Investigating motor planning in children with DCD: Evidence from simple and complex grip-selection tasks

The authors of this paper are (affiliations listed below): Ranila Bhoyroo[1], Beth Hands[1], Kate Wilmut[2], Christian Hyde[3] and Adam Wigley[1]

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

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

[3] Deakin Child Study Centre, School of Psychology, Deakin University, Victoria, Australia

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

☎ +61 8 9433 0296

fax +61 8 9433 0210

ranila.bhoyroo1@my.nd.edu.au

Abstract

Several studies suggest that children with Developmental Coordination Disorder (DCD) may be able to plan simple movements as well as their peers, but experience increasing difficulties as the movements become complex. The present study aimed to clarify the nature of motor planning in DCD, including a putative deficit, by being the first to investigate motor planning using converging measures of simple and complex motor planning in a single sample of children with DCD. Boys aged between 8 – 12 years with (n = 10) and without DCD (n = 17) completed three commonly used ‘simple’ (bar grasping, sword, and bar transport tasks) measures and one ‘complex’ (octagon task) measure of end-state-comfort (ESC), a classic measurement of motor planning ability. To achieve ESC when manipulating an object, a person may choose to start with an uncomfortable grip in order to end the movement in a comfortable position. Results indicate that the participants with DCD planned for ESC as efficiently as their peers when performing the ‘simple’ measures of ESC but were significantly less likely to end their performances in ESC than those without DCD for the more ‘complex’ octagon task. Taken together, our data suggest that school-aged children with DCD may be able to plan simple movements as efficiently as their peers, but have more difficulty doing so for multi-movement or complex sequences. Based on the assumption that the efficiency of such motor planning is dependent on the integrity of internal modelling systems, we argue that our study provides indirect support for the internal modelling deficit hypothesis.

Keywords: children, developmental coordination disorder, end-state-comfort, ESC, internal model

1 Introduction

Developmental Coordination Disorder (DCD) is a neurodevelopmental condition that affects a person's ability to perform coordinated movements and significantly interferes with their academic performance and activities of daily living (American Psychiatric Association, 2013). These difficulties become apparent from an early age and persist into adulthood in up to 75% of those diagnosed at an early age (Kirby, Sugden, & Purcell, 2014). The motor difficulties cannot be explained by other neurodevelopmental disorders such as cerebral palsy. A growing number of researchers have found that poor planning of movements is commonly identified in children with DCD (see Adams, Lust, Wilson, & Steenbergen, 2014 for a review).

Many of the simple tasks we perform in our daily life require complex motor planning skills, for instance, picking up a pencil and writing or grasping house keys to lock or unlock a door. Since any given action can be performed using an almost infinite series of motor commands [known as the *degrees of freedom* problem (Bernstein, 1967)], consideration of the best way to perform a task given the environmental and biomechanical constraints is important to allow efficient completion of the actions. For example, if the end of the house key to be inserted in the lock lies in the same direction a person is facing, then that person is likely to pick up the key using a comfortable hand position: this allows them to also end the movement comfortably. However, if the key lies in the opposite direction then to complete the movement comfortably the individual must sacrifice a comfortable start grip in order to lock/unlock the door in a comfortable way. This is known as the 'end-state-comfort' (ESC) effect (Rosenbaum, Herbort, van der Wei, & Weiss, 2014; Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Stöckel, Hughes, & Schack, 2012). It has been observed that the tendency for individuals to end their movements in ESC increases into early adulthood in typically developing individuals (Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Crajé, & Steenbergen, 2013; Stöckel et al., 2012; Thibaut & Toussaint, 2010; van Swieten et al., 2010; Wilmut & Byrne, 2014b). However, clinical populations with difficulties planning movement, such as those with cerebral palsy, are often less likely to complete movements in ESC than healthy individuals (Crajé et al., 2010; Steenbergen, Jongbloed-Pereboom, Spruijt, & Gordon, 2013). Accordingly, it is generally accepted that a greater tendency to terminate movements in ESC reflects optimization of motor planning (Rosenbaum et al., 1992).

Motor planning in individuals with DCD may also be compromised as those with DCD have reported an inability to perform many activities of daily living (e.g. brushing teeth, dressing and using utensils) that require complex motor planning skills (Zwicker, Harris, & Klassen, 2013). Consequently, investigations of motor planning in individuals with DCD have become common in recent years, with most studies using ‘grip-selection’ tasks. These tasks require that an individual grasps an object using an uncomfortable initial position to enable completion of the movement in a comfortable end position known as ESC (Rosenbaum et al., 1990). Results are mixed, which could be due to the variety of grip selection tasks used that place varying demands on motor planning (e.g. Adams, Lust, Wilson, & Steenbergen, 2017; Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016). To date, the majority of studies using ‘simple’ grip-selection tasks to investigate motor planning in children with DCD have found no differences between their DCD and control groups. For example, Smyth and Mason (1997) assessed children aged between 4 – 8 years with and without DCD on a bar transport and a handle rotation task. The bar transport task required children to simply pick up a wooden bar and place it so that the indicated end was facing them when placed to either their right or left. To complete this with a comfortable end state, participants had to reach and grasp a wooden bar using an overhand grip to place the right end facing them, or using an underhand grip to place the left end facing them. For the handle rotation task, participants had to grasp a handle and rotate it to 180° so that a tab covered a picture. To complete this task in ESC, the participant's thumb should point towards the tab when the handle is grasped. For both tasks, the initial grip was noted to assess for ESC. The authors found no difference in performance between those with and without DCD suggesting that children with DCD could plan for ESC. This finding has been replicated in studies using tasks of similar design. For instance, Noten, Wilson, Ruddock, and Steenbergen (2014) used a bar rotation task where children with and without DCD aged between 7 – 12 years grasped a bar and placed the specified end into a cup. To complete this task comfortably, participants had to end their movements with their thumb pointing in an upwards direction. Again, no significant group differences between individuals with and without DCD were observed. In another study, Adams, Ferguson, Lust, Steenbergen, and Smits-Engelsman (2016) used the same bar rotation task (low precision) and the sword task (high precision) with 6 – 11 years old children with and without DCD to address whether task complexity affected motor planning in this population. The bar rotation task was as described above and to complete the sword task in ESC, participants had to grasp the handle of the sword which was oriented differently each time and insert it into a hole making sure their thumb pointed towards the hole. The authors found significant group differences for the latter only and concluded that children with DCD planned less for ESC when the task required precision on completion. Interestingly, when the same participants were tested on the sword task two years later, no group differences were observed (Adams et al., 2017). This suggests a possible lag in the development of motor planning skills for ESC in children with DCD and that the sword task which was of high complexity for younger children was no longer as complex for those aged 8 – 13 years. Of note, all the above tasks had two grip choices (reach-to-grasp the bar with a thump up/thumb down or using an underhand/overhand grip) and consisted of two movement sequences (reach-to-grasp – place/turn). Given the simplicity of these task parameters, it is likely that demands on motor planning were low for certain age groups, which may explain why those with DCD consistently performed at the same level as those without DCD. This view is supported by findings from other studies using similar grip-selection tasks that have reported that individuals with DCD are able to perform simple movements as effectively as their same age peers (Adams, Ferguson, et al., 2016; Adams et al., 2017; Noten et al., 2014; Smyth & Mason, 1997).

A recent meta-analysis reported that impaired motor planning in those with DCD become more apparent with an increase in task complexity (Wilson et al., 2017). For grip selection tasks, complexity increases when the number of initial grip choices and/or possible movement sequences increase. Studies using a more 'complex' octagon grip selection task have found significant differences between children with DCD and their typically developing peers aged 8- to 12- years (Fuelscher et al., 2016) and 7- to 11-years (Wilmut & Byrne, 2014a). To complete this task, participants select a grip and turn a pointer which is initially at 0° to the colored stripes arrayed around the eight-sided dial in one, two or three color sequences. Studies found that healthy adults show a decreased propensity to terminate movements in ESC as the number of colors involved in a trial increases, with accuracy falling as low as 55% for the three color sequences (Wilmut & Byrne, 2014a, 2014b). Fuelscher and colleagues (2016) and Wilmut and Byrne (2014a) also found that all participants were more likely to choose ESC for the one color sequence than for the other color sequences. At the between group level, Wilmut and Byrne (2014a) found that children with DCD ended significantly fewer trials in ESC than their typically developing peers on the one and three color sequences. Interestingly, for the three color sequences both the typically developing children and those with DCD terminated less than 50% of their trials in ESC. Fuelscher et al. (2016) also showed that children with DCD are less likely to terminate their movements in ESC while performing the octagon task providing further support to the idea that children with DCD are less able to plan complex movements than their typically developing peers.

Taken together, the available evidence indicates that performances on simple motor planning tasks are similar for those with and without DCD, and that both groups are able to plan movements at age appropriate levels (Adams, Ferguson, et al., 2016; Adams et al., 2017; Noten et al., 2014; Smyth & Mason, 1997). This could indicate that the tasks were insufficiently complex to discriminate between the two groups. A decrease in performance efficiency is consistently observed on complex tasks indicating that a deficit in motor planning may become more pronounced when task demands are high (Fuelscher et al., 2016; Wilmut & Byrne, 2014a). While this view is consistent with the clinical profile of many with DCD, results to-date do not provide a clear understanding about the motor planning deficit in children with DCD based on the differences in methodology in each study (e.g., screening procedures, age groups and tasks). Therefore, an empirical investigation administering both simple and complex tasks to a single sample of children with and without DCD is necessary in order to draw conclusions about the nature of the putative motor planning deficit in children with DCD.

The purpose of the studyis to assess 8 – 12 year old children with and without DCD on three 'simple' (bar rotation, sword task, bar transport) and one 'complex' (octagon) motor planning tasks. As described, each has different task demands and levels of complexity. We hypothesised there would be no group differences between children with and without DCD on the simpler tasks of ESC; the bar grasping, sword and bar transport tasks. ESC would become less evident when planning demands increased in the complex octagon tasks.

Accordingly, we expected group performance differences to be observed on all the three color sequences of the octagon task.

2 Method

2.1 Participants

Participants were recruited from local schools, advertisements in the local newspaper and on websites for professional Occupational Therapist, Physiotherapist and Disability associations. The final sample comprised 27 boys aged 8- to 12 years. Only boys were included in order to eliminate any potential gender differences given the small sample size. All participants were screened on the four criteria for DCD (A, B, C, and D) described in the Diagnostic and Statistical Manual of Mental Disorders (DSM-5; APA, 2013). Criterion A was based on the participant's Neuromuscular Developmental Index (NDI) derived from the McCarron Assessment of Neuromuscular Development (MAND; McCarron, 1997) and the observations of expert assessors. In accordance with the MAND guidelines, those with an NDI of less than 85 which is equivalent to the 15^{th} percentile were classified as DCD (n = 9) and those with NDI scores above or equal to 90 were classified as TD (n = 19; with one exception as noted below). To meet criterion B, parents completed the Developmental Coordination Disorder questionnaire (DCDQ07; Wilson, Crawford, Green, Roberts, Aylott & Kaplan, 2009) to confirm that movement difficulties significantly interfered with their children's activities of daily living. Criterion C was met if parents verbally confirmed that symptoms were evident in early childhood. Criterion D was met based on the absence of a prior diagnosis of a neurological condition from parent's report. Participants were excluded if they had any other neurological diagnosis affecting movement (e.g., cerebral palsy, muscular dystrophy). The participants were also screened for attention deficit hyperactive disorder (ADHD) using the Swanson Nolan and Pelham-IV ADHD questionnaire (SNAP; Bussing et al., 2008), as it commonly co-morbid with DCD. One participant was excluded from the study as their SNAP scores indicated ADHD.

One participant with an NDI above 85 was included in the DCD group. This decision was based on clinical observations of two independent experts, parent report and previous movement assessments. His parents reported that he experienced significant movement difficulties and significant functional difficulties were noted on the DCDQ07 questionnaire. In October 2016, this participant was diagnosed with DCD by an Occupational Therapist based on results from the DCDQ07 and the Bruininks-Oseretsky Test of Motor Proficiency-2 (Bruininks & Bruininks, 2005). The final sample consisted of 10 children with DCD (left-handed = 2; M_{age} = 10.10, *SD* = 1.26, range = 8.36 – 12.00) and 17 without DCD (left-handed = 2; M_{age} = 10.36, *SD* = 1.04, range = 8.28 – 11.81).

The study was approved by the Human Research Ethics Committee at The University of Notre Dame Australia (reference number: 016130F). All parents and participants provided written informed consent.

2.2 Tasks and procedures

In this cross-sectional study, participants completed three ‘simple’ measures; bar grasping, sword and bar transport task, and one ‘complex’ measure; the octagon task, of motor planning. The order of the tasks was set to provide a gentle, balanced progression of cognitive load and stimulation; as follows, bar rotation (easy) sword task (medium), octagon task (incrementally increasing difficulty) and finally bar transport task (low). The participants sat comfortably in front of the apparatus at a distance ensuring they could complete the tasks without difficulty, and placed their palms down on the provided handshapes (see Fig. 1).

Performances were recorded using a video camera mounted on a tripod. Each task included a set of non-critical and critical trials. The non-critical trials allowed participants to both start and end in a comfortable state. For the critical trials, the children were required to start with an uncomfortable position to order to end in a comfortable position. Participants were provided two practice trials for the bar grasping, sword and octagon tasks. All participants completed the practice trials successfully and commenced the experimental trials. There was no practice for the bar transport task. No explicit instructions were provided to the participants about grip comfort either at the start or end of the movements. For all the tasks, participants were informed that they could not change their grasp once they gripped the equipment. If they changed their grasp during the experiment, the trial was re-started. This occurred mostly for the longer three color sequence on the octagon task. In all cases, the participants successfully completed the trial on the 2nd or 3rd attempt. Participants completed all four tasks within 15 – 20 minutes (including 1 - 2 minutes break between each task). Before commencing each task, participants were asked to inform the researcher if they were tired during the session. In this instance, testing would be stopped and resumed when the participants were ready. None of the participants reported tiredness during the session.

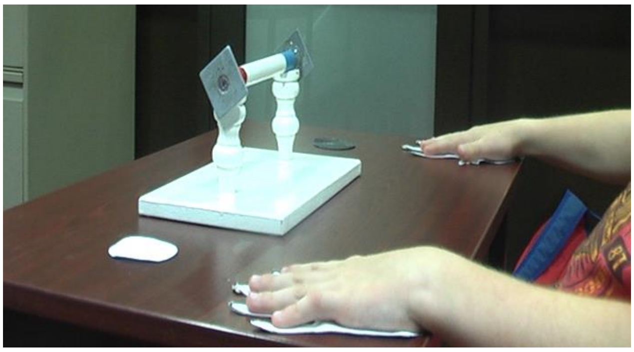

Figure 1. Example set up of participant of bar transport task. Participants place their hands on the handshapes when not executing the trials.

2.3 Simple measures of motor planning

2.3.1 Bar grasping task

The apparatus for bar grasping task (Adams, Ferguson, et al., 2016; Crajé et al., 2010; Noten et al., 2014) comprised a black square frame with a wooden bar, half painted white and half yellow placed in the middle. In front of the frame, a white cup was placed (see Fig. 2). The bar could be rotated to place the yellow end at specific orientations; 30°, 90°, 150°, 210°, 270° and 330°. For the task, children were asked to grasp the bar using their whole hand, remove it from the frame and place the yellow end in the cup. The children completed all the trials with their preferred hand. After each trial, the end posture of the hand was scored, which could be either comfortable (thumb up) or uncomfortable (thumb down). For right-handed participants, the critical trials were 30°, 270° and 330° and 30°, 90° and 330° for left-handed participants.

Figure 2. Set up of bar grasping task. The yellow end of bar set up is placed at 0°.

2.3.2 Sword task

The sword task (Adams, Ferguson, et al., 2016; Adams, Lust, Wilson, & Steenbergen, 2016; Adams et al., 2017; Crajé et al., 2010; Jongbloed-Pereboom et al., 2013) required participants to use a whole hand grip to pick up a wooden sword from the table and insert it into a slot of a 'treasure chest'. There were six possible orientations for the sword to be presented, including the null orientation where the sword points directly at the slot (see Fig. 3). Orientation 1 (the null orientation) served as the practice trial and was not included in the experiment. For right-handed participants, orientations 2 and 3 and for left-handed participants, orientations 5 and 6 serve as critical trials. At the end of each trial, the end posture of the hand was scored, which could be comfortable (thumb close to treasure box) or uncomfortable (thumb away from treasure box).

Figure 3. Set up of sword task. The sword is placed at the null (demonstration) orientation.

2.3.3 Bar transport task

The bar transport task (Rosenbaum et al., 1990; Smyth & Mason, 1997; Thibaut & Toussaint, 2010) consisted of a wooden bar that rested on two supports (see Fig. 4). One end of the bar was painted blue and the other red. From the participant's perspective, the blue end was placed on the right and red end on the left. A white disk was placed at the left side of the support and a black disk on the right. Instruction was given to grasp the bar with a whole hand grip and to place the specified end on the specified disk. Participants could use either an underhand or an overhand grip to grasp the bar. This grip was noted.

For right handed participants, a comfortable end state was achieved with an initial underhand grasp when placing the red end of the bar on a disk or an overhand grasp when placing the place blue end on a disk. For left-handed participants a reverse grasp type was required to complete the same movements in ESC. Participants completed four trials for the task. Critical trials were identified as placing the red end on the white disk and the blue end on the black disk for both right and left handed participants.

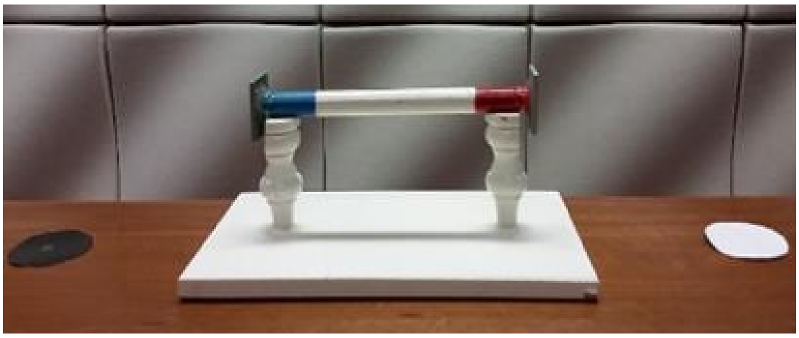

Figure 4. Set up of bar transport task. The right end of the bar is placed on the left from participant's perspective.

2.4 Complex measure of motor planning

2.4.1 Octagon task

The apparatus for the octagon task (Fuelscher et al., 2016; Wilmut & Byrne, 2014a, 2014b) consisted of a wooden octagon mounted on a wooden black board. Each side of the octagon had a different color stripe; purple, red, blue, brown, green, grey, pink, yellow (see Fig. 5). A smaller "dial" octagon with a black pointer was placed onto the bigger one. A selection of dial sizes was available between 6.5 cm to 12.5 cm, with participants choosing the one that most comfortably fits their grip. Before starting any trial, the researcher ensured that the pointer was at 0° (pointing upwards to the purple color).

One, two and three color sequences were used for this task. The experiment consisted of four trials for each color sequence and participants complete a total of 12 trials for the entire task. Each trial began when the researcher called out the color or the color sequence. The participants were required to reach and grasp the small octagon by placing each finger on one flat side of the octagon and turn the pointer to the given color or color sequences. Participants were free to grasp the octagon in any way they liked and rotate the octagon either clockwise or anticlockwise. Any combination of rotations could be used for two and three color sequences to complete sequences.

Following the Wilmut and Byrne (2014a) and Fuelscher et al. (2016) experimental procedure, color sequences were presented in blocked order, starting with one color sequences and ending with three color sequences. For two and three color sequences, participants rotated the octagon to the first color of the sequence and then rotate to the next until the sequence is completed. All sequences ending with a green color required a 180° rotation of the hand and thus needed the participant to grasp the octagon in an uncomfortable start position in order to end the movement in a comfortable position, therefore a comfortable grasp would not suffice. These sequences were therefore classified as critical trials. To determine end state comfort, for each color sequence the initial position of the thumb, rotation and end color was noted. A comfort rating was assigned using the validated coding scheme developed by Wilmut and Byrne (2014a).

Figure 5. Set up of octagon task. The pointer is placed at purple color.

2.5 Data analysis

Data were examined for normality and as the data violated the assumptions for normality, non-parametric tests were used. Data analyses were performed using SPSS version 24.0. For all the tasks, the trials were scored as being comfortable (1) or uncomfortable (0). For each participant, percentage ESC for each task was calculated as follows: number of trials ending in ESC /total trials undertaken x 100. The Mann Whitney U test was used to compare the mean percentage ESC for each task as well as the non-critical and critical conditions for each task between groups (DCD v TD). Alpha was set to 0.05 for all analyses. *r* was calculated using the procedure outlined in Field (2009) to estimate the practical significance of the results, where an *r*-value of 0.1 indicates a small effect, 0.3 a medium effect and 0.5 a large effect.

3 Results

3.1 Participant characteristics

There were no significant differences between the two groups for age and SNAP scores (Table 1). As expected, the DCD group scored significantly lower than the TD group for the NDI.

Table 1

Sample Characteristics for DCD and TD groups

	DCD (n = 10)		TD (n = 17)		*p-value*
	M	*SD*	*M*	*SD*	
Age	10.10	1.26	10.36	1.04	0.59
SNAP	1.05	0.61	0.94	0.56	0.64
NDI	67.00	16.66	105.88	12.32	**0.00**

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

3.2 End State Comfort for simple measures of motor planning

The Mann-Whitney *U*-test revealed no significant group differences in the percentage of trials ending in ESC for the bar grasping, sword and bar transport tasks. For these tasks, both groups ended their performances in comfortable end states more often with mean percentage ESC levels ranging between 61% - 75%. There were no differences between the DCD and the TD group for the non-critical and critical conditions for each simple task.

3.3 End State Comfort for complex measure of motor planning

Significant group differences were found in ESC on one color (U = 41.00, p = 0.019), two color (U = 32.00, p = 0.004), and three color sequences (U = 40.00, p = 0.007) of the octagon task (see Fig. 6). For all the color sequences, the TD group ended more of their movements in ESC than the DCD group. A medium effect was noted for the one color sequence (r = -0.45) while a large effect was observed for the two (r = -0.56) and three color sequences (r = -0.52). A consistent decrease in the mean percentage ending in ESC was observed in the TD group as the sequence length increased. In the DCD group, a similar decrease in mean ESC was observed for the two and three color sequences.

For all the critical conditions of each color sequence, it can be seen in Figure 7 that the mean percentage ESC was lower for the boys with DCD than those without DCD (1 color: U = 50.0, p = 0.021, r = -0.45; 2 colors: U = 47.0, p = 0.034, r = -0.41; 3 colors: U = 40.0, p = 0.006, r = -0.53). None of the participants with DCD could complete the critical trials in ESC for the one and three color sequence. For the non- critical condition, a significant group difference in performance ending in ESC was observed only for the two color sequence, U = 47.0, p = 0.038, r = -0.40.

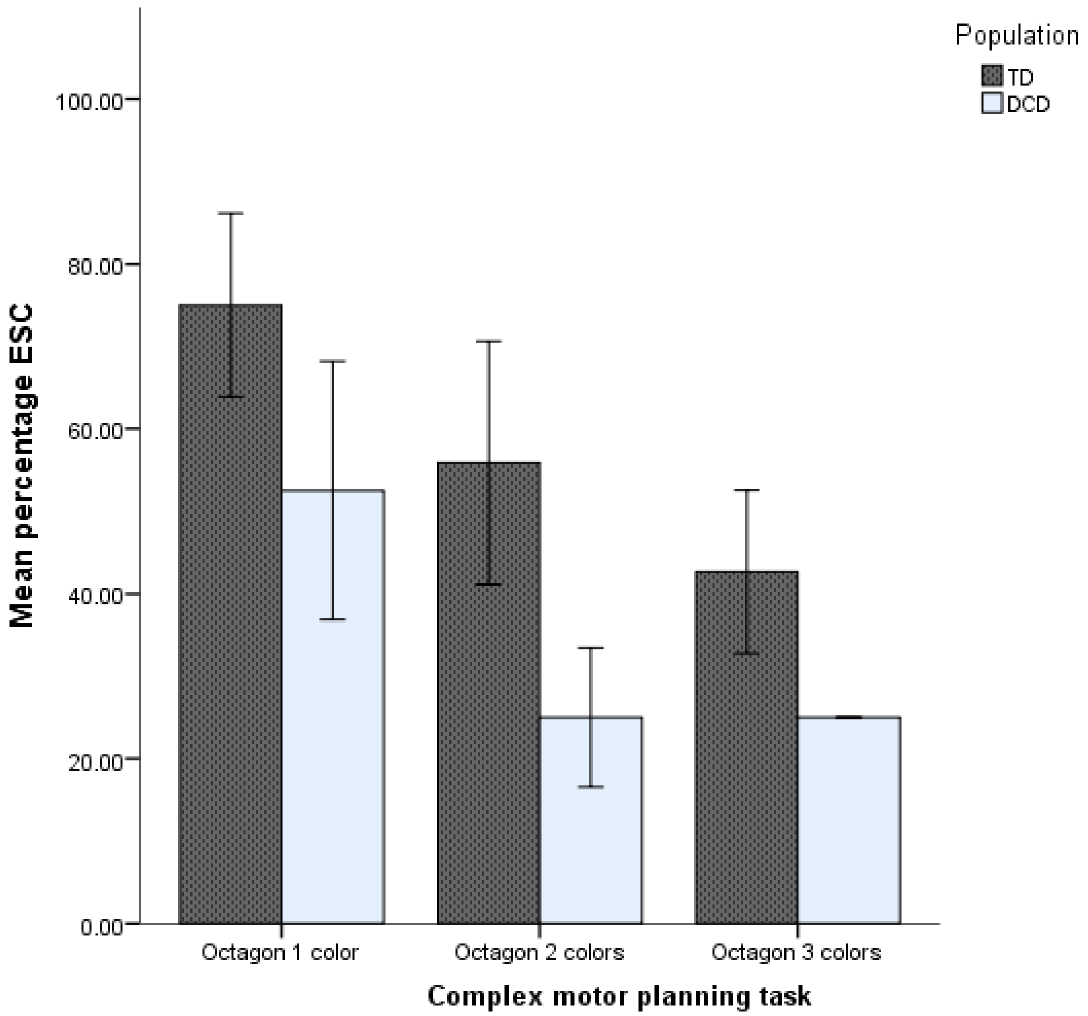

Figure 6. End-state-comfort for complex task. The mean percentage of trials that ended in end-state-comfort for the one, two and three color sequences of the octagon task for the TD and DCD group. The error bars represent 95% confidence intervals.

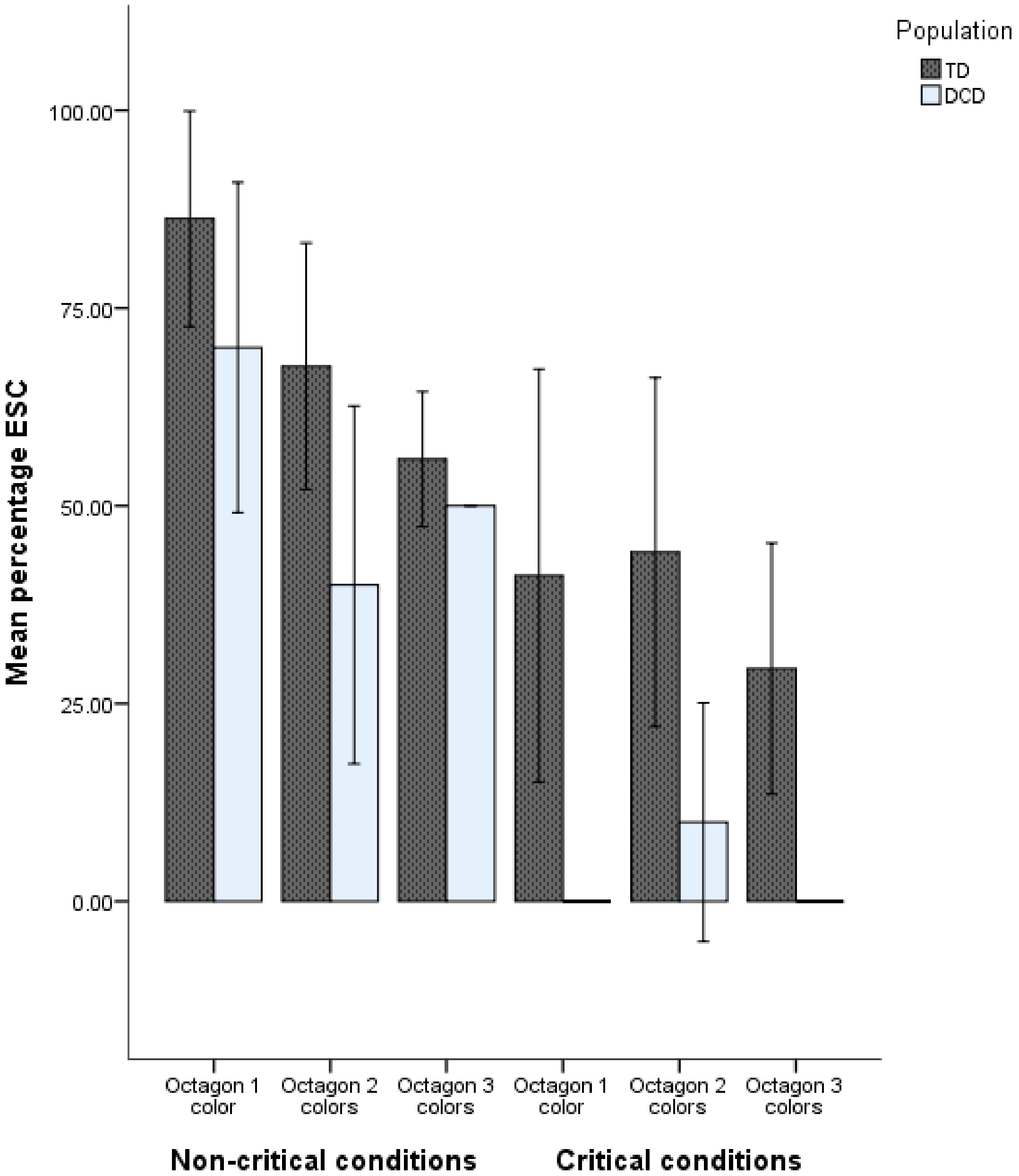

Figure 7. End-state-comfort for difficulty levels. The mean percentage of trials that ended in end-state-comfort for the non-critical and critical conditions of the one, two and three color sequences of the octagon task for the TD and DCD group. The error bars represent 95% confidence intervals.

4 Discussion

The current study aimed to clarify the nature of motor planning in children with DCD, by comparing performances on three simple (the bar grasping, sword and bar transport tasks) and one complex measure of motor planning (the octagon task) in children with and without DCD. As predicted, we found that both groups performed at similar levels for the simple tasks, regardless of non-critical or critical conditions. However, the participants with DCD ended less trials in ESC compared to their typically developing peers for all the color sequences of the complex octagon task. These findings supported the view that children with DCD experience motor planning difficulties which become more apparent as task complexity increases. Collectively, our results provide evidence for the putative motor planning deficit in children with DCD.

4.1 Planning of simple movements is age-appropriate in school-aged boys with DCD

Boys with DCD planned for ESC as well as TD children for the simple bar grasping, sword and bar transport task. This is in line with other motor planning studies which also found no group differences on these tasks (Adams et al., 2017; Noten et al., 2014; Smyth & Mason, 1997). The three simple tasks used in this study consisted of two steps and required participants to choose from an underhand or overhand grip or a thumb up or thumb down hand position and place the object in a cup, a hole or on a disk. Of note, regardless of the initial grip selection, these simple tasks could be completed without ending the movement in an awkward hand position whereas, the complex tasks described below are contingent on a specific initial grasp configuration for ESC. This could therefore decrease the sensitivity of assessing motor planning ability (Adams et al., 2017). In sum, our study showed that boys aged between 8 – 12 years with DCD can plan simple two step movements as efficiently as their TD peers.

4.2 Boys with DCD demonstrate atypical motor planning for complex movements

Similar to earlier studies (Fuelscher et al., 2016; Wilmut & Byrne, 2014a), young boys with DCD and their age-matched controls became less able to complete their action in ESC as the number of color sequences of the complex octagon task increased. That is, motor planning efficiency appeared to decrease as task complexity increased. This has previously been reported in studies involving young TD adults (Fuelscher et al., 2016; Wilmut & Byrne, 2014a, 2014b) and those with hemiparetic cerebral palsy (Mutsaarts, Steenbergen, & Bekkering, 2005). The current study further extends previous findings by showing for each color sequence of the 'complex' task, when children with DCD are presented with a harder condition within the same task, they completed fewer trials in ESC than their peers for the critical conditions. This indicates that the octagon task is sufficiently complex to differentiate motor planning ability in 8- to 12-year-old boys with and without DCD.

In line with Fuelscher et al. (2016) and Wilmut and Byrne (2014a), children with DCD ended their performances more frequently in ESC for the one color sequence, a two-step task than the three (two color) and four (three color) step tasks. Interestingly, while children with DCD performed similarly for the two and three color sequences, those without DCD demonstrated a decrease in performance from 56% to 43%. The three color sequences consisted of four sub movements inclusive of the initial decision of choosing one grasp from eight available choices. Many movement tasks require both motor and executive planning (Stöckel & Hughes, 2016; van Swieten et al., 2010) and tasks with greater cognitive costs affect planning for ESC to a greater extent than tasks with moderate or low cognitive costs

(Stöckel & Hughes, 2015). In the present study, the participants had to listen carefully to examiner's instructions which placed additional demands on their cognitive processes such as attention and working memory. It is therefore possible that successful planning for ESC in the longer three color sequences relied more heavily on executive functioning rather than motor planning skills, particularly for those with DCD (Fuelscher et al., 2018).

An alternative explanation could be that children aged between 8 – 12 years have insufficient experience to perform similar four step movements that allow efficient planning. Motor planning skills develop from previously learned behaviours (van Swieten et al., 2010). Therefore habitual movements are an important consideration for grasp selection (Herbort & Butz, 2011; Scharoun, Gonzalez, Bryden, & Roy, 2016; Stöckel et al., 2012). Most individuals become proficient with certain movements and can generalise this skill to many daily activities or when faced with new movement demands. The three color sequence is a four staged movement (reach-to-grasp – turn – turn – turn). Individuals are infrequently required to complete a movement consisting of four sub-movements in most daily activities. Given the limited opportunity to practice complex tasks in real life, it is less likely that individuals will learn to develop and apply complex planning skills as often as other simpler tasks, particularly for children relative to adults.

Of note, a linear decrease in performance was expected as the number of color sequences was increased for the non-critical conditions. Instead, we observed that the DCD group ended fewer trials in ESC for the non-critical conditions for the two color sequence compared to the three color sequences. In addition, for the critical conditions, children with DCD performed better for the two color sequences than for the one and three color sequences. While we have obtained significant results with the current sample size, we acknowledge that it is rather modest.

4.3 Motor planning deficit in children with DCD: support for a deficit in the internal model?

In short, our findings support the hypothesis that although boys with DCD are able to plan and conduct simple movements as well as TD children, they are less efficient as task complexity increases. This is the first study to administer a comprehensive battery of motor planning tasks including 'simple and 'complex' constraints, therefore our findings provide an important addition to the current body of literature describing the integrity of motor planning in children with DCD. These findings are consistent with the view that motor planning is impaired in people with DCD, though this profile is not by no means universal. One plausible explanation being explored regarding the reduced capacity for motor planning observed in the children with DCD in this study is a possible deficit in the internal model (e.g. Adams et al., 2017). This theory proposes that the poor motor skill typical of DCD may, at least partly, be attributable to difficulties generating and/or monitoring internal action representations. Completing the octagon task involves considering positioning of the thumb from 8 available choices, grasping the octagon in a supination or pronation position and rotating it in a clockwise or anticlockwise direction depending on the number of movement sequences and goal. To perform such an action, individuals must build internal representations of the required movement consisting of the inverse and forward model (Blakemore, Wolpert, & Frith, 2002; Kawato, 1999). When performing a desired movement, inverse models are constructed consisting of motor commands accommodating such variables as the force, timing, and trajectory of limbs – i.e., muscle coordination/sequencing, needed to achieve the goal. Based on this inverse model, a predictive model is generated to estimate the future states of the limbs from the current position (Wolpert, Diedrichsen, & Flanagan, 2011; Wolpert & Flanagan, 2001). If there is discrepancy between the predicted and the desired outcome, then an error signal is generated and the motor commands are adjusted accordingly to achieve the desired goal (Shadmehr & Krakauer, 2008; Shadmehr, Smith, & Krakauer, 2010). In support of the view that motor planning is engaged during the performance of complex tasks is dependent on this 'internal modelling' process, recent work has demonstrated that decreased efficiency performing motor imagery (a classic proxy for generating internal action representations) predicts a reduced likelihood of completing trials on the octagon task in ESC (Fuelscher et al., 2016). Accordingly, we suggest that the atypical motor planning in our sample of boys with DCD may be associated with difficulties engaging internal modelling mechanisms (as per the internal modelling deficit hypothesis; Adams et al., 2016).

4.4 Strengths and limitations of the study

The present study compared motor planning ability in a single sample of children with and without DCD using a variety of simple and complex commonly used motor tasks. Being the first to compare motor planning ability in both groups on both critical and non-critical trials within each simple and complex task demonstrated that motor planning ability is significantly impaired in children with DCD for complex tasks. Despite the strong findings, several limitations were noted. Firstly, recruitment of boys with DCD proved problematic, hence explaining our modest sample size. Secondly, poor motor planning performances on the three color sequence could indicate a deficit in both motor and executive functioning. However, no formal tests of executive planning were undertaken in the study that could support this. Future research aiming to use the octagon task with the DCD population should consider including tests of executive functioning as well. Thirdly, the classification of ESC for the octagon task has been developed based on typically developing adults. While this task has been shown to differentiate between children with and without DCD at a group level, future research should aim to validate this task for assessing inter-individual differences in both children with and without DCD.

5 Conclusion

The present study investigated the putative motor planning deficit in 8 – 12-year-old boys with and without DCD by administering a series of commonly used ‘simple’ and ‘complex’ motor planning tasks. We extend previous findings by indicating that school-aged children with DCD plan for ESC for simple tasks as efficiently as their peers however this ability decreases as task complexity increases. We found that the three sequence octagon task was too complex for this age group regardless of the developmental issue and that the one and two color sequence of the octagon task would be better measures of motor planning ability in this age group. As the efficiency of motor planning is dependent on the integrity of internal modelling systems, we argue that our study provides indirect support for the internal modelling deficit hypothesis.

Declaration of interest: None

Acknowledgements

We would like to thank the Collaborative Research Network for funding this research. Heartfelt thanks to all participants and parents and schools for their support.

References

Adams, I. L., 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., 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., 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., 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

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

Bernstein, N. A. (1967). *The co-ordination and regulation of movements*. Oxford: Pergamon Press.

Blakemore, S. J., Wolpert, D. M., & Frith, C. D. (2002). Abnormalities in the awareness of action. *Trends in Cognitive Sciences, 6*(6), 237-242. doi:Doi 10.1016/S1364-6613(02)01907-1

Bruininks, R. H., & Bruininks, B. D. (2005). *Bruininks-Oseretsky Test of Motor Proficiency, (BOT-2)* (2nd ed.). Minneapolis, MN: Pearson Assessment.

Crajé, C., van Elk, M., Beeren, M., van Schie, H. T., Bekkering, H., & Steenbergen, B. (2010). Compromised motor planning and Motor Imagery in right Hemiparetic Cerebral Palsy. *Research in Developmental Disabilities, 31*(6), 1313-1322. doi:10.1016/j.ridd.2010.07.010

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

Fuelscher, I., Caeyenberghs, K., Enticott, P. G., Williams, J., Lum, J., & Hyde, C. (2018). Differential activation of brain areas in children with developmental coordination disorder during tasks of manual dexterity: An ALE meta-analysis. *Neuroscience and Biobehavioral Reviews, 86*, 77-84. doi:10.1016/j.neubiorev.2018.01.002

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

Herbort, O., & Butz, M. V. (2011). Habitual and goal-directed factors in (everyday) object handling. *Experimental Brain Research, 213*(4), 371-382. doi:10.1007/s00221-011-2787-8

Jongbloed-Pereboom, M., Nijhuis-van der Sanden, M. W. G., Saraber-Schiphorst, N., Crajé, C., & Steenbergen, B. (2013). Anticipatory action planning increases from 3 to 10years of age in typically developing children. *Journal of Experimental Child Psychology, 114*(2), 295-305. doi:10.1016/j.jecp.2012.08.008

Kawato, M. (1999). Internal models for motor control and trajectory planning. *Current Opinion in Neurobiology, 9*(6), 718-727. doi:10.1016/S0959-4388(99)00028-8

Kirby, A., Sugden, D., & Purcell, C. (2014). Diagnosing developmental coordination disorders. *Archives of Disease in Childhood, 99*(3), 292-296. doi:10.1136/archdischild-2012-303569

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

Mutsaarts, M., Steenbergen, B., & Bekkering, H. (2005). Anticipatory Planning of Movement Sequences in Hemiparetic Cerebral Palsy. *Motor Control, 9*(4), 439.

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

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., 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

Scharoun, S. M., Gonzalez, D. A., Bryden, P. J., & Roy, E. A. (2016). The influence of action execution on end-state comfort and underlying movement kinematics: An examination of right and left handed participants. *Acta Psychologica, 164*, 1-9. doi:10.1016/j.actpsy.2015.12.002

Shadmehr, R., & Krakauer, J. W. (2008). A computational neuroanatomy for motor control. *Experimental Brain Research, 185*(3), 359-381. doi:10.1007/s00221-008-1280-5

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

Smyth, M. M., & Mason, U. C. (1997). Planning and execution of action in children with and without developmental coordination disorder. *Journal of Child Psychology and Psychiatry, 38*(8), 1023-1037. doi:10.1111/j.1469-7610.1997.tb01619.x

Steenbergen, B., Jongbloed-Pereboom, M., Spruijt, S., & Gordon, A. M. (2013). Impaired motor planning and motor imagery in children with unilateral spastic cerebral palsy: challenges for the future of pediatric rehabilitation. *Developmental Medicine and Child Neurology, 55*(s4), 43-46. doi:10.1111/dmcn.12306

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

Stöckel, T., & Hughes, C. M. L. (2015). Effects of Multiple Planning Constraints on the Development of Grasp Posture Planning in 6- to 10-Year-Old Children. *Developmental Psychology, 51*(9), 1254-1261. doi:10.1037/a0039506

Stöckel, T., & Hughes, C. M. L. (2016). The relation between measures of cognitive and motor functioning in 5- to 6-year-old children. *Psychological Research, 80*(4), 543-554. doi:10.1007/s00426-015-0662-0

Thibaut, J. P., & Toussaint, L. (2010). Developing motor planning over ages. *Journal of Experimental Child Psychology, 105*(1), 116-129. doi:10.1016/j.jecp.2009.10.003

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

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., 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

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

Zwicker, J. G., Harris, S. R., & Klassen, A. F. (2013). Quality of life domains affected in children with developmental coordination disorder: a systematic review. *Child: Care, Health and Development, 39*(4), 562-580. doi:10.1111/j.1365-2214.2012.01379.x