Activity*, 11(1), pp. 35-46. DOI: https://doi.org/10.1515/jirspa-2016-0007

Martin, K. A. and Hall, C. R. (1995). 'Using mental imagery to enhance intrinsic motivation.' *Journal of Sport and Exercise Psychology*, 17(1), pp. 54-69.

DOI: https://doi.org/10.1123/jsep.17.1.54

Maruff, P., Wilson, P., Trebilcock, M. and Currie, J. (1999). 'Abnormalities of imagined motor sequences in children with developmental coordination disorder.' *Neuropsychologia*, 37(11), pp. 1317-1324. DOI: https://doi.org/10.1016/S0028-3932(99)00016-0

Maslovat, D., Hodges, N. J., Krigolson, O. E. and Handy, T. C. (2010). 'Observational practice benefits are limited to perceptual improvements in the acquisition of a novel coordination skill.' *Experimental Brain Research*, 204(1), pp. 119-130.

Mattar, A. A. and Gribble, P. L. (2005). 'Motor learning by observing.' *Neuron*, 46(1), pp. 153-160. DOI: https://doi.org/10.1016/j.neuron.2005.02.009

May-Benson, T., Ingolia, P. and Koomar, J. (2002). 'Daily living skills and developmental coordination disorder.' *Developmental Coordination Disorder*, pp. 140-156.

McCormick, S. A., Causer, J. and Holmes, P. S. (2012). 'Eye gaze metrics reflect a shared motor representation for action observation and movement imagery.' *Brain and Cognition*, 80(1), pp. 83-88. DOI: https://doi.org/10.1016/j.bandc.2012.04.010

McCormick, S. A., Causer, J. and Holmes, P. S. (2013). 'Active vision during action execution, observation and imagery: evidence for shared motor representations.' *PLoS One*, 8(6), pp. 1-8. DOI: https://doi.org/10.1371/journal.pone.0067761

McIntosh, R. D. and Schenk, T. (2009). 'Two visual streams for perception and action: Current trends.' *Neuropsychologica*, 47, pp. 1391-1396.

DOI: 10.1016/j.neuropsychologia.2009.02.009

Méndez-Rebolledo, G., Gatica-Rojas, V., Torres-Cueco, R., Albornoz-Verdugo, M. and Guzmán-Muñoz, E. (2017). 'Update on the effects of graded motor imagery and mirror therapy on complex regional pain syndrome type 1: a systematic review.' *Journal of Back and Musculoskeletal Rehabilitation*, 30(3), pp. 441-449. DOI: 10.3233/BMR-150500

Miles, C. A. L., Wood, G., Vine, S. J., Vickers, J. N. and Wilson, M. R. (2015). 'Quiet eye training facilitates visuomotor coordination in children with developmental coordination disorder.' *Research in Developmental Disabilities*, 40, pp. 31-41. DOI: https://doi.org/10.1016/j.ridd.2015.01.005

Milner, A. D. and Goodale, M. A. (2008). 'Two visual systems re-viewed.' *Neuropsychologia*, 46(3), pp. 774-785. DOI: https://doi.org/10.1016/j.neuropsychologia.2007.10.005

Missiuna, C. (1994). 'Motor skill acquisition in children with developmental coordination disorder.' *Adapted Physical Activity Quarterly*, 11(2), pp. 214-235. DOI: https://doi.org/10.1123/apaq.11.2.214

Missiuna, C., Rivard, L. and Pollock, N. (2004). 'They're Bright but Can't Write: Developmental Coordination Disorder in School Aged Children.' *Teaching Exceptional Children Plus*, 1(1), pp. 1-11.

Mombarg, R., Jelsma, D. and Hartman, E. (2013). 'Effect of Wii-intervention on balance of children with poor motor performance.' *Research in Developmental Disabilities*, 34(9), pp. 2996-3003. DOI: https://doi.org/10.1016/j.ridd.2013.06.008

Mon-Williams, M., Tresilian, J. R., Bell, V. E., Coppard, V. L., Nixdorf, M. and Carson, R. G. (2005). 'The preparation of reach-to-grasp movements in adults, children and children with movement problems.' *The Quarterly Journal of Experimental Psychology Section A*, 58(7), pp. 1249-1263. DOI: https://doi.org/10.1080/02724980443000575

Moschner, C., Crawford, T. J., Heide, W., Trillenberg, P., Kömpf, D. and Kennard, C. (1999). 'Deficits of smooth pursuit initiation in patients with degenerative cerebellar lesions.' *Brain*, 122(11), pp. 2147-2158. DOI: https://doi.org/10.1093/brain/122.11.2147

Mouthon, A., Ruffieux, J., Wälchli, M., Keller, M. and Taube, W. (2015). 'Task-dependent changes of corticospinal excitability during observation and motor imagery of balance tasks.' *Neuroscience*, 303, pp. 535-543.

DOI: https://doi.org/10.1016/j.neuroscience.2015.07.031.

Mulder, T. (2007). 'Motor imagery and action observation: cognitive tools for rehabilitation.' *Journal of Neural Transmission*, 114(10), pp. 1265-1278.

Mulder, T., de Vries, S. and Zijlstra, S. (2005). 'Observation, imagination and execution of an effortful movement: more evidence for a central explanation of motor imagery.' *Experimental Brain Research*, 163(3), pp. 344-351.

Nedelko, V., Hassa, T., Hamzei, F., Schoenfeld, M. A. and Dettmers, C. (2012). 'Action imagery combined with action observation activates more corticomotor regions than action observation alone.' *Journal of Neurologic Physical Therapy*, 36(4), pp. 182-188. DOI: https://doi.org/10.1097/NPT.0b013e318272cad1.

Neggers, S. F. and Bekkering, H. (2000). 'Ocular gaze is anchored to the target of an ongoing pointing movement.' *Journal of Neurophysiology*, 83(2), pp. 639-651. DOI: https://doi.org/10.1152/jn.2000.83.2.639

Neggers, S. F. and Bekkering, H. (2001). 'Gaze anchoring to a pointing target is present during the entire pointing movement and is driven by a non-visual signal.' *Journal of Neurophysiology*, 86(2), pp. 961-970. DOI: https://doi.org/10.1152/jn.2001.86.2.961

Neuper, C., Scherer, R., Wriessnegger, S. and Pfurtscheller, G. (2009). 'Motor imagery and action observation: modulation of sensorimotor brain rhythms during mental control of a brain–computer interface.' *Clinical Neurophysiology*, 120(2), pp. 239-247. DOI: https://doi.org/10.1016/j.clinph.2008.11.015

Neuman, B. and Gray, R. (2013). 'A direct comparison of the effects of imagery and action observation on hitting performance.' *Movement and Sport Sciences-Science and Motricité*, (79), pp. 11-21. DOI: https://doi.org/10.1051/sm/2012034.

Nordin, S. M. and Cumming, J. (2005). 'More than meets the eye: Investigating imagery type, direction and outcome.' *The Sport Psychologist*, 19(1), pp. 1-17.

DOI: https://doi.org/10.1123/tsp.19.1.1

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

Oldfield, R. C. (1971). 'The assessment and analysis of handedness: the Edinburgh inventory.' *Neuropsychologia*, 9(1), pp. 97-113. DOI: https://doi.org/10.1016/0028-3932(71)90067-4.

Ong, N. T. and Hodges, N. J. (2010). 'Absence of after-effects for observers after watching a visuomotor adaptation.' *Experimental Brain Research*, 205(3), pp. 325-334.

Ong, N. T., Larssen, B. C. and Hodges, N. J. (2012). 'In the absence of physical practice, observation and imagery do not result in updating of internal models for aiming.' *Experimental Brain Research*, 218(1), pp. 9-19.

Ono, Y., Wada, K., Kurata, M. and Seki, N. (2018). 'Enhancement of motor-imagery ability via combined action observation and motor-imagery training with proprioceptive neurofeedback.' *Neuropsychologia*, 114, pp. 134-142.

DOI: https://doi.org/10.1016/j.neuropsychologia.2018.04.016

Paccalin, C. and Jeannerod, M. (2000). 'Changes in breathing during observation of effortful actions.' *Brain Research*, 862(1-2), pp. 194-200. DOI: https://doi.org/10.1016/S0006-8993(00)02145-4

Page, S. J., Levine, P., Sisto, S. and Johnston, M. V. (2001). 'A randomized efficacy and feasibility study of imagery in acute stroke.' *Clinical Rehabilitation*, 15(3), pp. 233-240. DOI: https://doi.org/10.1191/026921501672063235

Page, S. J., Levine, P. and Leonard, A. C. (2005). 'Effects of mental practice on affected limb use and function in chronic stroke.' *Archives of Physical Medicine and Rehabilitation*, 86(3), pp. 399-402. DOI: https://doi.org/10.1016/j.apmr.2004.10.002

Page, S. J., Levine, P. and Leonard, A. (2007). 'Mental practice in chronic stroke: results of a randomized, placebo-controlled trial.' *Stroke*, 38(4), pp. 1293-1297.

Paolucci, T., Altavilla, D., Turriziani, C., Scienza, S., Sorgi, M., Luciani, M., Torquati, A., Lai, C. and Santilli, V. (2018). 'The rehabilitative role of motor imagery in the treatment of pain in fibromyalgia syndrome: Preliminary results.' *Annals of Physical and Rehabilitation Medicine*, 61, pp. e111-e112. DOI: https://doi.org/10.1016/j.rehab.2018.05.241

Parr, J. V. V., Vine, S. J., Harrison, N. R. and Wood, G. W. (2018). 'Examining the spatiotemporal disruption to gaze when using a myoelectric prosthetic hand.' *Journal of Motor Behavior*, 50(4), pp. 416-425. DOI: https://doi.org/10.1080/00222895.2017.1363703

Peens, A., Pienaar, A. E. and Nienaber, A. W. (2008). 'The effect of different intervention programmes on the self-concept and motor proficiency of 7-to 9-year-old children with DCD.' *Child: Care, Health and Development*, 34(3), pp. 316-328. DOI: https://doi.org/10.1111/j.1365-2214.2007.00803.x

Pelosin, E., Avanzino, L., Bove, M., Stramesi, P., Nieuwboer, A. and Abbruzzese, G. (2010). 'Action observation improves freezing of gait in patients with Parkinson's disease.' *Neurorehabilitation and Neural Repair*, 24(8), pp. 746-752. DOI: https://doi.org/10.1177/1545968310368685

Piek, J. P. and Dyck, M. J. (2004). 'Sensory-motor deficits in children with developmental coordination disorder, attention deficit hyperactivity disorder and autistic disorder.' *Human Movement Science*, 23(3-4), pp. 475-488.

DOI: https://doi.org/10.1016/j.humov.2004.08.019

Piek, J. P., Dyck, M. J., Francis, M. and Conwell, A. (2007). ‘Working memory, processing speed and set-shifting in children with developmental coordination disorder and attention-deficit–hyperactivity disorder.’ *Developmental Medicine and Child Neurology*, 49(9), pp. 678-683. DOI: https://doi.org/10.1111/j.1469-8749.2007.00678.x

Querne, L., Berquin, P., Vernier-Hauvette, M. P., Fall, S., Deltour, L., Meyer, M. E. and de Marco, G. (2008). ‘Dysfunction of the attentional brain network in children with developmental coordination disorder: a fMRI study.’ *Brain Research*, 1244, pp. 89-102. DOI: https://doi.org/10.1016/j.brainres.2008.07.066

Ram, N., Riggs, S. M., Skaling, S., Landers, D. M. and McCullagh, P. (2007). ‘A comparison of modelling and imagery in the acquisition and retention of motor skills.’ *Journal of Sports Sciences*, 25(5), pp. 587-597. DOI: https://doi.org/10.1080/02640410600947132

Ramnani, N. (2006). ‘The primate cortico-cerebellar system: anatomy and function.’ *Nature Reviews Neuroscience*, 7(7), pp. 511-522.

Raos, V., Kilintari, M. and Savaki, H. E. (2014). ‘Viewing a forelimb induces widespread cortical activations.’ *Neuroimage*, 89, pp. 122-142.

DOI: https://doi.org/10.1016/j.neuroimage.2013.12.010

Rentsch, S. and Rand, M. K. (2014). ‘Eye-hand coordination during visuomotor adaptation with different rotation angles.’ *PLoS One*, 9(10), pp. 1-15.

DOI: https://doi.org/10.1371/journal.pone.0109819

Reynolds, J. E., Billington, J., Kerrigan, S., Williams, J., Elliott, C., Winsor, A. M., Codd, L., Bynevelt, M. and Licari, M. K. (2017). ‘Mirror neuron system activation in children with developmental coordination disorder: A replication functional MRI study.’ *Research in Developmental Disabilities*, [Online] ‘Article in press’ published 22nd November 2017. DOI: https://doi.org/10.1016/j.ridd.2017.11.012

Reynolds, J. E., Thornton, A. L., Elliott, C., Williams, J., Lay, B. S. and Licari, M. K. (2015). ‘A systematic review of mirror neuron system function in developmental coordination disorder: imitation, motor imagery and neuroimaging evidence.' *Research in Developmental Disabilities*, 47, pp. 234-283. DOI: https://doi.org/10.1016/j.ridd.2015.09.015

Ridderinkhof, K. R. and Brass, M. (2015). 'How Kinesthetic Motor Imagery works: a predictive-processing theory of visualization in sports and motor expertise.' *Journal of Physiology-Paris*, 109(1-3), pp. 53-63. DOI: https://doi.org/10.1016/j.jphysparis.2015.02.003

Rizzolatti, G., Fadiga, L., Gallese, V. and Fogassi, L. (1996). 'Premotor cortex and the recognition of motor actions.' *Cognitive Brain Research*, 3(2), pp. 131-141.

DOI: https://doi.org/10.1016/0926-6410(95)00038-0

Rizzolatti, G., Fogassi, L. and Gallese, V. (2001). 'Neurophysiological mechanisms underlying the understanding and imitation of action.' *Nature reviews. Neuroscience*, 2(9), pp. 661-670.

Robert, M. P., Ingster-Moati, I., Albuisson, E., Cabrol, D., Golse, B. and Vaivre-Douret, L. (2014). 'Vertical and horizontal smooth pursuit eye movements in children with developmental coordination disorder.' *Developmental Medicine and Child Neurology*, 56(6), pp. 595-600. DOI: https://doi.org/10.1111/dmcn.12384

Robin, N., Dominique, L., Toussaint, L., Blandin, Y., Guillot, A. and Her, M. L. (2007). 'Effects of motor imagery training on service return accuracy in tennis: The role of imagery ability.' *International Journal of Sport and Exercise Psychology*, 5(2), pp. 175-186. DOI: https://doi.org/10.1080/1612197X.2007.9671818

Roby-Brami, A. and Burnod, Y. (1995). 'Learning a new visuomotor transformation: error correction and generalization.' *Cognitive Brain Research*, 2(4), pp. 229-242. DOI: https://doi.org/10.1016/0926-6410(95)90014-4

Romano-Smith, S., Wood, G., Wright, D. J. and Wakefield, C. J. (2018). 'Simultaneous and alternate action observation and motor imagery combinations improve aiming performance.' *Psychology of Sport and Exercise*, 38, pp. 100-106. DOI: https://doi.org/10.1016/j.psychsport.2018.06.003.

Sailer, U., Flanagan, J. R. and Johansson, R. S. (2005). 'Eye–hand coordination during learning of a novel visuomotor task.' *Journal of Neuroscience*, 25(39), pp. 8833-8842. DOI: https://doi.org/10.1523/JNEUROSCI.2658-05.2005

Sakamoto, M., Muraoka, T., Mizuguchi, N. and Kanosue, K. (2009). 'Combining observation and imagery of an action enhances human corticospinal excitability.' *Neuroscience research*, 65(1), pp. 23-27. DOI: https://doi.org/10.1016/jneures.2009.05.003.

Sakreida, K., Schubotz, R. I., Wolfensteller, U. and von Cramon, D. Y. (2005). 'Motion class dependency in observers' motor areas revealed by functional magnetic resonance imaging.' *Journal of Neuroscience*, 25(6), pp. 1335-1342.

DOI: https://doi.org/10.1523/JNEUROSCI.4170-04.2005

Sarasso, E., Gemma, M., Agosta, F., Filippi, M. and Gatti, R. (2015). 'Action observation training to improve motor function recovery: a systematic review.' *Archives of Physiotherapy*, 5(1), pp. 1-12. DOI: https://doi.org/10.1186/s40945-015-0013-x

Schoemaker, M. M. and Smits-Engelsman, B. C. (2015). 'Is treating motor problems in DCD just a matter of practice and more practice?' *Current Developmental Disorders Reports*, 2(2), pp. 150-156.

Schott, N. (2012). 'Age-related differences in motor imagery: Working memory as a mediator.' *Experimental Aging Research*, 38(5), pp. 559-583. DOI: https://doi.org/10.1080/0361073X.2012.726045

Sciutti, A., Nori, F., Jacono, M., Metta, G., Sandini, G. and Fadiga, L. (2011). 'Proactive gaze behavior: Which observed action features do influence the way we move our eyes?' A*nticipation,* 1, DOI: 10.1167/11.11.509

Scott, M., Taylor, S., Chesterton, P., Vogt, S. and Eaves, D. L. (2018). 'Motor imagery during action observation increases eccentric hamstring force: an acute non-physical intervention.' *Disability and Rehabilitation*, 40(12), pp. 1443-1451. DOI: https://doi.org/10.1080/09638288.2017.1300333.

Sigmundsson, H., Hansen, P. C. and Talcott, J. B. (2003). 'Do 'clumsy' children have visual deficits?' *Behavioural Brain Research*, 139(1-2), pp. 123-129.

DOI: https://doi.org/10.1016/S0166-4328(02)00110-9

Sgandurra, G., Ferrari, A., Cossu, G., Guzzetta, A., Fogassi, L. and Cioni, G. (2013). 'Randomized trial of observation and execution of upper extremity actions versus action alone in children with unilateral cerebral palsy.' *Neurorehabilitation and Neural Repair*, 27(9), pp. 808-815. DOI: https://doi.org/10.1177/1545968313497101

Skinner, R. A. and Piek, J. P. (2001). 'Psychosocial implications of poor motor coordination in children and adolescents.' *Human Movement Science*, 20(1-2), pp. 73-94. DOI: https://doi.org/10.1016/S0167-9457(01)00029-X

Smith, D., Holmes, P. S., Whitemore, L. and Devonport, T. (2001). 'The effect of theoretically-based imagery scripts on field hockey performance.' *Journal of Sport Behavior*, 24(4), pp. 408-419.

Smith, D., Wright, C. J. and Cantwell, C. (2008). 'Beating the bunker: The effect of PETTLEP imagery on golf bunker shot performance.' *Research Quarterly for Exercise and Sport*, 79(3), pp. 385-391. DOI: https://doi.org/10.1080/02701367.2008.10599502

Smits-Engelsman, B. C., Niemeijer, A. S. and van Galen, G. P. (2001). 'Fine motor deficiencies in children diagnosed as DCD based on poor grapho-motor ability.' *Human Movement Science*, 20(1-2), pp. 161-182. DOI: https://doi.org/10.1016/S0167-9457(01)00033-1

Smits-Engelsman, B. C. M., Wilson, P. H., Westenberg, Y. and Duysens, J. (2003). 'Fine motor deficiencies in children with developmental coordination disorder and learning disabilities: An underlying open-loop control deficit.' *Human Movement Science*, 22(4-5), pp. 495-513. DOI: https://doi.org/10.1016/j.humov.2003.09.006

Smits-Engelsman, B., Schoemaker, M., Delabastita, T., Hoskens, J. and Geuze, R. (2015). 'Diagnostic criteria for DCD: Past and future.' *Human Movement Science*, 42, pp. 293-306. DOI: https://doi.org/10.1016/j.humov.2015.03.010

Stinear, C. M., Byblow, W. D., Steyvers, M., Levin, O. and Swinnen, S. P. (2006). 'Kinesthetic, but not visual, motor imagery modulates corticomotor excitability.' *Experimental Brain Research*, 168(1-2), pp. 157-164. DOI: https://doi.org/10.1007/s00221-005-0078-y.

Summers, J., Larkin, D. and Dewey, D. (2008). 'Activities of daily living in children with developmental coordination disorder: dressing, personal hygiene and eating skills.' *Human Movement Science*, 27(2), pp. 215-229. DOI: https://doi.org/10.1016/j.humov.2008.02.002

Sumner, E., Hutton, S. B., Kuhn, G. and Hill, E. L. (2018). 'Oculomotor atypicalities in developmental coordination disorder.' *Developmental Science*, 21(1), pp. 1-12. DOI: 10.1111/desc.12501

Sun, Y., Wei, W., Luo, Z., Gan, H. and Hu, X. (2016). 'Improving motor imagery practice with synchronous action observation in stroke patients.' *Topics in Stroke Rehabilitation*, 23(4), pp. 245-253. DOI: https://doi.org/10.1080/10749357.2016.1141472.

Tamir, R., Dickstein, R. and Huberman, M. (2007). 'Integration of motor imagery and physical practice in group treatment applied to subjects with Parkinson's disease.' *Neurorehabilitation and Neural Repair*, 21(1), pp. 68-75. DOI: https://doi.org/10.1177/1545968306292608

Taube, W., Lorch, M., Zeiter, S. and Keller, M. (2014). 'Non-physical practice improves task performance in an unstable, perturbed environment: motor imagery and observational balance training.' *Frontiers in Human Neuroscience*, 8(972) pp. 1-10. DOI: https://doi.org/10.3389/fnhum.2014.00972

Taube, W., Mouthon, M., Leukel, C., Hoogewoud, H. M., Annoni, J. M. and Keller, M. (2015). 'Brain activity during observation and motor imagery of different balance tasks: an fMRI study.' *Cortex*, 64, pp. 102-114. DOI: https://doi.org/10.1016/j.cortex.2014.09.022.

Taylor, J. A., Krakauer, J. W. and Ivry, R. B. (2014). 'Explicit and implicit contributions to learning in a sensorimotor adaptation task.' *Journal of Neuroscience*, 34(8), pp. 3023-3032. DOI: https://doi.org/10.1523/JNEUROSCI.3619-13.2014

Thach, W. T., Goodkin, H. P. and Keating, J. G. (1992). 'The cerebellum and the adaptive coordination of movement.' *Annual Review of Neuroscience*, 15(1), pp. 403-442.

Tsai, C. L., Wu, S. K. and Huang, C. H. (2008). 'Static balance in children with developmental coordination disorder.' *Human Movement Science*, 27(1), pp. 142-153. DOI: https://doi.org/10.1016/j.humov.2007.08.002

Unity Technologies. (2017) *Unity3D.* Version 5.6.3p2 [Software] San Francisco: Unity Technologies.

Utley, A., Steenbergen, B. and Astill, S. L. (2007). 'Ball catching in children with developmental coordination disorder: control of degrees of freedom.' *Developmental Medicine and Child Neurology*, 49(1), pp. 34-38. DOI: https://doi.org/10.1017/S0012162207000096.x

Vannuscorps, G. and Caramazza, A. (2016). 'Typical action perception and interpretation without motor simulation.' *Proceedings of the National Academy of Sciences*, 113(1), pp. 86-91. DOI: https://doi.org/10.1073/pnas.1516978112

Vickers, J. N. (2007). '*Perception, cognition and decision training: The quiet eye in action*. Leeds: Human Kinetics.

Villiger, M., Bohli, D., Kiper, D., Pyk, P., Spillmann, J., Meilick, B., Curt, A., Hepp-Reymond, M. C., Hotz-Boendermaker, S. and Eng, K. (2013). 'Virtual reality–augmented neurorehabilitation improves motor function and reduces neuropathic pain in patients with incomplete spinal cord injury.' *Neurorehabilitation and Neural Repair*, 27(8), pp. 675-683. DOI: https://doi.org/10.1371/journal.pone.0072403.

Vine, S. J., Masters, R. S., McGrath, J. S., Bright, E. and Wilson, M. R. (2012). 'Cheating experience: Guiding novices to adopt the gaze strategies of experts expedites the learning of technical laparoscopic skills.' *Surgery*, 152(1), pp. 32-40.

DOI: https://doi.org/10.1016/j.surg.2012.02.002

Vine, S. J., Chaytor, R. J., McGrath, J. S., Masters, R. S. and Wilson, M. R. (2013). 'Gaze training improves the retention and transfer of laparoscopic technical skills in novices.' *Surgical Endoscopy*, 27(9), pp. 3205-3213.

Vine, S. J., Moore, L. J., Cooke, A., Ring, C. and Wilson, M. R. (2013). 'Quiet eye training: A means to implicit motor learning.' *International Journal of Sport Psychology*, 44(4), pp. 367-386.

Vine, S. J. and Wilson, M. R. (2011). 'The influence of quiet eye training and pressure on attention and visuo-motor control.' *Acta Psychologica*, 136(3), pp. 340-346.

Vogt, S., Di Rienzo, F., Collet, C., Collins, A. and Guillot, A. (2013). 'Multiple roles of motor imagery during action observation.' *Frontiers in Human Neuroscience*, 7(807), pp. 1-13. DOI: https://doi.org/10.3389/fnhum.2013.00807.

Wade, M. G. and Kazeck, M. (2016). 'Developmental Coordination Disorder and its cause: the road less travelled.' *Human Movement Science*, 57, pp. 489-500.

DOI: https://doi.org/10.1016/j.humov.2016.08.004

Wang, J. and Lei, Y. (2015). 'Direct-effects and after-effects of visuomotor adaptation with one arm on subsequent performance with the other arm.' *Journal of neurophysiology*, 114(1), pp. 468-473. DOI: https://doi.org/10.1152/jn.00298.2015

Werner, S. and Bock, O. (2010). 'Mechanisms for visuomotor adaptation to left–right reversed vision.' *Human Movement Science*, 29(2), pp. 172-178.

DOI: https://doi.org/10.1016/j.humov.2010.02.004

Werner, J. M., Cermak, S. A. and Aziz-Zadeh, L. (2012). 'Neural correlates of developmental coordination disorder: The mirror neuron system hypothesis.' *Journal of Behavioral and Brain Science*, 2(02), pp. 258-268. DOI: 10.4236/jbbs.2012.22029

Williams, J., Thomas, P. R., Maruff, P. and Wilson, P. H. (2008). 'The link between motor impairment level and motor imagery ability in children with developmental coordination disorder.' *Human Movement Science*, 27(2), pp. 270-285.

DOI: https://doi.org/10.1016/j.humov.2008.02.008

Williams, S. E., Cooley, S. J. and Cumming, J. (2013). ‘Layered stimulus response training improves motor imagery ability and movement execution.’ *Journal of Sport and Exercise Psychology*, 35(1), pp. 60-71. DOI: https://doi.org/10.1123/jsep.35.1.60

Williams, S. E., Cumming, J. and Edwards, M. G. (2011). ‘The functional equivalence between movement imagery, observation and execution influences imagery ability.’ *Research Quarterly for Exercise and Sport*, 82(3), pp. 555-564.

DOI: https://doi.org/10.1080/02701367.2011.10599788

Wilmut, K. and Byrne, M. (2014). ‘Grip selection for sequential movements in children and adults with and without Developmental Coordination Disorder.’ *Human Movement Science*, 36, pp. 272-284. DOI: https://doi.org/10.1016/j.humov.2013.07.015

Wilmut, K., Byrne, M. and Barnett, A. L. (2013). ‘Reaching to throw compared to reaching to place: A comparison across individuals with and without Developmental Coordination Disorder.’ *Research in Developmental Disabilities*, 34(1), pp. 174-182. DOI: https://doi.org/10.1016/j.ridd.2012.07.020

Wilmut, K. and Wann, J. (2008). ‘The use of predictive information is impaired in the actions of children and young adults with Developmental Coordination Disorder.’ *Experimental Brain Research*, 191(4), pp. 403-418.

Wilmut, K., Wann, J. P. and Brown, J. H. (2006). ‘Problems in the coupling of eye and hand in the sequential movements of children with developmental coordination disorder.’ *Child: Care, Health and Development*, 32(6), pp. 665-678. DOI: https://doi.org/10.1111/j.1365-2214.2006.00678.x

Wilson, B. N., Kaplan, B. J., Crawford, S. G. and Roberts, G. (2007). ‘The developmental coordination disorder questionnaire 2007 (DCDQ’07).’ Alberta Children’s Hospital, Calgary, Canada.

Wilson, B. N., Crawford, S. G., Green, D., Roberts, G., Aylott, A. and Kaplan, B. J. (2009). ‘Psychometric properties of the revised developmental coordination disorder questionnaire.’ *Physical and Occupational Therapy in Pediatrics*, 29(2), pp. 182-202. DOI: https://doi.org/10.1080/01942630902784761

Wilson, M., McGrath, J., Vine, S., Brewer, J., Defriend, D. and Masters, R. (2010). ‘PsychoMotor Control in a virtual laparoscopic surgery training environment: gaze control parameters differentiate novices from experts.’ *Surgical Endoscopy*, 24(10), pp. 2458-2464.

Wilson, M. R., Vine, S. J., Bright, E., Masters, R. S. W., Defriend, D. and McGrath, J. S. (2011). ‘Gaze training enhances laparoscopic technical skill acquisition and multi-tasking performance: a randomized, controlled study.’ *Surgical Endoscopy,* 25, pp. 3731–3739. DOI: https://doi.org/10.1007/s00464-011-1802-2

Wilson, P. H. (2005). ‘Practitioner review: approaches to assessment and treatment of children with DCD: an evaluative review.’ *Journal of Child Psychology and Psychiatry*, 46(8), pp. 806-823. DOI: https://doi.org/10.1111/j.1469-7610.2005.01409.x

Wilson, P. H., Adams, I. L., Caeyenberghs, K., Thomas, P., Smits-Engelsman, B. and Steenbergen, B. (2016). ‘Motor imagery training enhances motor skill in children with DCD: A replication study.’ *Research in Developmental Disabilities*, 57, pp. 54-62.

DOI: https://doi.org/10.1016/j.ridd.2016.06.014

Wilson, P. H., Maruff, P., Butson, M., Williams, J., Lum, J. and Thomas, P. R. (2004). ‘Internal representation of movement in children with developmental coordination disorder: a mental rotation task.’ *Developmental Medicine and Child Neurology*, 46(11), pp. 754-759. DOI: https://doi.org/10.1017/S001216220400129X

Wilson, P. H. and McKenzie, B. E. (1998). ‘Information processing deficits associated with developmental coordination disorder: A meta-analysis of research findings.’ *The Journal of Child Psychology and Psychiatry and Allied Disciplines*, 39(6), pp. 829-840.

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

Wilson, P. H., Thomas, P. R. and Maruff, P. (2002). 'Motor imagery training ameliorates motor clumsiness in children.' *Journal of Child Neurology*, 17(7), pp. 491-498. DOI: https://doi.org/10.1177/088307380201700704

Wolpert, D. M. (1997). 'Computational approaches to Motor Control.' *Trends in Cognitive Sciences*, 1(6), pp. 209-216. DOI: https://doi.org/10.1016/S1364-6613(97)01070-X

Wood, G., Miles, C. A., Coyles, G., Alizadehkhaiyat, O., Vine, S. J., Vickers, J. N. and Wilson, M. R. (2017). 'A randomized controlled trial of a group-based gaze training intervention for children with Developmental Coordination Disorder.' *PloS one*, 12(2), pp. 1-16. DOI: https://doi.org/10.1371/journal.pone.0171782.

Woodruff, S. J., Bothwell-Myers, C., Tingley, M. and Albert, W. J. (2002). 'Gait pattern classification of children with developmental coordination disorder.' *Adapted Physical Activity Quarterly*, 19(3), pp. 378-391. DOI: https://doi.org/10.1123/apaq.19.3.378

Woodworth, R. S. (1899). 'Accuracy of voluntary movement.' *The Psychological Review: Monograph Supplements*, 3(13), pp. 1-119. DOI: http://dx.doi.org/10.1037/h0092992

Wright, D. J., McCormick, S. A., Williams, J. and Holmes, P. S. (2016). 'Viewing instructions accompanying action observation modulate corticospinal excitability.' *Frontiers in Human Neuroscience*, 10, 17. DOI: https://doi.org/10.3389/fnhum.2016.00017.

Wright, D. J., Williams, J. and Holmes, P. S. (2014). 'Combined action observation and imagery facilitates corticospinal excitability.' *Frontiers in Human Neuroscience*, 8(951), pp. 1-9. DOI: 10.3389/fnhum.2014.00951

Wulf, G., Chiviacowsky, S., Schiller, E. and Ávila, L. T. G. (2010). 'Frequent external focus feedback enhances motor learning.' *Frontiers in Psychology*, 1(190), pp. 1-7.

DOI: https://doi.org/10.3389/fpsyg.2010.00190

Wulf, G., McNevin, N. and Shea, C. H. (2001). 'The automaticity of complex motor skill learning as a function of attentional focus.' *The Quarterly Journal of Experimental Psychology: Section A*, 54(4), pp. 1143-1154.

Wulf, G., Shea, C. and Lewthwaite, R. (2010). 'Motor skill learning and performance: a review of influential factors.' *Medical Education*, 44(1), pp. 75-84.

DOI: https://doi.org/10.1111/j.1365-2923.2009.03421.x

Zachry, T., Wulf, G., Mercer, J., & Bezodis, N. (2005). 'Increased movement accuracy and reduced EMG activity as the result of adopting an external focus of attention.' *Brain Research Bulletin*, 67(4), pp. 304-309. DOI: https://doi.org/10.1016/j.brainresbull.2005.06.035

Zwicker, J. G., Missiuna, C. and Boyd, L. A. (2009). 'Neural correlates of developmental coordination disorder: a review of hypotheses.' *Journal of Child Neurology*, 24(10), pp. 1273-1281. DOI: https://doi.org/10.1177/0883073809333537

Zwicker, J. G., Missiuna, C., Harris, S. R. and Boyd, L. A. (2011). 'Brain activation associated with motor skill practice in children with developmental coordination disorder: an fMRI study.' *International Journal of Developmental Neuroscience*, 29(2), pp. 145-152. DOI: https://doi.org/10.1016/j.ijdevneu.2010.12.002

Zwicker, J. G., Missiuna, C., Harris, S. R. and Boyd, L. A. (2012). 'Developmental coordination disorder: a review and update.' *European Journal of Paediatric Neurology*, 16(6), pp. 573-581. DOI: https://doi.org/10.1016/j.ejpn.2012.05.005

Appendix A: The Edinburgh Handedness Inventory (Oldfield, 1971)

Name: ____ Date: _______________

Date of birth: __________________________________ Sex: ________________

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

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

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

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

Appendix B: The Developmental Coordination Disorder Questionnaire (Wilson et al., 2007)

Name of child: Click here to enter text.

Person completing questionnaire: Click here to enter text.

Relationship to child: Click here to enter text.

Does your child need to wear glasses? Yes☐ No☐

Does your child attend a specialist school? Yes☐ No☐

Does your child have a formal diagnosis of ADHD? Yes☐ No☐

Does your child suffer from any general medical condition known to affect motor function (e.g. cerebral palsy, hemiplegia, muscular dystrophy)? Yes☐ No☐

	Day	Month	Year
Today's date	Click here to enter text.	Click here to enter text.	Click here to enter text.
Child's birth	Click here to enter text.	Click here to enter text.	Click here to enter text.

Most of the motor skills that this questionnaire asks about are things that your child does with his or her hands, or when moving.

A child's coordination may improve each year as they grow and develop. For this reason, it will be easier for you to answer the questions if you think about other children that you know who *are the same age as your child.*

Please compare the degree of coordination your child has with other children of the same age when answering the questions.

For each question, check the one box next to the number that best describes your child.

If you are unclear about the meaning of a question, or about how you would answer a question to best describe your child, email b.marshall@mmu.ac.uk for assistance.

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

1. Your child *throws* a ball in a controlled and accurate fashion.
   1☐ 2☐ 3☐ 4☐ 5☐

2. Your child *catches* a small ball (e.g. tennis ball size) thrown from a distance of 6 to 8 feet (1.8 to 2.4 meters).
   1☐ 2☐ 3☐ 4☐ 5☐

3. Your child *hits* an approaching *ball* with a bat or racquet accurately.
   1☐ 2☐ 3☐ 4☐ 5☐

4. Your child *jumps* easily *over* obstacles found in the garden or play environment.
1☐ 2☐ 3☐ 4☐ 5☐

5. Your child *runs* as fast and in a *similar* way to other children of the same gender and age.
1☐ 2☐ 3☐ 4☐ 5☐

6. If your child has a *plan* to do a motor *activity*, he/she can organize his/her body to follow the plan and effectively complete the task (e.g. building a cardboard or cushion "fort", moving on playground equipment, building a house or a structure with blocks, or using craft materials).
1☐ 2☐ 3☐ 4☐ 5☐

7. Your child's printing or *writing* or drawing in class is *fast* enough to keep up with the rest of the children in the class.
1☐ 2☐ 3☐ 4☐ 5☐

8. Your child's printing or *writing* letters, numbers and words is *legible*, precise and accurate or, if your child is not yet printing, he or she *colours and draws* in a coordinated way and makes pictures that you can recognise.
1☐ 2☐ 3☐ 4☐ 5☐

9. Your child uses appropriate *effort* or tension when printing or writing or drawing (no excessive pressure or tightness of grasp on the pencil, writing is not too heavy or dark, or too light).
1☐ 2☐ 3☐ 4☐ 5☐

10. Your child *cuts* out pictures and *shapes* accurately and easily.
1☐ 2☐ 3☐ 4☐ 5☐

11. Your child is interested in and *likes* participating in *sports or active* games requiring good motor skills.
1☐ 2☐ 3☐ 4☐ 5☐

12. Your child learns *new motor tasks* (e.g. swimming, rollerblading) easily and does not require more practice or time than other children to achieve the same level of skill.
1☐ 2☐ 3☐ 4☐ 5☐

13. Your child is *quick and competent* in tidying up, putting on shoes, tying shoes, dressing, etc.
1☐ 2☐ 3☐ 4☐ 5☐

14. Your child would *never* be described as a "*bull in a china shop*" (that is, appears so clumsy that he or she might break fragile things in a small room).
1☐ 2☐ 3☐ 4☐ 5☐

15. Your child does *not fatigue easily* or appear to slouch and "fall out" of the chair if required to sit for long periods.
1☐ 2☐ 3☐ 4☐ 5☐

Thank you. When you have answered all the questions, please check through your answers to make sure you have not missed any boxes. Once you are happy with your responses, save this document under a new name that includes your initials (e.g. Coordination Questionnaire BM). Please email your completed questionnaire to b.marshall@mmu.ac.uk

Appendix C: In-house questionnaire for visuomotor task feedback

To be completed after each block (10 trials) of the task

Please rate the extent to which you were trying to perform the task as quickly and accurately as possible.

Block 1

1	2	3	4	5	6	7
Not at all	Before very few trials	Before a few trials	Neutral	Before some trials	Before most trials	Before every trial

Block 2

1	2	3	4	5	6	7
Not at all	Before very few trials	Before a few trials	Neutral	Before some trials	Before most trials	Before every trial

Block 3

1	2	3	4	5	6	7
Not at all	Before very few trials	Before a few trials	Neutral	Before some trials	Before most trials	Before every trial

Block 4

1	2	3	4	5	6	7
Not at all	Before very few trials	Before a few trials	Neutral	Before some trials	Before most trials	Before every trial

Block 5

1	2	3	4	5	6	7
Not at all	Before very few trials	Before a few trials	Neutral	Before some trials	Before most trials	Before every trial

Did you use any other strategies to assist your performance? If so, please list them below.
____
____
____
____
____
____
____