The influence of task paradigm on motor imagery ability in children with Developmental Coordination Disorder

G.D. Ferguson a, P.H. Wilson b, B.C.M. Smits-Engelsman a,c,*

a Faculty of Health Sciences, Department of Health and Rehabilitation Sciences, University of Cape Town, F45 Old Main Building, Groote Schuur Hospital, Observatory, Cape Town 7925, South Africa
b School of Psychology, Australian Catholic University, 115 Victoria Pde., Melbourne, VIC 3065, Australia
c Faculty of Kinesiology and Rehabilitation Sciences, Department of Kinesiology, Movement Control and Neuroplasticity Research Group, Katholieke Universiteit Leuven, Tervuursevest 101, Postbox 1501, B-3001 Heverlee, Belgium

ABSTRACT

Children with Developmental Coordination Disorder (DCD) have difficulty imagining movements such that they conform to the customary temporal constraints of real performance. We examined whether this ability is influenced by the choice of task used to elicit motor imagery (MI). Performance of typically developing (TD) \((n = 30)\) and children with DCD \((n = 30)\) was compared on two tasks: the Visually Guided Pointing Task (VGPT) and the Computerized Virtual Radial Fitts Task (C-VRFT). Since the VGPT places higher demands on executive functions like working memory but requires less spatial planning, we reasoned that the C-VRFT would provide a purer measure of motor imagery (or simulation). Based on our earlier work, we predicted that imagery deficits in DCD would more likely manifest on the C-VRFT. Results showed high correlations between tasks in terms of executed and imagined movement time suggest that both tasks measure MI ability. However, group differences were more pronounced in the imagined condition of the radial Fitts’ task. Taken together, the more spatially complex C-VRFT appears to be a more sensitive measure of motor imagery, better discriminating between DCD and TD. Implications for theory and practice are discussed.

1. Introduction

Children with Developmental Coordination Disorder (DCD) have difficulty performing coordinated movements which, by definition, affects their functioning in daily life (American Psychiatric Association, 2013). Building knowledge of the underlying motor control deficits in DCD through research is critical for designing interventions that can ameliorate their motor control issues (Smits-Engelsman et al., 2013).

Among other issues in motor control, a recent meta-analysis regarding the underlying deficits associated with DCD reported moderate to large effect sizes on measures of predictive motor control, consistent with the internal modeling deficit (IMD) account of DCD (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). Internal modeling is thought to be critical for online control and the process of motor learning. A critical aspect of control is the capacity of the motor control...
system to model its own dynamics or, more precisely, the systematic relationship between input and output signals. This function enables the performer to predict the consequences of a movement (forward internal model) and to calculate the necessary control parameters (e.g. force, timing, distance, etc.) to enable the realization of a desired goal state (inverse model) thereby ensuring the efficiency of the motor system (Kawato, 1999; Shadmehr & Krakauer, 2008; Wolpert & Miall, 1996).

In a comprehensive meta-analysis of the literature, Wilson et al. (2013) assemble converging data that show children with DCD have a reduced ability to develop and update internal models and, as such, require more time and practice to build action representations. Further to the IMD account, immaturities in neurodevelopment (Hyde & Wilson, 2013) have been suggested in DCD, specifically in areas of the brain that process and store action representations such as the posterior parietal cortex and cerebellum (Desmurget et al., 1999; Desmurget & Sirigu, 2009).

Motor Imagery (MI) is a cognitive process that can be studied via different methods. MI is defined as the ability to mentally represent discrete motor tasks or a sequence of movements without active movement (Decety, 1996; Jeannerod & Decety, 1995). To best elicit MI, participants are asked to imagine and feel themselves making movements from a first-person, egocentric perspective (Gabbard, 2009; Vogt, Di Rienzo, Collet, Collins, & Guillot, 2013).

The link between MI and internal models is also shown in studies which demonstrate that MI elicits activation of similar neural networks as those responsible for planning, executing and controlling overt movements. These networks include the parietal cortex, supplementary motor cortex, primary motor cortex, cerebellum and premotor cortex, all of which are activated, albeit to a lesser extent, when imagining movements (Higuchi, Imamizu, & Kawato, 2007; Ryding, Decety, Sjoholm, Stenberg, & Ingvar, 1993). As well, MI conforms to the same kinematic rules and biomechanical and environmental constraints that govern real movements (Decety & Jeannerod, 1995; Jeannerod & Decety, 1995). Notably, imagined movement time is highly correlated with actual movement time (MT), and both show the characteristic trade-off between speed and accuracy that is defined by Fitts’ law (Sirigu et al., 1995; Smits-Engelsman & Wilson, 2013a). Indeed, by older childhood, the correlation between real and imagined movement is around .70 (Smits-Engelsman & Wilson, 2013b), and the logarithmic relationship defined by Fitts’ law – which describes the trade-off between MT and target size – approaches an R value of .90 (Wilson, Maruff, Ives, & Currie, 2001). Fitts’ law is one of the most robust phenomena in motor control, one that is expressed even under conditions of restricted visual feedback (Wu, Yang, & Honda, 2010). For this reason, the Fitts paradigm has been used extensively to examine the structure of motor representations in children and adults. In studies of children, use of possible heuristics like counting movements or time, without reference to task constraints like target size, does not explain the pattern of results on the Fitts task because they would need to draw on explicit knowledge of the trade-off, which is generally not considered by children (Wilson, Maruff, Ives, & Currie, 2001).

While a number of studies have shown motor imagery deficits in children with DCD (Deconinck, Spitaels, Fias, & Lenoir, 2009; Lewis, Vance, Maruff, Wilson, & Cairney, 2008; Maruff, Wilson, Trebilcock, & Currie, 1999; Williams, Omizzolo, Galea, & Vance, 2013; Williams, Thomas, Maruff, & Wilson, 2008), the use of many different paradigms and task constraints has clouded the interpretation of findings across studies. Mental chronometry paradigms involve explicit use of MI and measure ability by the correlation between real and imagined action. The most common tasks require imagined pointing and include the Visually Guided Pointing Task (VGPT) (Maruff, Wilson, Trebilcock, & Currie, 1999; Sirigu et al., 1996) and the Computerized Virtual Radial Fitts Task (C-VRFT) (Caeyenberghs, Tsoupas, Wilson, & Smits-Engelsman, 2009; Caeyenberghs, Wilson, van Roon, Swinnen, & Smits-Engelsman, 2009; Smits-Engelsman, Van Galen, & Duysens, 2002).

Both tasks have been used successfully to assess MI ability in children however, each requires different levels of motor planning, control and executive function, which are relevant when examining MI performance in children with DCD. For the VGPT (Fig. 1A), demands on motor planning are moderate but cognitive demands are relatively high. Participants perform a series of reciprocal tapping movements (consecutive back and forth movements), using a pen, from one side of a line drawn on a page to a target box of varying sizes. Earlier studies using the VGPT have showed that the index of performance is higher during reciprocal movements than during discrete movements and it is suggested that information processing is more economical (Smits-Engelsman, Swinnen, & Duysens, 2006; Smits-Engelsman, Van Galen, & Duysens, 2002).

While executing tasks on the VGPT motor control parameters related to speed, force and amplitude must be set carefully in relation to target location, but the repeated movements to stable locations in space provide the performer with ongoing feedback for error correction. However, at the same time, the performer must keep count of the number of completed movements, enlisting working memory. In the imagined condition, the cognitive demand increases because the performer must not only keep count but also alert the assessor verbally when the imagined movement ends at the appropriate repetition. The motor and cognitive components of the VGPT give it a dual-task quality. A number of studies suggest that children with DCD have problems with executive functioning and dual tasking (Wilson et al., 2013). Taken together, the higher cognitive load may confound the assessment of MI, especially among children with DCD.

The computerized VRFT eliminates the need for counting (and the associated cognitive bias) because a sequence of five distinct targets is presented and participants are not required to indicate task commencement or completion (Caeyenberghs, Wilson, et al., 2009). However, where cognitive demands are reduced in the C-VRFT, motor planning demands are increased which relate more directly to the motor simulation required of the task (Vogt et al., 2013). It requires a sequence of five back-and-forth movements to distinct targets located on a radial axis from a home base (see Fig. 1B). Varied trajectories for each target impose higher motor planning demands on this task compared with the set spatial configuration of the VGPT. In addition, the endpoint characteristics of the movements in the two tasks are different. For the VGPT, surface breaking occurs each time the pen taps inside the target. For the C-VRFT, however, each movement occurs over the surface of a digitizer, stops
within the target area, and then reverses back to the starting point. Homing in on discrete targets through parameterization of hand trajectory and endpoint is thus more demanding for the C-VRFT if one is to preserve accuracy. Together, the C-VRFT imposes a higher motor planning load (and movement complexity) for the assessment of MI. We would expect these constraints to be particularly challenging for children with DCD who show poor parameterization of movement across spatial, timing and force dimensions (Wilson et al., 2013). Specifically, variability in execution would reflect an inability to filter the noise produced by small muscles, and it could be due to deficits in precise control between agonists and antagonist muscle activation in children with DCD (Ferguson, Duysens, & Smits-Engelsman, 2015). Another advantage of the C-VRFT is the use of the digitizer that permits measurement of the kinematic profile of the movement and accuracy.

Assessment of MI ability using the VGPT has consistently shown that children with DCD do not conform to Fitts’ law when imagining movements (Lewis et al., 2008; Maruff et al., 1999; Williams et al., 2013; Wilson et al., 2001). For the C-VRFT, validity in the assessment of MI among typically developing (TD) children was demonstrated by Caeyenberghs and colleagues (Caeyenberghs, Tsoupas, et al., 2009; Caeyenberghs, Wilson, et al., 2009). However to date, the C-VRFT has not been used to examine the performance of children with DCD, although it has been used in studies of children with traumatic brain injury (TBI) (Caeyenberghs, van Roon, Swinnen, & Smits-Engelsman, 2009).

Our work presented here extends previous research on MI in several ways. First, the critical issue is that no study has compared two measures of explicit MI ability in the same population. Caeyenberghs, Tsoupas, et al. (2009), Caeyenberghs, van Roon, et al. (2009) and Caeyenberghs, Wilson, et al. (2009) examined the performance of children (7–12 years) using the C-VRFT, a mental hand rotation task (HRT) and a letter rotation task (LRT). Correlations between indices of motor and visual imagery showed a marginal positive correlation between the responses on the HRT and the LRT overall ($r = 0.35$) and a weak, non-significant correlation between the C-VRFT and LRT ($r = 0.16$). It was concluded that the HRT may tap more automatic processes that require implicit knowledge of body-centred movement representations (viz. body schema) whereas the C-VRFT requires more controlled processing and active manipulation of covert motor plans (Caeyenberghs, Tsoupas, et al. 2009; Schwoebel, Buxbaum, & Coslett, 2004). Williams et al. (2013) found that deficits in MI ability among children with Attention Deficit with Hyperactivity and DCD (ADHD + DCD) were far more apparent on the HRT than the VGPT. Although both tasks are deemed to measure MI, only a weak correlation was found between the two, which may be attributed to differences in the underlying construct (as per Caeyenberghs) and/or cognitive load. The results of these two studies provide some indication that group differences, which were attributed to underlying mechanisms, may be a function of the tasks used.

The first aim of this study was to verify whether children with DCD perform differently to TD children when assessed on the computer based C-VRFT. The second aim was to determine whether MI ability is influenced by the choice of the MI task using a mental chronometry approach, and to determine which test is more sensitive and thus better able to detect MI deficits in children with DCD. A third aim was to describe differences between groups in endpoint control using kinematic profiles, extracted when children performed the C-VRFT on a digitizer. We reasoned that since the VGPT places higher demands on executive functions like working memory but requires less spatial planning, the C-VRFT would provide a purer measure of motor imagery (or simulation). And, based on converging data presented in recent meta-analyses, we predicted that imagery deficits in DCD would more clearly manifest on the C-VRFT. We also predicted reduced endpoint control in DCD on the C-VRFT.

---

1 Body schema has been likened to a kinaesthetic representation of body position in space Schwoebel & Coslett, 2005 and reflects the ability to accurately imitate actions or simulate them through imagery. In computational terms, body-centred representations are based on the learned correlation between movement output and input signals, something built through practice and error-based learning (Wolpert & Miall, 1996).
2. Methods

2.1. Participants

Children between the ages of 6 and 10 years old who were in grade one to four, were recruited using convenience sampling at two mainstream primary schools in Cape Town, South Africa. We chose this age-range because as we found in our earlier studies that younger children had difficulty executing these tasks and because motor imagery and executive functioning is still developing in this age range (Caeyenberghs, Tsoupas, et al., 2009). Written informed consent and assent for sampling at two mainstream primary schools in Cape Town, South Africa. We chose this age-range because as we found in our earlier studies that younger children had difficulty executing these tasks and because motor imagery and executive functioning is still developing in this age range (Caeyenberghs, Tsoupas, et al., 2009). Written informed consent and assent for participating was obtained from parents and children, respectively. Ethical approval was granted by the University of Cape Town Human Research Ethics Committee and the study was performed in accordance with the ethical standards outlined in the Declaration of Helsinki (World Medical Association, 2013). Authorization for conducting research in schools was granted by the Western Cape Education Department.

Children with DCD were selected using criteria based on recommendations for diagnosing DCD, as outlined in the Diagnostic and Statistical Manual of Mental Disorders fourth edition (American Psychiatric Association, 2000). Children with motor coordination problems were first identified by their class teacher and/or parents who provided information regarding the presence of a motor coordination problem that was interfering with daily function at home or school. Motor performance was then assessed using the Movement Assessment Battery for Children-second edition (MABC-2) (Henderson, Sugden, & Barnett, 2007). Children whose level of movement skill was reported to compromise their activities of daily life and who scored at or below the 5th percentile on the MABC-2 were eligible for inclusion in the DCD group. Children would have been excluded if they had failed any grade level at school more than once and if there was a diagnosis of a cerebral palsy or other significant neurological disorder (e.g. severe epilepsy, acquired brain injury or spinal cord lesions), as reported by a parent. In this case, however, no children were excluded.

An age and gender matched sample of typically developing children (TD) was selected to form the control group. A ratio of 1:1 was used to select one TD child randomly for every child identified with DCD. Children were eligible for inclusion in the TD group if (i) their motor function in daily life was believed to be within the normal range for age and gender according to their teacher and/or parent, (ii) they scored above the 16th percentile on the MABC-2, (iii) they had not failed a grade level at school and (iv) there were no neurological disorders as reported by a parent. No children were excluded.

The data were incomplete for two children and were not used in the analysis. No trials were missing from the paper task or computer task for the other participants.

The final sample thus consisted of 30 children with DCD (16 boys) with a mean age of 8.3 ± 1.4 years and 30 TD children (15 boys), with a mean age of 8.4 ± 1.4 years. All children had normal or corrected-to-normal vision.

2.2. Description of the motor imagery tasks

2.2.1. Visually Guided Pointing Task

The Visually Guided Pointing Task (VGPT) was presented on five sheets of paper (A4) each containing an 80 mm vertical line and a target box situated 150 mm from the right-hand side of the line (Fig. 1A). The width of the target box varied on each of the five sheets (i.e. 2.5 mm, 5 mm, 10 mm, 20 mm and 40 mm) representing five levels of task difficulty, converted to an Index of Difficulty (ID) using Fitts’ law (ID = 6.9, 5.9, 4.9, 3.9 and 2.9, respectively). For each digital, participants were required to make tapping movements by lifting and placing an ordinary pen, beginning from the far side of the vertical line to touch the inside of the target box and back to the far side of the vertical line five times, as quickly and accurately as possible. A stopwatch was used to record the duration of the movements (MT) for each trial with a precision of 0.01 s.

2.2.2. Computerized Virtual Radial Fitts Task

For the computerized Virtual Radial Fits Task (VRFT), participants were presented with five A4 size paper sheets, placed on a digitizer. Each sheet contained five grey target boxes of varying width, representing the same five IDs, presented along 150 mm long radials from the red (home) target circle, located between green start and stop boxes (Fig. 1B).

Participants were required to perform the task by moving a special non-marking digital pen from the start box to a red target circle and then, in an alternating sequence, to each of the five grey target boxes before returning to the stop box without lifting the pen off the digitizer. The digitizer recorded the time in milliseconds from the moment the pen left the start box until it stopped in the stop box. The pen movements were recorded at a rate of 206 Hz with a spatial accuracy of 0.1 mm. The 2D positional data of the pen were filtered with low-pass filter using a zero phase lag, 2nd-order Butterworth filter with a cut-off frequency of 10 Hz.

All data were analysed using algorithms provided the Oasis software (Smits-Engelsman et al., 2002).

Each task (VGPT and VRFT) included 10 imagined and 10 real trials (more detail given in the Procedures below).

2.3. Procedure

Participants were tested individually in a quiet room by two researchers trained in the administration of the tasks. Each participant was given a demonstration by the administrator at the beginning of each task. To ensure that participants fully understood these instructions, they were given practice trials under both movement conditions (real and imagined) using
the largest target width. The experiment did not commence until the participants demonstrated that they understood the task. All participants used their dominant hand, which was defined as the hand normally used for writing or drawing, to perform the tasks.

For each task, two trials were given per target size $(2 \times 5)$ and each trial was conducted under two conditions – real and imagined – giving a total of 10 real and 10 imagined trials for both the VGPT and the VRFT (in total 40 trials per child). The order of administration of the target widths and task types (real or imagined) was counterbalanced across participants.

In the imagined condition, the experimenter stressed to the participants that they should "picture the movement in their minds" and "feel themselves making the movement" while keeping their eyes open. The participants were encouraged to generate the feeling of actually moving their hand in the first-person perspective of the motor image. If the participant lost concentration during a trial or any other problem arose, the trial was stopped and results excluded from the analysis. For the VGPT imaginary trials, participants were told to imagine putting the pen down inside the borders of the target square and to say the word "Start" out loud as soon as they started imagining the movement and then to say "Stop" out loud upon completion of the fifth return movement to the left side of the vertical line (see Fig. 1A).

In the Radial Fitts Task, participants were required to imagine the back and forth movements between the red target circle and the five grey target boxes without actually moving their hand (see Fig. 1B). MT was recorded as the interval between leaving the start box and entering the stop box.

## 2.4. Data analysis

Alpha was set at 0.05 for all analyses. T-tests and Pearson’s Chi-squared tests were used to compare differences in participant characteristics (i.e. age, MABC-2 scores and gender) between groups.

### 2.4.1. Evaluation of movement time and motor imagery ability

Movement time (MT) was calculated in each condition for each ID per child. Spearman rank correlation between executed and imagined MT was established on each task for the total sample and for each group separately (DCD and TD). A non-parametric comparison between groups (Fisher exact test) was performed on the mean correlations between executed and imagined MT. To test the effect on MT, a General Linear Model (GLM), repeated measures ANOVA was used, with task (VGPT and VRFT) and condition (Virtual and Real movements) as the within-subjects and group (TD and DCD) as the between-subjects factor. Post hoc t-tests were performed if needed. For each task, data was missing from one child.

### 2.4.2. Evaluation of kinematic profile

Kinematic variables related to the executed movements on the real Radial Fitts Task were compared between groups. We described the differences in movement patterns between the two groups using three metrics: time to peak velocity (TTPV), number of changes in velocity per second (Velocity Peaks) and spatial accuracy (Error).

TTPV is defined as the time between the start of the movement and the moment that peak velocity is achieved and the remaining time until the movement stopped was used as deceleration time. The TTPV determines the portion of the movement time used for the initial sub-movement and what portion was covered after the peak velocity was reached in which additional corrective actions to end in the target can be made. Additionally, as a measure of smoothness, the number of velocity peaks per second was counted.

Spatial accuracy was measured by target error (Smits-Engelsman, Bloem-van der Wel, & Duysens, 2006; Smits-Engelsman, Sugden, & Duysens, 2006; Smits-Engelsman, Swinnen, et al., 2006). We computed the target error as the distance to the center of the target at the end of the movement. The deviation of the endpoint in terms of the direction of the movement (Amplitude error) or orthogonal to movement direction (Directional error) was calculated separately because it has been proposed that they are planned independently (Krakauer, 2009). Difficulties in braking within the target area are captured by the amplitude error (under and overshoots), while poor aiming at the target leads to directional errors (ending either right or left of the target). A repeated measure ANOVA over 10 repetitions of the executed task was performed to test for differences between groups (2) on the kinematic variables.

## 3. Results

### 3.1. Participant characteristics

By definition, the two groups were significantly different on MABC-2 total standard scores: DCD (3.90 ± 1.27) and TD (11.37 ± 1.75) ($t = 18.91, df = 1, 58, p < 0.001$). Each group had equivalent numbers of left-handed ($n = 2$) and right-handed ($n = 28$) children. No significant differences were found for age ($t = 0.01, df = 1, 58, p = 0.93$) or gender ($\chi^2 = 0.07, p = 0.80$).

### 3.2. Motor imagery ability (MI ability)

To compare how MI ability is represented on the VGPT and the C-VRFT, the correlation between imagined and real MT on each task was calculated for the data of the two groups together. High correlations were observed between imagined and
real on MT within the C-VRFT ($r_s = 0.73, p < 0.001$) and between imagined and real on the VGPT ($r_s = 0.72, p < 0.001$) suggesting that both tasks measure MI ability.

3.2.1. Correlations between real and imagined performance for each group

To verify whether children with DCD perform differently to TD children when assessed on the computer based C-VRFT, we examined the correlation between executed and imagined MT for the two groups. We hypothesized the correlation would be lower in the DCD group on the C-VRFT as this task was more complex compared to the VGPT.

For the TD group, a significant, high correlation was found for both the C-VRFT ($r_s = 0.82, p < 0.001$) and the VGPT ($r_s = 0.88, p < 0.001$) task. For the DCD group, the correlation was moderate for the C-VRFT ($r_s = 0.64, p = 0.001$) and the VGPT ($r_s = 0.53, p = 0.02$). The between group comparison showed that the correlation was significantly lower for the DCD group than for the TD group on both the C-VRFT, $z = -2.19, p = 0.032$, and the VGPT, $z = -2.61, p = 0.008$, suggesting poorer MI in DCD. Fig. 2 shows the scatterplots of MT in the real and imagined condition for the two tasks.

3.2.2. Movement time

Generally, MT on the VGPT was shorter (6.90 ± 2.55 s) than MT on the C-VRFT (10.94 ± 5.53 s). In the C-VRFT, the increase per unit in ID was greater (0.74 per ID) than the VGPT (0.26 per ID) (see Fig. 2).

The interaction between MI task and condition was significant, $F(1, 58) = 21.66; p < 0.001$, partial $\eta^2 = 0.27$. Real tasks were slower than imagined tasks on both the VGPT (real vs. imagined: 8.13 ± 2.68 s vs. 5.67 ± 1.66 s) and on the C-VRFT (real vs. imagined: 13.10 ± 5.74 s vs. 8.81 ± 4.36 s). The mean difference between tasks was larger in the C-VRFT (4.29 s) than on the VGPT (2.46 s).

We hypothesized that the C-VRFT would be better at detecting MI deficits in children with DCD since it was more spatially complex. Importantly, a significant interaction was found between MI task, condition and group, $F(1, 58) = 4.71$;
The differences in MT between groups became clearer when the children performed the imagined task on the C-VRFT (TD vs. DCD: 7.96 ± 2.41 s vs. 9.65 ± 5.56 s) and the real task on the VGPT (TD vs. DCD: 7.59 ± 2.47 s vs. 8.66 ± 2.78 s). In both these situations, the DCD group was slower than the TD group. Fig. 3 shows how the two groups responded on the different tasks in different conditions. Importantly, post hoc tests showed that the differences between the groups on the imagined computer based VRFT was significantly different ($t = -2.08, df = 1, 58, p < 0.05$) while this was not the case for the VGPT ($t = -0.61, df = 1, 58, p = 0.54$).

### 3.3. Group comparisons on kinematic parameters for the real Radial Fitts Task

Finally, we examined endpoint control parameters (temporal and spatial) to verify the hypothesis that the C-VRFT would reveal differences in performances more clearly than the VGPT.

#### 3.3.1. Temporal variables

The TD group had fewer velocity changes during the movement trajectory (number of velocity peaks per second = $1.87 ± 0.43$) compared with the DCD group (2.17 ± 0.60), $F(1, 58) = 11.73, p = 0.001$, partial $\eta^2 = 0.17$.

Importantly, no differences between groups were found for time to peak velocity (TD: 0.44 ± 0.23 s vs. DCD: 0.46 ± 0.26 s), $F(1, 58) = 0.59, p = 0.45$, partial $\eta^2 = 0.01$, nor in the time taken to decelerate ($F(1,58) = 0.49, p = 0.48$, partial $\eta^2 = 0.01$). This indicates that the velocity profile was comparable between groups.

#### 3.3.2. Spatial variables

The DCD group was less accurate and ended a further distance (1.01 cm ± 1.07) from the middle of the targets compared to the TD group (0.70 cm ± 0.52) who made fewer endpoint errors, $F(1, 58) = 6.8, p = 0.01$, partial $\eta^2 = 0.11$.

Amplitude error was significantly greater for the DCD group (0.77 cm ± 0.80) compared to the TD group (0.53 cm ± 0.33), $F(1, 58) = 16.55, p < 0.001$, partial $\eta^2 = 0.22$ as was directional error (TD = 0.34 cm ± 0.41, DCD = 0.51 cm ± 0.68, $F(1, 58) = 17.33, p < 0.001$, partial $\eta^2 = 0.16$.

### 4. Discussion

We hypothesized that children with DCD would perform differently to TD children when assessed on the spatially complex computer based VRFT, which was not used in DCD before. Data confirmed that motor imagery ability was poorer in the DCD group than in the TD group. Secondly, we aimed to compare differences in MI ability between children with and without DCD using two mental chronometry tasks. Our findings suggest that both the paper-based VGPT and the computer-based VRFT are valid measures in terms of assessing motor imagery ability as demonstrated by the high correlations in the temporal relationship between executed and imagined movement and by the participants’ adherence to Fitts’ law on both tasks (see Fig. 2). However, some differences emerged when comparing the groups on the two tasks. In accordance with other studies using the HRT (Deconinck et al., 2009; Williams et al., 2013) and the VGPT (Lewis et al., 2008), our study confirms poorer motor imagery ability in children with DCD. Importantly, however, our study suggests that the type of task may moderate the group effect. Finally, comparison of kinematic profiles on the real radial Fitts’ task showed deficits in endpoint
control among children with DCD. These deficits in accuracy occurred despite a general pattern of movement slowness in this group; as such, a speed-accuracy trade-off did not explain the performance deficit in DCD.

4.1. Differences between the tasks

Motor control demands are higher in the C-VRFT as parameterization of endpoint characteristics such as force, amplitude and direction is needed. Unlike in the VGPT, the endpoint of the movement is not limited by the physical surface but, rather, by movement along the horizontal surface, which requires accurate timing of the prime movers and the antagonist muscles in the hand and arm. Since it is known that reduced spatial accuracy is characteristic of movement in children with DCD, measures of endpoint accuracy may prove diagnostic and add vital information on changes in performance over time and as a result of therapy.

The greater complexity of the C-VRFT (as suggested in the introduction) is confirmed by a (30%) longer movement time and an almost threefold larger increase in MT per increment in task difficulty (0.74 vs. 0.26 per ID), relative to the VGPT. By comparison, the VGPT allows cyclical movements between two fixed locations. The expectation that this made the VGPT easier was confirmed in this study (mean index of performance (ID/MT) in VGPT was 6.5 and C-VRFT was 4.3 bits/s).

The C-VRFT requires that the position of the upcoming target be updated (or anticipated) as each aiming movement is completed along another radius in each movement. Again, this level of spatial processing may explain some of the differences found in the time needed to perform the two MI tasks.

4.2. Comparison between DCD and TD groups

Impaired use of motor imagery in DCD was evident on examination of the correlation between real and imagined performance on both tasks. The adaptation of the MT to the target size was far more variable in DCD than TD group as seen by the dispersion of points in the real task. As well, children with DCD were less able to predict the duration of their movements compared with TD children.

The low correlation between real and imagined MT seen in the DCD group presents a pattern of performance similar to that seen in patients with damage to parietal cortex (Sirigu et al., 1996). Neurons in the posterior parietal cortex have been linked to the process of forward modeling (Mulliken, Musallam, & Andersen, 2008). Neuroimaging data shows strong involvement of both the posterior parietal cortex and cerebellum during explicit MI tasks and other tasks requiring rapid online modulation of movement in response to visual perturbation (Cunnington et al., 2001; Higuchi et al., 2007; Wolpert, Miall, & Kawato, 1998), tasks that require predictive control. The parietal cortex is also intimately involved in processing multimodal inputs, which contribute to one’s body schema and ability to code prospective changes in body position (Kochanska, Barry, Stellern, & O’Bleness, 2009). Other studies of DCD have also suggested dysfunction to the parieto-cerebellar axis, more generally (Cantin, Polatajko, Thach, & Jaglal, 2007; O’Hare and Khalid, 2002). Taken together, our data corroborate early studies showing MI deficits in DCD, consistent with the broader hypothesis that internal (forward) modeling may be compromised (Adams, Lust, Wilson, & Steenbergen, 2014; Wilson et al., 2013).

4.3. Kinematic profiles

Although children with DCD moved more slowly as the task became more difficult, thus obeying Fitts’ law (see Fig. 2), this did not lead to accurate movements as revealed by the kinematic data. In other words, slowing down did not confer significant benefit in this group. In addition, children with DCD made more velocity changes while moving than did those in the TD group but these movement were meant as corrective movements and not mere variability in the movement execution, this did not seem to create great advantage either. Taken together, the kinematic data provide evidence of pervasive deficits in the spatio-temporal control of goal directed movements.

The kinematic profile that we observed is consistent with other studies in which children with DCD were also found to be more variable with regards to timing and force control in handwriting and manual tracing tasks (Chang & Yu, 2010; Lundy-Ekman, Ivry, Keele, & Woollacott, 1991; Smits-Engelsman, Niemeijer, & van Galen, 2001), and less able to control the endpoint variability in response to changing task constraints (Smits-Engelsman, Wilson, Westenberg, & Duysens, 2003).

One possible hypothesis about the source of deficits in endpoint control concerns the level of neuromotor noise in children with DCD. Smits-Engelsman and Wilson (2013b) refer to the “noisy blueprint” of movement that results in greater movement variability in DCD (Smits-Engelsman & Wilson, 2013b). Variability is natural in our movements and the motor system corrects these errors. The noise arises to a lesser extent centrally in movement planning and to a larger extent peripherally in movement execution (van Beers, 2009). Evidence from the kinematic data obtained from the real Radial Fitts Task in the present study confirms increased movement variability in the endpoints in children with DCD. This is in line with previous studies stating that children with DCD have increased levels of noise resulting mainly from variability in movement execution (Smits-Engelsman et al., 2001). In the present study, the DCD group recorded larger amplitude errors indicating that the ability to generate the right amount of force (parameterization) was more impaired than aiming in the right direction. The origin of the increased noise in DCD (motor neuron, muscle, spinal circuit, etc) remains unclear to date and its relation with deficits in building an internal representation of goal directed movement requires further study.
4.4. Limitations of the study and suggestion for future research

This study has two main limitations: the absence of an explicit test for the presence of possible covariates; firstly Attention Deficit with Hyperactivity Disorder (ADHD) and secondly impaired working memory. It is reported that ADHD and reduced working memory both mediate the ability to perform MI tasks (Gabbard, 2009).

Since DCD and ADHD frequently co-occur in DCD, it is plausible that some of the children in the study may have been affected by this condition. However, studies show that the motor imagery performance of children with DCD and ADHD is less disrupted than that of children with DCD alone (Lewis et al., 2008; Williams et al., 2013). Thus, the possible co-existence of DCD with ADHD in some children in our study may only serve to reduce the magnitude of the significant effects that were observed. Although none of the parents in our study reported a diagnosis of either ADD or ADHD in our questionnaire, it was not possible to confirm this through formal testing.

The relationship between motor imagery and motor planning is also an important area of future research. Both motor imagery tasks and tasks examining the ability to make judgments of end-state comfort (Wilmut & Byrne, 2014) require prospective judgments of limb trajectory and position. It may therefore be useful to investigate the relationships between these two types of tasks in relation to the internal modeling deficit.

5. Conclusions

The findings of this study show that both the Visually Guided Pointing Task and the Virtual Radial Fitts Task measure aspects of motor imagery. We confirm that children with DCD have poorer MI ability. Importantly, we have isolated more sensitive test for discriminating between DCD and TD children in terms of compliance with Fitts’ law. The more complex Virtual Radial Fitts Task, appears to measure different processes and likewise results are different for this test as the differences in MT became clearer when the children with DCD had to imagine performing the Radial Fitts Task.

Our results on both tasks suggest that children with DCD have difficulty enlisting motor imagery and that this is likely to reflect a reduced capacity to use internal (forward) models for the prospective control of action. This also accords with previous studies showing poor predictive control in DCD (Hyde & Wilson, 2013). Delayed maturation or micro-structural damage to of parieto-cerebellar pathways may underlie this difficulty, which is supported by recent neuroimaging data in this population (Kashiwagi, Iwaki, Narumi, Tamai, & Suzuki, 2009; Zwicker, Missiuna, Harris, & Boyd, 2012).

It is apparent that assessment of MI ability is dependent on the choice of task and that differences in task complexity may explain variable findings across studies. More complex tasks that require higher levels of parameterization according to target size and position appear to be more sensitive to deficits of motor imagery. Our kinematic data suggests that even though children with DCD try to trade speed for accuracy, this is not translated to adequate levels of accuracy. Moreover, the kinematic profiles on the Radial Fitts Task show that even though children with DCD make more corrective movements when aiming at an array of distinct targets, they still do not reach the same level of accuracy as the TD children. Increased motor noise will complicate error correction because it makes it impossible to know what the aiming point of the previous movement was. We hypothesize that the presence of increased neuromotor noise is likely to constrain the ability to build accurate internal (forward) models, which in turn, results in impaired motor imagery.

Our results support the idea that motor imagery training may be a useful treatment modality for DCD (see Wilson, Thomas, & Maruff, 2002). Understanding how specific task constraints affect the way MI is enlisted (as our current data suggest) should therefore be an important consideration when developing more effective and targeted training strategies.

Acknowledgment

The authors wish to acknowledge Lieke Martens and Hanneke van Oudheusden for collecting the data.

References


