Title: Motor planning with and without motor imagery in children with Developmental Coordination Disorder

Running Title: Motor planning and motor imagery in DCD

Ranila Bhoyroo[1], Beth Hands[1], Kate Wilmut[2], Christian Hyde[3] and Adam Wigley[1]

Institutional affiliations

[1]Institute for Health Research, University of Notre Dame Australia, Perth, WA

[2]Faculty of Health and Life Sciences, Oxford Brookes University, Oxford OX3 0BP, United Kingdom

[3]Cognitive Neuroscience Unit, School of Psychology, Deakin University, Geelong, VIC, Australia

Corresponding author

Ms Ranila Bhoyroo

✉ Institute of Health Research, The University of Notre Dame Australia, 19 Mouat Street (PO Box 1225), Fremantle, WA, 6959, Australia.

ranila.bhoyroo1@my.nd.edu.au

Declarations of interest: none

Abstract

Children with Developmental Coordination Disorder (DCD) demonstrate inefficient motor planning ability with a tendency to opt for non-optimal planning strategies. Motor imagery can provide an insight to this planning inefficiency, as it may be a strategy for improving motor planning and thereby motor performance for those with DCD. In this study, we investigated the prevalence of end-state-comfort (ESC) and the minimal rotation strategy using a grip selection task in children with DCD with and without motor imagery instructions. Boys with (*n* = 14) and without DCD (*n* = 18) aged 7 – 12 years completed one, two and three colour sequences of a grip selection (octagon) task. Two conditions were examined; a Motor Planning (MP) condition requiring only the performance of the task and a Motor Imagery and Planning (MIP) condition, which included an instruction to imagine performing the movement before execution. For the MP condition, children with DCD ended fewer trials in ESC for the one (*p*=0.001) and two colour (*p*=0.002) sequences and used a minimal rotation strategy more often than those without DCD. For the MIP condition, the DCD group significantly increased their use of the ESC strategy for the one colour sequences (*p*=0.014) while those without DCD improved for the two colour (*p*=0.008) sequences. ESC level of the DCD group on the MIP condition was similar to those without DCD at baseline for all colour sequences. Motor imagery shows potential as a strategy for improving motor planning in children with DCD. Implications and limitations are discussed.

Keywords: ESC, end-state-comfort, task complexity, minimal rotation, grip selection

1. Introduction

Developmental coordination disorder (DCD) is a neurodevelopmental condition that is characterised by the inability to acquire and execute well-coordinated movements at an age appropriate level (American Psychiatric Association, 2013). With a prevalence of 5 - 6% of the population, this condition significantly affects performance in many physical and everyday activities (American Psychiatric Association, 2013; Zwicker, Suto, Harris, Vlasakova, & Missiuna, 2018). The symptoms become apparent at an early age and cannot be explained by intellectual disability, visual impairment or other neurological conditions affecting movement (e.g. cerebral palsy) (American Psychiatric Association, 2013).

There is substantial evidence indicating that poor motor planning is a core feature of children with DCD (Adams, Ferguson, Lust, Steenbergen, & Smits-Engelsman, 2016; Bhoyroo, Hands, Wilmut, Hyde, & Wigley, 2018; Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016; Wilmut & Byrne, 2014a). Generally, motor planning reflects the process of selecting movement plans from an infinite number of possible movement combinations or solutions by which the desired goal could be achieved (Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992). Behaviourally, one way this process can be assessed is with grip selection tasks that elicit the 'end-state-comfort' (ESC) effect (Rosenbaum et al., 1992). This effect illustrates the tendency to prioritise grasping objects in such a way that movements can be ended comfortably, even if this means sacrificing comfort at the beginning and/or during a movement. While children with DCD have demonstrated a reduced tendency to plan for ESC in grip selection tasks, this effect is most stable (or stronger) when the complexity of the motor planning tasks increase (Wilson et al., 2017). Supporting this, recently, Bhoyroo et al. (2018) investigated motor planning ability in children with and without DCD using a variety of simple and complex grip selection tasks. They found that children with DCD demonstrated similar ESC performances to their peers for the easier tasks (i.e., bar rotation, bar transport and sword tasks) but were less likely to plan for ESC for the complex task (i.e., octagon task) as often as their typically developing (TD) peers.

During motor planning, an internal model of action is thought to be engaged (Flanagan & Wing, 1997). This model comprises both inverse and forward models. To perform a certain action, the inverse model generates the motor plan to achieve the required goal. The forward model provides stability to motor systems enabling rapid error correction by predicting the outcome from the generated motor plan before slower, sensorimotor feedback becomes available (Shadmehr, Smith, & Krakauer, 2010; Wolpert, 1997; Wolpert, Diedrichsen, & Flanagan, 2011). This forward model provides a template of the upcoming sensory consequences of an action. This is important when using grip selection tasks to ensure an appropriate movement plan is selected to complete actions comfortably (Johnson-Frey, McCarty, & Keen, 2004; Rosenbaum, Herbort, van der Wei, & Weiss, 2014).

Motor imagery provides a window into the neurological processes involved in representing actions and is hypothesised to play an important role in effective action planning (Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009; Jeannerod & Decety, 1995; Johnson, 2000; Wolpert & Flanagan, 2001). Motor imagery refers to the ability to imagine a movement without any overt execution of the movement (Decety & Grezes, 1999) and is thought to recruit the forward modelling aspect of the internal models to predict the sensory consequences of the imagined actions (Kilteni, Andersson, Houborg, & Ehrsson, 2018; Sirigu et al., 1996; Wolpert & Kawato, 1998). At a neurological level, motor imagery is thought to share common networks (e.g., parietal cerebellar structures and premotor cortices) with areas involved in planning and executing actions (Hanakawa, Dimyan, & Hallett, 2008; Sharma & Baron, 2013). In a seminal behavioural study, Rosenbaum et al. (1990) found that when asked to grasp a horizontal wooden bar and place the left or right end of the bar onto a target disk, most participants chose a grip that enabled their final hand position to be comfortable regardless of the target location. Researchers argue that the final grasp postures might be specified before movements are initiated (Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001). In another study, researchers investigated the motor planning and development of cognitive representation of grasp postures in TD children aged 7 – 9 years (Stöckel, Hughes, & Schack, 2012). They found that by mentally representing certain grasp postures, children could improve their ESC level. In TD individuals, efficiency in motor imagery performance is associated with a greater tendency to terminate movements in ESC (Fuelscher et al., 2016; Toussaint, Tahej, Thibaut, Possamai, & Badets, 2013). However, this relationship has not been observed in children with DCD (Fuelscher et al., 2016; Noten, Wilson, Ruddock, & Steenbergen, 2014). Fuelscher and colleagues (2016) found that performance on a hand rotation task was not related to the effect of ESC in those with DCD, as a result, they concluded that children with DCD appear less likely to automatically engage internal representations to plan grip selection tasks.

When required to grasp and rotate an object, many children with DCD opted for non ESC strategies, in particular, a minimal rotation strategy (van Swieten et al., 2010; Wilmut & Byrne, 2014a). Using this strategy, participants move their hand as little as possible, minimising initial wrist rotation at the start of a movement. For example, van Swieten and colleagues (2010) asked 5- to 13-year-old children with and without DCD to grasp and rotate a handle. They found that those with DCD used the minimal rotation strategy more than an ESC strategy compared to TD children. In another study involving the octagon task where participants had to reach and grasp a dial then rotate it to the assigned colour sequences, Wilmut and Byrne (2014a) obtained similar results. These findings suggest children with DCD favour a minimal rotation strategy (van Swieten et al., 2010; Wilmut & Byrne, 2014a) rather than the optimal ESC strategy that is associated with action representation to plan grip selection tasks (Fuelscher et al. 2016). Of note, for the octagon task, completing movements in uncomfortable states do not necessarily involve the use of a minimal rotation strategy. Some researchers, as mentioned above, simply reported this commonly used strategy for all the trials that ended in uncomfortable states.

Motor imagery can improve motor performance, in particular movement accuracy and efficacy (Di Rienzo et al., 2016). This imagery-driven motor learning can generalise to other tasks that are physically executed (Schuster et al., 2011; Theeuwes, Liefooghe, De Schryver, & De Houwer, 2018). Motor imagery is an emerging strategy to improve performances for elite athletes (Weinberg, 2008), musicians (Keller, 2012), and for the rehabilitation of neurological patients (Oostra, Vereecke, Jones, Vanderstraeten, & Vingerhoets, 2012; Spruijt et al., 2013) including those with DCD (Wilson et al., 2016; Wilson, Thomas, & Maruff, 2002). Motor imagery instructions have been used in studies involving DCD populations to encourage the adoption of a first-person perspective when performing a task and improving motor representations (Reynolds, Licari, Elliott, Lay, & Williams, 2015; Williams, Thomas, Maruff, & Wilson, 2008). Given the purported link between motor imagery and motor planning, the overlap of neural structures that support these processes and the improved motor imagery ability using motor imagery instructions, imagining motor tasks prior to execution could be an effective strategy to improve the planning ability of children with DCD.

In summary, children with DCD show a reduced tendency to plan grasp selection tasks compared to their TD peers. This could result from their reduced ability to engage internal models of action and default to using less efficient strategies such as minimal rotation. Motor imagery may provide an insight to poor planning ability as it could facilitate the generation of accurate internal models sub-serving motor planning and may be an effective strategy in improving motor skills of those with DCD. In this study, we investigated the pattern of grasping behaviours of children with and without DCD, specifically their selection of ESC or the minimal rotation strategies when completing a grip selection task. In addition, we investigated whether introducing motor imagery would influence their grip selection strategy. Finally, we looked at whether children with DCD could improve grip selection tasks to TD levels with motor imagery. In doing so, this study is the first to assess the influence of motor imagery on grasping behaviours in children with and without DCD.

2. Method

2.1. Participants

Thirty-six boys aged between 7- to 12 years were recruited from local schools, advertisements in the local newspaper and on websites for professional Occupational Therapist, Physiotherapist and Disability associations. All participants were screened to determine suitability and group status (DCD or TD).

Those in the DCD group (*n* = 17) satisfied the four Diagnostic and Statistical Manual of Mental Disorders (DSM-5) criteria (American Psychiatric Association, 2013). Conforming to Criteria A, participants with DCD scored less or equal to 85 (equivalent to the 15th percentile or lower) on their Neuromuscular Developmental Index (NDI) derived from the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997). Using the Developmental Coordination Disorder questionnaire (DCDQ07; Wilson, Crawford, Green, Roberts, Aylott & Kaplan, 2009), parents confirmed that movement difficulties significantly interfered with their children’s activities of daily living (criteria B). Criteria C and D were based on parent’s report. Parents reported that the onset of symptoms were evident in early childhood (criteria C). Moreover, as their children attended regular primary schools and did not have a diagnosis of a learning disorder, an IQ of greater than 70 was inferred. Confirmations of any visual impairments or neurological diagnoses (e.g., cerebral palsy, muscular dystrophy) that could affect movement were obtained from parents (criteria D). As attention deficit hyperactivity disorder (ADHD) is highly comorbid with those with DCD (Dewey, Kaplan, Crawford, & Wilson, 2002), parents completed the Swanson Nolan and Pelham-IV ADHD questionnaire (Bussing et al., 2008). Children with a neurological condition (*n* = 2) or showed an indication of ADHD (*n* = 1) were excluded from the study.

A cut-off NDI equal or above 90 (equivalent to the 20th percentile) was used to allocate participants into the TD group (*n* = 18). In addition, all those in the TD group had no diagnosed movement difficulties or neurological conditions. They all attended regular primary schools and there were no concerns regarding their academic performance or learning ability. The final sample consisted of 14 children with DCD (left handed = 2) and 18 TD (left handed = 1) children.

2.2. Experimental task - Octagon

The task required participants to grasp a small octagon dial by placing each finger on one flat side of the octagon and then turn it to direct a pointer to the named colour/s. Participants were free to grasp the octagon in their preferred way and rotate it in a clockwise or anticlockwise direction. This task is typically administered in one, two and three colour sequences (Bhoyroo et al., 2018; Fuelscher et al., 2016; Wilmut & Byrne, 2014a, 2014b) with complexity increasing as the number of sequences increases. For two and three colour sequences, participants were instructed to pause between colours. Any combination of clockwise-anticlockwise rotations could be used for a given colour sequence. Once the movement started, participants were asked not to adjust their grasp, doing so resulted in the trial being re-started. This occurred for five participants, in one or two trials, and for the two or three colour sequences only. They all successfully completed the trial on the second attempt.

2.3. Procedure

The cross-sectional study was approved by the Human Research Ethics Committee at the University where the research was undertaken (reference number: 016130F). Participating children and their parents provided written informed consent. The researcher was blinded to group status as scoring of the motor assessment was conducted after all tests were completed.

Participants were tested individually in a quiet room. They sat comfortably in front of the apparatus at a distance ensuring they could complete the tasks without difficulty, and placed their palms on their thighs. The colour sequences were presented in a blocked order, starting with the simplest sequence (one colour sequence). Participants completed two practice trials for each colour sequence. After successful completion of the practice trials the experimental trials commenced. The colour sequence/s used for the practice trials were not included in the experimental trials. Participants completed four different experimental trials for each colour sequence.

Participants completed the octagon task under two conditions. In condition one, Motor Planning (MP), instructions were given to grasp the octagon and turn the pointer to the assigned colour/s. No explicit instruction about grasping or imagining to grasp was given. In condition two, Motor Imagery and Planning (MIP), participants were provided with the same colour sequences as the MP condition. For each colour sequence, they were instructed to first imagine *how* they would grasp the octagon and rotate the pointer to the assigned colour/s, and then perform the action. Similar explicit instruction has been previously used in studies looking at motor imagery (e.g. Ehrsson, Geyer & Naito, 2003). The following instruction was given: '*I want you to imagine how you will grab the octagon and turn the pointer to colour one (for one colour sequences) or, to colour one and then to colour two (for two colour sequences) or, to colour one, then to colour two and finally to colour three (for three colour sequences). You will start imagining after I give the colour/s and say start.'* This process could be completed with eyes closed or open. When finished imagining the colour sequence, participants were instructed to say 'stop'. To ensure that participants imagined the actions, at the end of the imagination phase the participants indicated where they placed their thumb on the dial and whether their first rotation was clockwise or anticlockwise. Following this, they were instructed to complete the task the same way they imagined it. Participants completed all the colour sequences for the MP condition followed by the MIP condition. A 15-minute break was allocated between each condition.

Participants completed the task with their preferred hand as determined by the MAND (McCarron, 1997). For each colour sequence the initial position of the thumb, the dial rotation direction and end colour were recorded. To determine ESC we followed the comfort rating scheme used by Wilmut and Byrne (2014a). A binary code: comfortable (1) and uncomfortable (0) was used to score each colour sequence. For all trials that did not end in ESC, if the thumb was positioned on nodes 6 or 7 for right handed participants or 4 or 5 for left handed participants, the trial was categorised as using the 'minimal rotation' strategy [a strategy employed by Fuelscher et al. (2016), van Swieten et al. (2010) and Wilmut and Byrne (2014a)]. Each colour sequence was then scored using a binary code based on the absence or presence of the minimal rotation strategy. All trials were coded and scored by two independent researchers. In four cases, the videos were reviewed together to reach agreement.

2.4. Statistical analysis

Data analyses were performed using SPSS version 25.0 (IBM Corporation, Armonk, NY, USA). The data for descriptive statistics met the assumptions of normality and group differences were analysed using independent sample t-tests. The experimental data violated the assumption of normality, therefore non-parametric tests were used to examine between and within group patterns. Percentage ESC and percentage minimal rotation (the dependent variables) were calculated for each condition for each participant, for example: number of trials ending in ESC/total trials undertaken x 100 and similarly for minimal rotation. The higher the percentage, the higher the proportion of ESC or minimal rotation used. To compare between group differences in the motor planning strategy used for the MP and MIP condition the Mann Whitney U test was used. To investigate whether the groups changed their choice of strategy with MI instructions, a Wilcoxon Signed Rank test (Z) was used. We also compared the ESC level of the DCD group on the MIP condition to that of the TD group on the MP condition to determine whether the DCD group improved to TD levels with motor imagery using the Mann Whitney U test. Using the same test, interactions between the two groups were tested using the performance difference for ESC between MIP and MP for each colour sequence. Alpha was adjusted for the different analyses to control for multiple comparisons using Bonferroni corrections. The effect size, r, was calculated to estimate the practical significance of the results, an r-value of 0.1 indicates a small effect, 0.3 a medium effect and 0.5 a large effect (Field, 2009).

3. Results

3.1 Participant characteristics

Mean (M) and standard deviation (SD) for participant characteristics are shown in Table 1.

Table 1.
Mean (M) and standard deviation (SD) for participant characteristics

	DCD (n = 14)	TD (n = 18)	t	Group
	M (SD)	M (SD)		Difference
Age	10.05 (1.30)	10.05 (1.30)	0.004	1.00
NDI	72.29 (15.71)	106.61 (13.03)	6.76	< 0.001
SNAP	1.11 (0.77)	0.96 (0.57)	-0.55	0.60

Note. NDI=Neuromuscular Developmental Index, SNAP=Swanson Nolan and Pelham-IV ADHD score.

3.2 Motor planning under MP condition

Between group comparisons for the MP condition revealed that the DCD group ended in a significantly lower percentage of ESC than the TD group for the one colour (U = 42.50, p = 0.001, Md_{DCD} = 50.00, IQR_{DCD} = 31.25, Md_{TD} = 75.00, IQR_{TD} = 25.00) and the two colour (U = 55.50, p = 0.002, Md_{DCD} = 25.00, IQR_{DCD} = 6.25, Md_{TD} = 50.00, IQR_{TD} = 50.00) sequences (Figure 1A and Figure 1B). Effect sizes were large for both the one (r = 0.60) and two colour sequences (r = 0.50).

Children with DCD used the minimal rotation strategy more often than their TD peers for the one (U = 44.00, p = 0.001, r = 0.58, Md_{DCD} = 50.00, IQR_{DCD} = 31.25, Md_{TD} = 25.00, IQR_{TD} = 25.00) and two colour sequences (U = 49.00, p = 0.002, r = 0.54, Md_{DCD} = 62.50,

IQR_{DCD} = 25.00, Md_{TD} = 25.00, IQR_{TD} = 50.00) with large effect sizes. No difference in performances were observed for the three colour sequences (Figure 2A and 2B).

3.3 Motor planning across conditions

Within group analyses revealed that the DCD group had significantly higher percentages of ESC with large effect sizes for the MIP condition compared to the MP condition for the one colour sequence only ($Z = 2.460$, $p = 0.014$, $r = 0.66$) (Figure 1A and 1C). The opposite was found for the MIP condition where the minimal rotation strategy was used less compared to the MP condition for all sequences (one: $Z = 2.801$, $p = 0.005$, $r = 0.75$; two: $Z = 3.025$, $p = 0.002$, $r = 0.81$; three: $Z = 2.719$, $p = 0.007$, $r = 0.73$; Figure 1B and 1D).

A different outcome was found for the TD group for the two colour sequence only. For this sequence TD children demonstrated a higher percentage ESC for the MIP condition compared to the MP condition for the two colour sequences with a large effect size ($Z = 2.460$, $p = 0.014$, $r = 0.58$). There was no difference between conditions for the one and three colour sequences (Figure 2A and 2B). As can be seen in Figure 2B and 2D, the TD group were less likely to use the minimal rotation strategy for the MIP condition than the MP condition for the two colour sequence ($Z = 2.714$, $p = 0.007$, $r = 0.64$) only.

3.4 Motor planning of DCD group on MIP condition compared to TD group under MP condition

In order to determine whether children with DCD could improve their ESC performance to a TD level of motor imagery, we compared ESC level of the DCD group on the MIP condition to the TD group for the MP condition. For this analysis, no significant differences in ESC were found for any of the colour sequences between the groups. When group change in performance from the MIP to the MP condition was examined, a significant between group difference in ESC level was found for the one colour sequence only with a large effect size ($U = 47.00$, $p = 0.001$, $r = 0.56$).

3.5 Motor planning under MIP condition

The DCD group ended fewer trials in ESC than their peers for the MIP condition for the two colour sequence only ($U = 55.50$, $p = 0.004$, $r = 0.55$, Md_{DCD} = 25.00, IQR_{DCD} = 25.00, Md_{TD}

= 75.00, $IQR_{\mathrm{TD}} = 31.25$) with a large effect size. No significant between group differences were found for the all the colour sequences using the minimal rotation strategy.

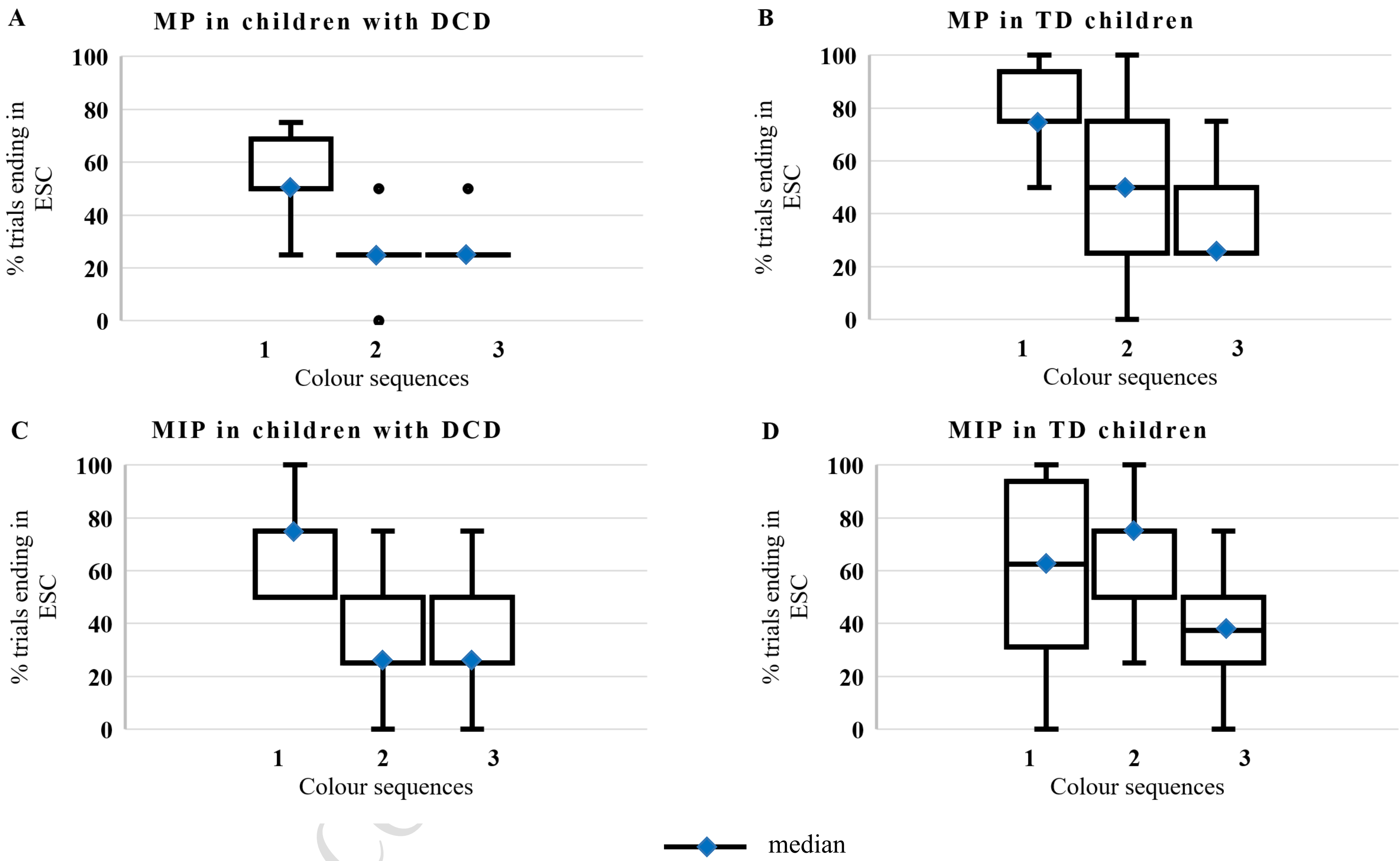

Figure 1. Box plots representing end-state-comfort (ESC) for the Motor Planning condition (MP) and Motor Planning and Imagery condition (MIP) for one, two and three colour sequences. A. ESC in children with DCD for MP condition. B. ESC in TD children for MP condition. C. ESC in children with DCD for MIP condition. D. ESC in TD children for MIP condition.

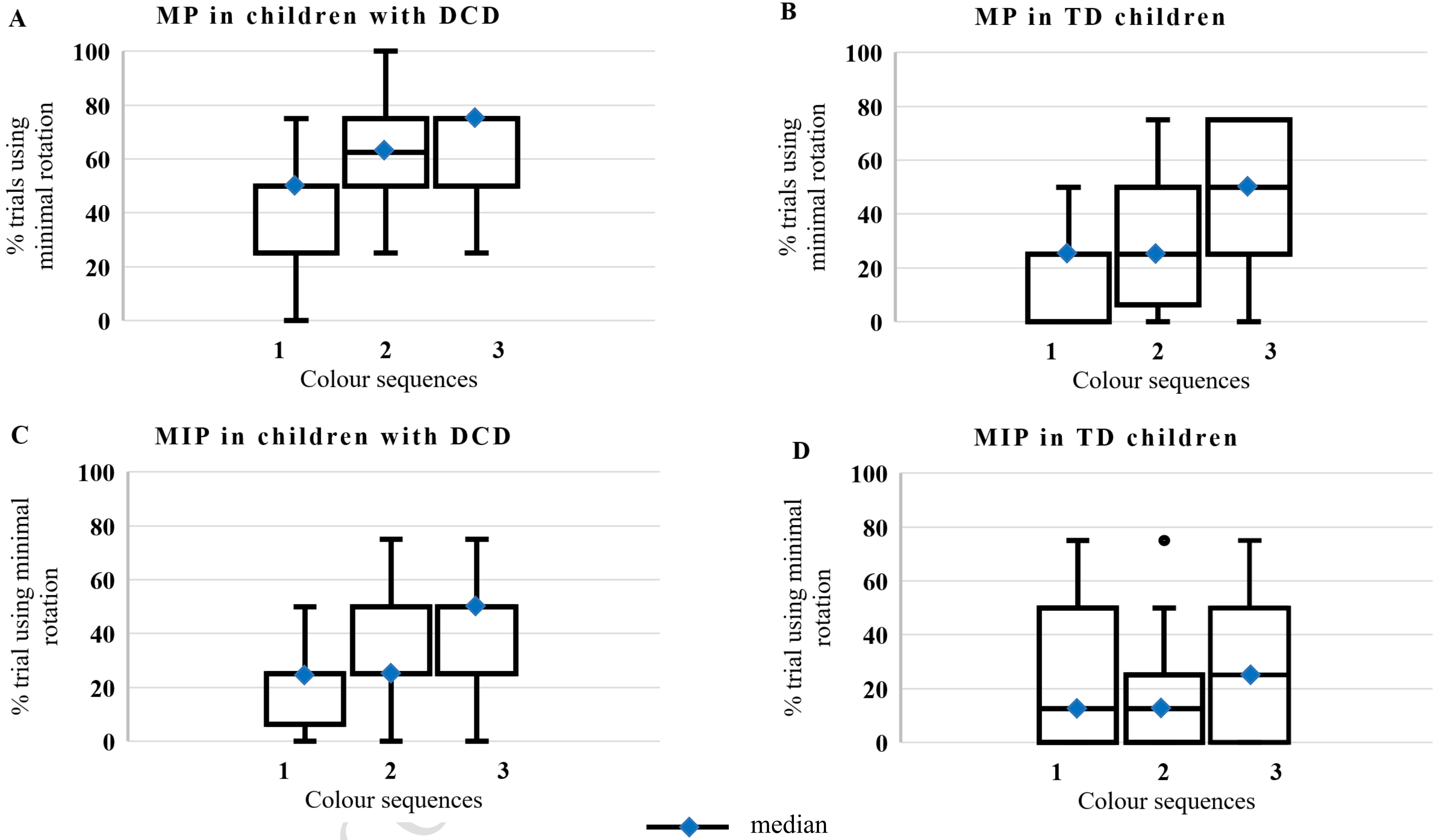

Figure 2. Box plots representing minimal rotation for the Motor Planning condition (MP) and Motor Planning and Imagery condition (MIP) for one, two and three colour sequences. A. Minimal rotation in children with DCD for MP condition. B. Minimal rotation in TD children for MP condition. C. Minimal rotation in children with DCD for MIP condition. D. Minimal rotation in TD children for MIP condition.

4. Discussion

In this study, the strategy used to plan movement sequences was examined in children with and without DCD on a motor planning condition and a motor planning and imagery condition. There were several key findings. First, in line with previous motor planning studies using the octagon task (Fuelscher et al., 2016; Wilmut & Byrne, 2014a), motor planning ability as demonstrated by the percentage of trials ending in ESC, was significantly lower in children with DCD compared to TD children for the one and two colour sequences. Second, also similar to previous research (van Swieten et al., 2010; Wilmut & Byrne, 2014a), children with DCD preferred to use a minimal rotation strategy when planning movements. Again, this was observed for the one and two colour sequences. Third, with motor imagery instructions, the DCD group showed significant improvements in their movement selections for ESC for the one colour sequence only. Interestingly, they significantly reduced their use of the minimal rotation strategy for all colour sequences. In the TD group, an increase in the percentage of trials ending in ESC was observed together with a reduction in using the minimal rotation strategy for the two colour sequence only. Finally, when motor imagery instructions were given to the DCD group, a significant improvement in their motor planning ability was observed for all the colour sequences resulting in similar outcomes to the TD group on the MP condition.

Similar to previous studies employing reach to grasp and object rotation tasks (Fuelscher et al., 2016; van Swieten et al., 2010; Wilmut & Byrne, 2014a), the DCD group were less likely to finish in ESC for the octagon tasks than their peers. Instead, they showed a preference for the minimal rotation strategy (van Swieten et al., 2010; Wilmut & Byrne, 2014a). This supports the findings by Wilmut and Byrne (2014a) that children with DCD consistently opted for the minimal rotation strategy compared to their peers. The internal model of action suggests that in planning for sequential action tasks, accurate specification of the motor commands of the sub movements are required to anticipate the sensory outcomes based on these motor commands (Flanagan, Bowman, & Johansson, 2006; Flanagan & Wing, 1997; Johansson & Flanagan, 2009). Accordingly, action representation may be associated with planning for an optimal grip selection (Johnson, 2000; Rosenbaum et al., 2001). While this association has been found in TD children (Toussaint et al., 2013), the failure to find an association between motor imagery and motor planning in children with DCD led to the conclusion that they may adopt a less optimal planning strategy by relying less on the internal model of action (Fuelscher et al., 2016).

Our findings suggest that children with DCD adopted an easier alternative, a minimal rotation strategy, which does not account for comfort at the end of the task. After an instruction for motor imagery, performance of the DCD group improved to a similar level as the TD group on the MP condition (without explicit instruction) for all colour sequences. This suggests that children with DCD may build well-defined internal representations of the action that promotes ESC when prompted to do so. This was supported by the finding that, across conditions, the DCD group significantly decreased their use of the minimal rotation strategy. In two previous studies, the researchers explicitly asked their participants that they might think about their grasp (van Swieten et al., 2010; Wilmut & Byrne, 2014a). However, in both studies, participants still completed more movements using the minimal rotation strategy. The instruction to mentally represent the whole action, rather than the grip or initial starting point prior to performance forces the adoption of a first person perspective. This in turn may facilitate the performer to consider the task constraints and thereby enable an internal representation of appropriate grasp postures that lead to ESC. To-date, this is the case for all studies that have tested motor imagery ability using explicit instructions in children with and without DCD (Reynolds et al., 2015; Williams et al., 2008).

Children without DCD significantly increased their ESC performance and decreased their use of the minimal rotation strategy for the two colour sequence on the MIP condition compared to the MP condition. For the most complex three colour sequence, they planned for ESC to a similar extent under both conditions. As previously discussed by Bhoyroo et al. (2018), children may not be able to proficiently plan a four-step task given their limited exposure to such tasks. It appears that simply imagining such actions once prior to completion may not be sufficient to improve their performances. This was observed for the DCD group for the one colour sequence only. However, although this group also reduced the minimal rotation strategy for the two and three colour sequences, a significant increase in their ESC level was not observed. It is probable that for the DCD group, the two colour sequence is a complex sequence to plan. The percentage of trials ending in ESC was still significantly lower than their TD peers on the MIP condition for this colour sequence.

Further, motor planning performance in children with DCD appears to be task dependent (Noten et al., 2014; Wilson et al., 2017). The observed poor motor planning performance has been associated with a deficit in predictive modelling (Adams, Lust, Wilson, & Steenbergen, 2014, 2016, 2017). In the present study, we observed that children with DCD significantly lowered their use of the minimal rotation strategy for the two and three colour sequences but did show non-significant increase in their ESC level. This suggests that the two colour sequence may be an easy task for the TD population but complex for the DCD population. Accordingly, children with DCD are unable to build accurate motor presentations for complex tasks resulting in an inefficiency in their motor planning ability.

Schoemaker and Smits-Engelsman (2015) found that many of those with DCD are not able to improve their motor skills simply with practice. Motor imagery training has now been implemented as an intervention to improve a range of motor skills in the DCD population (Adams, Smits-Engelsman, Lust, Wilson, & Steenbergen, 2017; Wilson et al., 2016; Wilson et al., 2002). Together with the findings of the present study, it is possible that a motor imagery strategy implemented immediately prior to completing an action, may deliver improved outcomes. It would also be of interest to investigate whether this group is able to retain or generalise this strategy. Consequently, replication of the study with a larger sample size and a wider range of tasks may determine the generalisability of the findings. This may provide an important avenue for improving planning of activities of daily living in children with DCD.

While our results are encouraging, care must be taken interpreting them considering the limitations in the design. As is typical of research focusing on neurodivergent populations, recruitment of children with DCD proved to be difficult and numbers were low, precluding the inclusion of a DCD control group. There is a possibility that the positive results may be due to a practice effect and counterbalancing of the conditions was not undertaken considering the modest sample size. However, several aspects in the design minimised this effect. For instance, while participants were informed that they were going to imagine and perform tasks, they did not know that the tasks were the same as those presented in the MP condition. Also, the participants completed the trials only once instead of the usual 12 times for each colour sequence as in previous studies (Fuelscher et al., 2016; Wilmut & Byrne, 2014a) which minimises the possibility for an observable practice effect. Further, participants had a 15-minute break between the two conditions. It has already been established that, many individuals with DCD have difficulty solving motor problems with practice alone (Schoemaker & Smits-Engelsman, 2015). . While this study provides an insight into the positive effect of motor imagery on planning motor actions, including a DCD and TD control group may further our knowledge regarding a learning effect.

5. Conclusion

Children with DCD favoured the minimal rotation strategy for completing the octagon grasp selection tasks. However, with the instruction to imagine the tasks prior to completion, they used an ESC strategy more often which improved their performance to baseline TD level. Their inability to imagine and complete the more complex tasks as efficiently as their peers may indicate a deficit in their predictive modelling. Together, it is possible that encouraging children with DCD to imagine their actions prior to execution could make a difference to their performance. This study identifies avenues for future research to develop well-designed motor imagery strategies to plan action.

Acknowledgements: We thank all the children and parents who participated in this study.

Funding: This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

6. References

Adams, I. L. J., Ferguson, G. D., Lust, J. M., Steenbergen, B., & Smits-Engelsman, B. C. (2016). Action planning and position sense in children with Developmental Coordination Disorder. *Human Movement Science, 46*, 196-208. doi:10.1016/j.humov.2016.01.006

Adams, I. L. J., Lust, J. M., Wilson, P. H., & Steenbergen, B. (2014). Compromised motor control in children with DCD: a deficit in the internal model?—A systematic review. *Neuroscience and Biobehavioral Reviews, 47*, 225-244. doi:10.1016/j.neubiorev.2014.08.011

Adams, I. L. J., Lust, J. M., Wilson, P. H., & Steenbergen, B. (2016). Testing predictive control of movement in children with developmental coordination disorder using converging operations. *British Journal of Psychology, 108*(1), 73-90. doi:10.1111/bjop.12183

Adams, I. L. J., Lust, J. M., Wilson, P. H., & Steenbergen, B. (2017). Development of motor imagery and anticipatory action planning in children with developmental coordination disorder – A longitudinal approach. *Human Movement Science, 55*, 296-306. doi:10.1016/j.humov.2017.08.021

Adams, I. L. J., Smits-Engelsman, B., Lust, J. M., Wilson, P. H., & Steenbergen, B. (2017). Feasibility of Motor Imagery Training for Children with Developmental Coordination Disorder – A Pilot Study. *Frontiers in Psychology, 8*(1271). doi:10.3389/fpsyg.2017.01271

American Psychiatric Association. (2013). *Diagnostic and statistical manual of mental disorders: DSM-5* (5th ed.). Washington, D.C: American Psychiatric Association.

Bhoyroo, R., Hands, B., Wilmut, K., Hyde, C., & Wigley, A. (2018). Investigating motor planning in children with DCD: Evidence from simple and complex grip-selection tasks. *Human Movement Science, 61*, 42-51. doi:10.1016/j.humov.2018.07.006

Bussing, R., Fernandez, M., Harwood, M., Hou, W., Garvan, C. W., Eyberg, S. M., & Swanson, J. M. (2008). Parent and teacher SNAP-IV ratings of attention deficit hyperactivity disorder symptoms: psychometric properties and normative ratings from a school district sample. *Assessment, 15*(3), 317-328. doi:10.1177/1073191107313888

Caeyenberghs, K., Tsoupas, J., Wilson, P. H., & Smits-Engelsman, B. C. (2009). Motor imagery development in primary school children. *Developmental Neuropsychology, 34*(1), 103-121. doi:10.1080/87565640802499183

Decety, J., & Grezes, J. (1999). Neural mechanisms subserving the perception of human actions. *Trends in Cogntive Sciences, 3*(5), 172-178. doi:10.1016/S1364-6613(99)01312-1

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

Di Rienzo, F., Debarnot, U., Daligault, S., Saruco, E., Delpuech, C., Doyon, J., . . . Guillot, A. (2016). Online and Offline Performance Gains Following Motor Imagery Practice: A Comprehensive Review of Behavioral and Neuroimaging Studies. *Frontiers in Human Neuroscience, 10*, 315-315. doi:10.3389/fnhum.2016.00315

Ehrsson, H. H., Geyer, S., & Naito, E. (2003). Imagery of Voluntary Movement of Fingers, Toes, and Tongue Activates Corresponding Body-Part-Specific Motor Representations. *Journal of Neurophysiology, 90*(5), 3304-3316. doi:10.1152/jn.01113.2002

Field, A. (2009). *Discovering Statistics Using SPSS* (3 ed.). London: Sage Publications Ltd.

Flanagan, J. R., Bowman, M. C., & Johansson, R. S. (2006). Control strategies in object manipulation tasks. *Current Opinion in Neurobiology, 16*(6), 650-659. doi:10.1016/j.conb.2006.10.005

Flanagan, J. R., & Wing, A. M. (1997). The Role of Internal Models in Motion Planning and Control: Evidence from Grip Force Adjustments during Movements of Hand-Held Loads. *The Journal of Neuroscience, 17*(4), 1519-1528. doi:10.1523/jneurosci.17-04-01519.1997

Fuelscher, I., Williams, J., Wilmut, K., Enticott, P. G., & Hyde, C. (2016). Modeling the Maturation of Grip Selection Planning and Action Representation: Insights from Typical and Atypical Motor Development. *Frontiers in Psychology, 7*, 108. doi:10.3389/fpsyg.2016.00108

Hanakawa, T., Dimyan, M. A., & Hallett, M. (2008). Motor Planning, Imagery, and Execution in the Distributed Motor Network: A Time-Course Study with Functional MRI. *Cerebral Cortex, 18*(12), 2775-2788. doi:10.1093/cercor/bhn036

Jeannerod, M., & Decety, J. (1995). Mental motor imagery: A window into the representational stages of action. *Current Opinion in Neurobiology, 5*(6), 727-732. doi:10.1016/0959-4388(95)80099-9

Johansson, R. S., & Flanagan, J. R. (2009). Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience, 10*(5), 345-359. doi:10.1038/nrn2621

Johnson-Frey, S., McCarty, M., & Keen, R. (2004). Reaching beyond spatial perception: Effects of intended future actions on visually guided prehension. *Visual Cognition, 11*(2-3), 371-399. doi:10.1080/13506280344000329

Johnson, S. H. (2000). Thinking ahead: the case for motor imagery in prospective judgements of prehension. *Cognition, 74*(1), 33-70. doi:10.1016/S0010-0277(99)00063-3

Keller, P. E. (2012). Mental imagery in music performance: underlying mechanisms and potential benefits. *Annals of the New York Academy of Sciences, 1252*(1), 206-213. doi:10.1111/j.1749-6632.2011.06439.x

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

McCarron, L. T. (1997). *McCarron Assessment of Neuromuscular Development* (3rd ed.). Dallas, TX: McCarron-Dial Systems Inc.

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

Oostra, K. M., Vereecke, A., Jones, K., Vanderstraeten, G., & Vingerhoets, G. (2012). Motor Imagery Ability in Patients With Traumatic Brain Injury. *Archives of Physical Medicine and Rehabilitation, 93*(5), 828-833. doi:10.1016/j.apmr.2011.11.018

Reynolds, J. E., Licari, M. K., Elliott, C., Lay, B. S., & Williams, J. (2015). Motor imagery ability and internal representation of movement in children with probable developmental coordination disorder. *Human Movement Science, 44*, 287-298. doi:10.1016/j.humov.2015.09.012

Rosenbaum, D. A., Herbort, O., van der Wei, R., & Weiss, D. J. (2014). What's in a grasp? Simple acts of picking up a water glass or turning a handle are the product of multilayered cognitive plans and sophisticated neural computations. *American Scientist, 102*(5), 366-373. doi:10.1511/2014.110.366

Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J. D., & Jorgensen, M. J. (1990). Constraints for action selection: overhand versus underhand grips. In M. Jeannerod (Ed.), *Attention and performance XIII: motor representation and control.* (pp. 321-342). Lawrence Erlbaum Associates: Hillsdale, New Jersey.

Rosenbaum, D. A., Meulenbroek, R. J., Vaughan, J., & Jansen, C. (2001). Posture-based motion planning: Applications to grasping. *Psychological Review, 108*(4), 709-734. doi:10.1037/0033-295X.108.4.709

Rosenbaum, D. A., Vaughan, J., Barnes, H. J., & Jorgensen, M. J. (1992). Time Course of Movement Planning: Selection of Handgrips for Object Manipulation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*(5), 1058-1073. doi:10.1037/0278-7393.18.5.1058

Schoemaker, M. M., & Smits-Engelsman, B. C. M. (2015). Is Treating Motor Problems in DCD Just a Matter of Practice and More Practice? *Current Developmental Disorders Reports, 2*(2), 150-156. doi:10.1007/s40474-015-0045-7

Schuster, C., Hilfiker, R., Amft, O., Scheidhauer, A., Andrews, B., Butler, J., . . . Ettlin, T. (2011). Best practice for motor imagery: a systematic literature review on motor imagery training elements in five different disciplines. *BMC Medicine, 9*(1), 75-109. doi:10.1186/1741-7015-9-75

Shadmehr, R., Smith, M. A., & Krakauer, J. W. (2010). Error correction, sensory prediction, and adaptation in motor control. *Annual Review of Neuroscience, 33*, 89-108. doi:10.1146/annurev-neuro-060909-153135

Sharma, N., & Baron, J.-C. (2013). Does motor imagery share neural networks with executed movement: a multivariate fMRI analysis. *Frontiers in Human Neuroscience, 7*(564). doi:10.3389/fnhum.2013.00564

Sirigu, A., Duhamel, J. R., Cohen, L., Pillon, B., Dubois, B., & Agid, Y. (1996). The mental representation of hand movements after parietal cortex damage. *Science, 273*(5281), 1564-1566. doi:10.1126/science.273.5281.1564

Spruijt, S., Jouen, F., Molina, M., Kudlinski, C., Guilbert, J., & Steenbergen, B. (2013). Assessment of motor imagery in cerebral palsy via mental chronometry: the case of walking. *Research in Developmental Disabilities, 34*(11), 4154-4160. doi:10.1016/j.ridd.2013.08.044

Stöckel, T., Hughes, C. M., & Schack, T. (2012). Representation of grasp postures and anticipatory motor planning in children. *Psychological Research, 76*(6), 768-776. doi:10.1007/s00426-011-0387-7

Theeuwes, M., Liefooghe, B., De Schryver, M., & De Houwer, J. (2018). The role of motor imagery in learning via instructions. *Acta Psychologica, 184*, 110-123. doi:10.1016/j.actpsy.2017.05.002

Toussaint, L., Tahej, P. K., Thibaut, J. P., Possamai, C. A., & Badets, A. (2013). On the link between action planning and motor imagery: a developmental study. *Experimental Brain Research, 231*(3), 331-339. doi:10.1007/s00221-013-3698-7

van Swieten, L. M., van Bergen, E., Williams, J. H., Wilson, A. D., Plumb, M. S., Kent, S. W., & Mon-Williams, M. A. (2010). A test of motor (not executive) planning in developmental coordination disorder and autism. *Journal of Experimental Psychology: Human Perception and Performance, 36*(2), 493-499. doi:10.1037/a0017177

Weinberg, R. (2008). Does Imagery Work? Effects on Performance and Mental Skills. *Journal of Imagery Research in Sport and Physical Activity, 3*(1), 1-21. doi:10.2202/1932-0191.1025

Williams, J., Thomas, P. R., Maruff, P., & 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), 270-285. doi:10.1016/j.humov.2008.02.008

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

Wilmut, K., & Byrne, M. (2014b). Influences of grasp selection in typically developing children. *Acta Psychologica, 148*, 181-187. doi:10.1016/j.actpsy.2014.02.005

Wilson, B. N., Crawford, S. G., Green, D., Roberts, G., Aylott, A., & Kaplan, B. J. (2009). Psychometric properties of the revised Developmental Coordination Disorder Questionnaire. *Physical & occupational therapy in pediatrics, 29*(2), 184-204. doi:10.3109/01942638.2014.980928

Wilson, P. H., Adams, I. L. J., Caeyenberghs, K., Thomas, P. R., Smits-Engelsman, B., & Steenbergen, B. (2016). Motor imagery training enhances motor skill in children with DCD:

A replication study. *Research in Developmental Disabilities, 57*, 54-62. doi:10.1016/j.ridd.2016.06.014

Wilson, P. H., Smits-Engelsman, B., Caeyenberghs, K., Steenbergen, B., Sugden, D., Clark, J., . . . Blank, R. (2017). Cognitive and neuroimaging findings in developmental coordination disorder: new insights from a systematic review of recent research. *Developmental Medicine and Child Neurology, 59*(11), 1117-1129. doi:10.1111/dmcn.13530

Wilson, P. H., Thomas, P. R., & Maruff, P. (2002). Motor imagery training ameliorates motor clumsiness in children. *Journal of Child Neurolology, 17*(7), 491-498. doi:10.1177/088307380201700704

Wolpert, D. M. (1997). Computational approaches to motor control. *Trends in Cognitive Sciences, 1*(6), 209-216. doi:10.1016/S1364-6613(97)01070-X

Wolpert, D. M., Diedrichsen, J., & Flanagan, J. R. (2011). Principles of sensorimotor learning. *Nature Reviews Neuroscience, 12*(12), 739-751. doi:10.1038/nrn3112

Wolpert, D. M., & Flanagan, J. R. (2001). Motor prediction. *Current Biology, 11*(18), R729-732. doi:10.1016/S0960-9822(01)00432-8

Wolpert, D. M., & Kawato, M. (1998). Multiple paired forward and inverse models for motor control. *Neural Networks, 11*(7-8), 1317-1329. doi:10.1016/S0893-6080(98)00066-5

Zwicker, J. G., Suto, M., Harris, S. R., Vlasakova, N., & Missiuna, C. (2018). Developmental coordination disorder is more than a motor problem: Children describe the impact of daily struggles on their quality of life. *British Journal of Occupational Therapy, 81*(2), 65-73. doi:10.1177/0308022617735046