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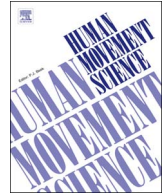
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Full Length Article

Development of motor imagery and anticipatory action planning in children with developmental coordination disorder – A longitudinal approach



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ABSTRACT

Children with impaired motor coordination (or Development Coordination Disorder – DCD) have difficulty with the predictive control of movements, evidenced by cross-sectional studies that show impaired motor imagery and action planning abilities. What remains unclear is whether this deficit in predictive control reflects immaturity of the motor system (a developmental delay) or some deviation from normal development (a disorder). To advance this discussion the present study used a longitudinal design to examine the development of motor imagery and action planning in children with DCD. Thirty children were included in the DCD group (aged 6–11 years) and age- and gender-matched to 30 controls. The DCD group had a mABC-2 score \leq 16th percentile, the control group $>$ 20th percentile. Motor imagery was assessed with the hand rotation task, action planning with a test for end-state comfort. Children participated in three measurements, with one year in between measurements. Results showed that children with DCD were slower and less accurate than their typically developing peers in all subsequent years but were able to improve their motor imagery ability over time. Furthermore, children with DCD showed less planning for ESC at the start of the present study, but were able to catch up with their peers during two-year follow up. These results exemplify that improvement of motor imagery and action planning ability is possible in DCD, and they lend theoretical support to the use of new training techniques that focus on training motor imagery to improve motor skills in children with DCD.

1. Introduction

Children with Developmental Coordination Disorder (DCD) show impaired motor abilities, in the absence of an identifiable developmental or neurological impairment (DSM-V – American Psychiatric Association, 2013). A prominent hypothesis about the etiology of DCD is the internal modeling deficit (IMD) hypothesis (Wilson & Butson, 2007; Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). In two recent systematic reviews, an underlying deficit in motor control and learning was linked specifically to the predictive control of movements (Adams, Lust, Wilson, & Steenbergen, 2014; Wilson et al., 2013). Predictive control is thought critical to the production of fluid, well-coordinated and efficient movements because it enables the performer to make online adjustments based on forward estimates of limb position (Flanagan, Vetter, Johansson, & Wolpert, 2003; Shadmehr,

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Smith, & Krakauer, 2010). What remains unclear is if and to what extent this ability develops in DCD. This is important in understanding the nature of the impaired performance and to further explore the possibilities and necessity of interventions aimed at improving predictive control in DCD, such as motor imagery training (Adams, Smits-Engelsman, Lust, Wilson, & Steenbergen, 2017; Adams, Steenbergen, Lust, & Smits-Engelsman, 2016; Wilson, Thomas, & Maruff, 2002; Wilson et al., 2016). Evidence so far, has been mainly gathered from cross-sectional studies (e.g. Deconinck, Spitaels, Fias, & Lenoir, 2009; Hyde & Wilson, 2013; Williams, Omizzolo, Galea, & Vance, 2013). The present study used a longitudinal design to describe and examine time related change of predictive control in children with DCD.

Two aspects of predictive control are motor imagery and anticipatory action planning. First, motor imagery involves the mental rehearsal or simulation of a motor task in the absence of overt movement (Decety, 1996; Sirigu et al., 1995). This implies mental representation (or internal modelling) of the motor task that is also important for the forward estimates of limb positions. A commonly used paradigm is the mental rotation paradigm in which laterality judgments of limb stimuli are made (e.g. left and right hands) displayed at different angles of rotation, and from different viewpoints as well (e.g. back vs. palm view). For limb-related stimuli, use of motor imagery is inferred when the biomechanical constraints of the simulated movement are reflected in the pattern of response time or error data. For example, for laterally orientated stimuli response times are longer than for medially orientated (Parsons, 1994; ter Horst, van Lier, & Steenbergen, 2010). Second, anticipatory action planning can be defined as the ability to take into account the demands of a given task and its ultimate goal when first manipulating an object (e.g. (Johnson-Frey, McCarty, & Keen, 2004). Adults prefer a less comfortable initial grasp if it allows a comfortable end posture (e.g. (Rosenbaum, vanHeugten, & Caldwell, 1996; Rosenbaum et al., 1990) referred to as the *end-state comfort effect*. Accurate mental representation of the task is a prerequisite for accurate anticipatory motor planning. The grip types used at the start and end of the task can be used to assess action planning (Craje, Aarts, Nijhuis-van der Sanden, & Steenbergen, 2010; Rosenbaum, Meulenbroek, Vaughan, & Jansen, 2001).

Deficits in predictive control in children with DCD are evident across many studies (reviewed in Adams et al., 2014; Wilson et al., 2013). Earlier studies showed that children with DCD are able to use motor imagery (as evidenced by increased reaction times to laterally rotated compared with medially rotated hand stimuli), but are slower and less accurate than their typically developing peers (e.g. Adams, Lust, Wilson, & Steenbergen, 2016; Deconinck et al., 2009). Evidence on the nature of age-related changes in motor imagery in DCD is more limited; however, some work suggests that subtle deficits persist into early adulthood (Hyde et al., 2014). On tasks assessing online motor control, there is evidence of developmental delay in DCD, both in cross-sectional studies (Hyde & Wilson, 2013) and in longitudinal modeling (Ruddock et al., 2016). In the study of Hyde and Wilson (2013) children with DCD showed similar performance as their younger typically developing peers during an online control task. In accordance, in the study of Ruddock et al. (2016) it was found that children with DCD need a more extended period of development to effectively couple online motor control and executive systems when completing anti-reach movements. Longitudinal studies on motor imagery and anticipatory action planning in children with DCD are currently lacking. These studies are warranted to provide insight into the development of motor imagery and action planning abilities over time and might inform therapeutic approaches.

The aim of the present study was to describe and examine changes over time on different aspects of predictive control in children with DCD. We studied the development of motor imagery and action planning in 60 children aged 6–11 years (30 with DCD) over a two year period, with three measurement occasions. Motor imagery was examined using a mental rotation paradigm using hand stimuli, that is also used in developmental studies in typically developing children (Spruijt, van der Kamp, & Steenbergen, 2015). Action planning was examined using the sword task, a task that was validated in children (Craje et al., 2010; Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Craje, & Steenbergen, 2013). The results of this study may advance the discussion of whether the frequently reported deficit in predictive control in children with DCD (Adams et al., 2014; Wilson review) reflects immaturity of the motor system (a developmental delay) or some deviation from normal development (a disorder). Based on current cross sectional studies (Fuelscher, Williams, Enticott, & Hyde, 2015; Hyde et al., 2014) and the results of the longitudinal modeling on online control (Ruddock et al., 2016) we hypothesized children with DCD to show a developmental delay in motor imagery and action planning skills.

2. Methods

2.1. Participants

A total of 60 children participated in this study, aged 6–11 years during the first measurement (T0). Thirty children (23 boys) met the DSM-V diagnostic criteria for DCD. The 30 control children were gender and age-matched (± 4 months). Mean age for the DCD group was 8.87 years ($SD = 1.40$), and 8.85 years ($SD = 1.40$) for the control group at T0. Two children in the DCD group and four children in the control group were left-handed, all other children were right-handed. Handedness was assessed by performing the manual tasks of the mABC-2, and confirmed by parent report on the health questionnaire.

The DCD group was recruited through pediatric physical therapists and via an advertisement on a website for parents of children with DCD. In the first year 33 children with DCD participated, gender and age-matched to 33 controls (this population is elaborately described in (Adams et al., 2016). In subsequent years, 30 children with DCD were able to participate at all three time points, and gender and age- matched to 30 controls. Fourteen of the DCD children were recruited via pediatric physical therapists, sixteen DCD children were recruited via an advertisement on a website for children with DCD. Between T0 and T1, 12 of the 27 DCD children received treatment of a pediatric physical therapist ($M = 5.19$ months, $SD = 5.96$). Eight of these 12 children still received treatment by a pediatric physical therapist between T1 and T2 ($M = 2.70$, $SD = 4.62$).

All children with DCD children met the following inclusion criteria, consistent with DSM-V: (1) mABC-2 (Dutch translation – (Smits-Engelsman, 2010)) total percentile score \leq 16th (criterion A DSM-V); (2) treated for a motor coordination problem by a pediatric physical therapist, the impact of motor issues on daily activities confirmed by parent report on the DCDQ (Dutch translation; Schoemaker, Reinders-Messelink, & de Kloet, 2008) (criterion B of DSM-V); (3) onset of DCD in early development, confirmed by parent report (Criterion C); (4) IQ $>$ 70. If children attended regular primary education and had not been diagnosed with a learning disorder, an IQ $>$ 70 was inferred. When children attended special education, IQ was verified by records held by parents (criterion D DSM-V), and (5) no visual impairments or neurological conditions that could affect their motor abilities, verified using a health questionnaire (criterion D DSM-V). Three children in the DCD group had a diagnosis ADHD and were excluded, along with their age-matched controls. This yielded a total of 27 children in each group. The mABC-2 percentile scores of the DCD group were in the range of 0.1–16.0 (Total Test Score $M = 50.63$, $SD = 14.22$).

The control group was recruited from two mainstream primary schools. Control children were included if they had a mABC-2 total percentile score $>$ 20th and IQ $>$ 70 (inferred as per the DCD group). The mABC-2 percentile scores were in the range of 25–98 (Total Test Score $M = 81.41$, $SD = 7.28$).

2.2. Experimental tasks

During both experimental tasks, participants were seated on a comfortable chair with their arms resting in front of them.

2.2.1. Motor imagery

For the hand rotation task, stimulus presentation and data recording was programmed using Presentation™ software (Neurobehavioral Systems, Albany, CA, USA). Stimuli were presented on a 14-inch laptop screen, placed 60 cm in front of the participants at chest height. Participants hands were placed palm-down on separate response buttons, with vision of the hands occluded by a towel. Participants were asked to determine whether each presented stimulus was a left or a right hand by pressing the corresponding button. The stimuli were custom-made 3D hand stimuli (length of hand stimuli on screen was 9 cm), designed in a 3D image software package (Autodesk Maya 2009, San Rafael, CA, USA). Stimuli were presented in six different orientations, starting at 0° (fingers pointing up) and rotated clockwise to 60°, 120°, 180°, 240° and 300°, for both left and right hand stimuli. This resulted in a total of 12 different stimuli in back view (block 1) and 12 different stimuli in palm view (block 2). Stimuli were presented in a random order, and every stimulus was presented three times, resulting in 36 stimuli per block. Every block was preceded by 18 practice trials. Outcome measures were reaction time (RTs) – time between appearance of the hand stimulus and button press – and number of response errors.

2.2.2. Action planning

Action planning was assessed with the sword task, specifically developed to measure action planning in children (Craje et al., 2010). The sword was composed of light timber (length 18.0 cm, width 2.0 cm, height 1.2 cm, handle length 9.5 cm), as was its receptacle or “treasure chest” (a wooden block of 27.0 cm \times 13.0 cm \times 13.0 cm with 2.0 \times 0.8 cm hole). The sword was always presented on a sheet of paper (30 cm length and 28 cm width) on which six possible sword orientations and the fixed position of the treasure chest were drawn (see Fig. 1). Four of these six starting orientations served as the control orientations, and two served as the critical orientations. In these critical orientations, children needed to sacrifice comfort of the start posture in order to be able to end the task in a comfortable posture on insertion of the sword into its slot (Orientations 2 and 3 for right-handed participants, Orientations 5 and 6 for left-handed participants). Children were instructed to pick up the sword using a whole hand grip with their dominant hand and subsequently place it in the slot of the treasure chest. The experiment started with a trial that did not require any sword rotation (Orientation 1). After successful completion of this trial, the experiment started. Every rotation was repeated three times, resulting in a total of 18 trials, presented in random order. The dependent measure was the percentage of comfortable end postures in both the critical and the control orientations. Test-retest reliability of this task is very high, with an intraclass correlation

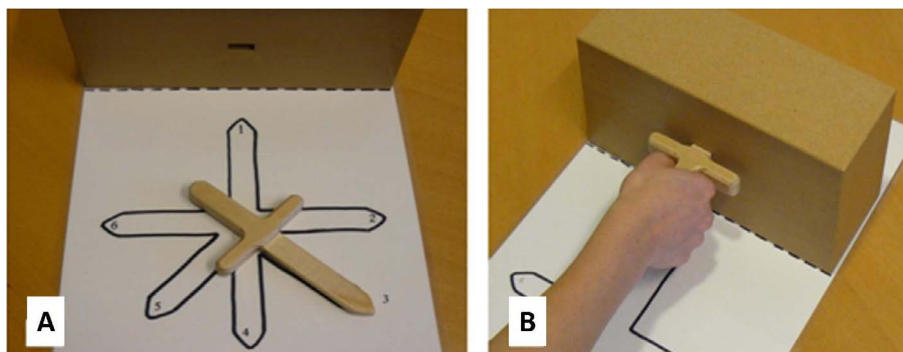


Fig. 1. (A) Setup of the action planning task, sword in orientation 3. The sword orientation with the blade towards the wooden block was designated as orientation 1. (B) Example of a comfortable end posture.

coefficient (ICC) of 0.90. Interrater reliability is also excellent with an ICC score of 0.95 (Jongbloed-Pereboom et al., 2013).

2.3. Procedure

Approval for the experiment was obtained from the local Ethical Committee (Registration number: 2013-1405-110a1). The parents of all participants signed a written informed consent prior to the study, and were asked to fill in the DCD-Q (Dutch translation – Schoemaker et al., 2008), the ADHD questionnaire (Scholte & van der Ploeg, 2004), and a questionnaire concerning the health of their child. The ADHDQ measured the main symptoms of ADHD (attention, hyperactivity, impulsivity). All participants performed the experimental tasks in the same order (1) hand rotation task, (2) sword task. The mABC-2 was assessed after the experimental tasks, and a break was provided in between the experimental tasks and the mABC-2 to prevent fatigue. Children needed 40 min to complete all tasks. Both experimental tasks and the mABC-2 were repeated at measurement occasion T1 and T2. In the DCD group experimental tasks were administered at home, the child's primary school or pediatric physical therapist's office. All children in the control group conducted the experimental tasks at their primary school. The first author assessed all children in all subsequent years.

2.4. Data analysis

All analyses were performed using SPSS version 21. Alpha level was set at 0.05.

2.4.1. Questionnaires

Total score on the DCD-Q and ADHDQ at T0 were compared between the DCD and control group with Mann Whitney *U*-tests. Lower scores on the DCD-Q imply lower motor proficiency. Higher scores on the ADHDQ indicate more signs of ADHD.

2.4.2. Motor imagery

Mean response times (RTs) and number of errors were calculated for each angle of rotation and for each condition. Anticipatory responses (< 250 ms) and RTs showing an abnormal delay (> 3.0 SDs above mean RT per condition per individual) were removed from analysis: 1.78% and 2.06% for back view stimuli for DCD and control group, respectively, and 2.28% and 2.37% for palm view. In addition, only children that had at least half of all trials (≥ 18 trials) correct at T0 were included in the analysis, this was considered for back and palm view separately. In the analysis of back view stimuli, 25 DCD and 27 controls were included. In the analysis of palm view stimuli, 24 DCD and 27 controls were included.

The RTs were compared with a 2 (lateral/medial) \times 3 (measurement occasion) \times 2 (group) repeated measures ANOVA to be able to analyze also the difference between lateral and medial orientated stimuli. Because the number of errors were not normally distributed, we used a Mann Whitney *U* test to compare the number of errors at each measurement occasion. To compare change trajectories in the number of errors, we used the difference in number of errors between T2 and T0 (T2-T0) and compared these scores between the DCD and control group with a Mann Whitney *U* test. Analyses were performed for back and palm view stimuli separately.

2.4.3. Anticipatory action planning

Because the proportion of comfortable end positions was not normally distributed, we used a Mann-Whitney *U* tests to compare the proportion of trials ended in a comfortable posture between children with DCD and controls at each measurement occasion (T0, T1, T2). To compare change trajectories in anticipatory action planning over time for each group, we used the difference in proportion of comfortable end positions between T2 and T0 (T2 – T0) and compared these scores between the DCD and control group with a Mann Whitney *U* test.

3. Results

3.1. Questionnaires

Total scores on the DCD-Q at T0 were lower for the DCD group (median total DCD-Q score = 38.0) than the control group (median total DCD-Q score = 67.0), $U = 25.50$, $p < 0.001$, $r = -0.80$. Total scores on the ADHDQ at T0 were higher for the DCD group (median = 22.0) than for the control group (median = 9.0), $U = 161.0$, $p < 0.001$, $r = -0.48$.

3.2. Motor imagery

We hypothesized that both groups would have longer RTs for lateral than for medial orientated stimuli which would signify the use of motor imagery. Furthermore, based on the hypothesis of a developmental delay we expected that the DCD group would show longer RTs at T0, but that both groups would show a similar decrease of RT over time. RTs for both back and palm view stimuli were not normally distributed, and were therefore log10 transformed. Untransformed data are presented in Tables 1 and 2.

For back view stimuli, the 2 (lateral/medial) \times 3 (measurement occasion) \times 2 (group) repeated measures ANOVA showed that there was a trend that the DCD group performed the hand rotation task slower than the control group, $F(1, 50) = 3.99$, $p = 0.051$, $\eta^2 = 0.074$. RTs to lateral orientated stimuli were longer than for medial orientated stimuli, in both groups, $F(1, 50) = 34.407$, $p < 0.001$, $\eta^2 = 0.408$. In addition, in both groups the RTs for both lateral and medial orientated stimuli decreased with time, $F(2, 1.461) = 37.730$, $p < 0.001$, $\eta^2 = 0.430$. Only the interaction lateral_medial * measurement * group was significant, $F(1.99,$

Table 1
Reaction times for back view stimuli at the three measurement occasions (T0, T1, T2).

		Lateral orientated stimuli		Medial orientated stimuli	
		Mean	SD	Mean	SD
T0	DCD	2725.87	1363.04	2365.44	911.66
	Control	2724.64	2489.92	2066.77	1174.91
T1	DCD	2388.89	967.96	1880.75	643.54
	Control	1855.09	759.26	1724.82	681.35
T2	DCD	1993.91	760.90	1654.49	632.13
	Control	1593.35	680.94	1302.70	377.70

Table 2
Reaction times for palm view stimuli at the three measurement occasions (T0, T1, T2).

		Lateral orientated stimuli		Medial orientated stimuli	
		Mean	SD	Mean	SD
T0	DCD	3382.68	1543.77	2486.91	1057.76
	Control	3381.07	1418.75	2465.48	1082.54
T1	DCD	3563.80	1662.47	2219.75	837.53
	Control	2540.94	773.58	1760.55	422.99
T2	DCD	2887.45	1118.19	2887.45	1118.19
	Control	2232.48	1028.34	2232.48	1028.34

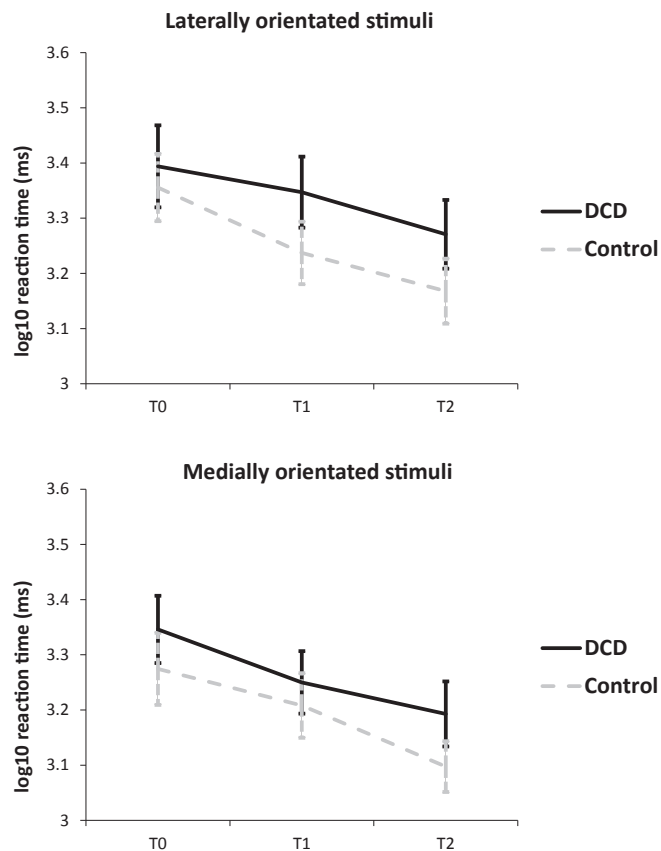


Fig. 2. Mean response time (log10 RT) for lateral and medial orientated Back View stimuli. Solid line refers to DCD group.

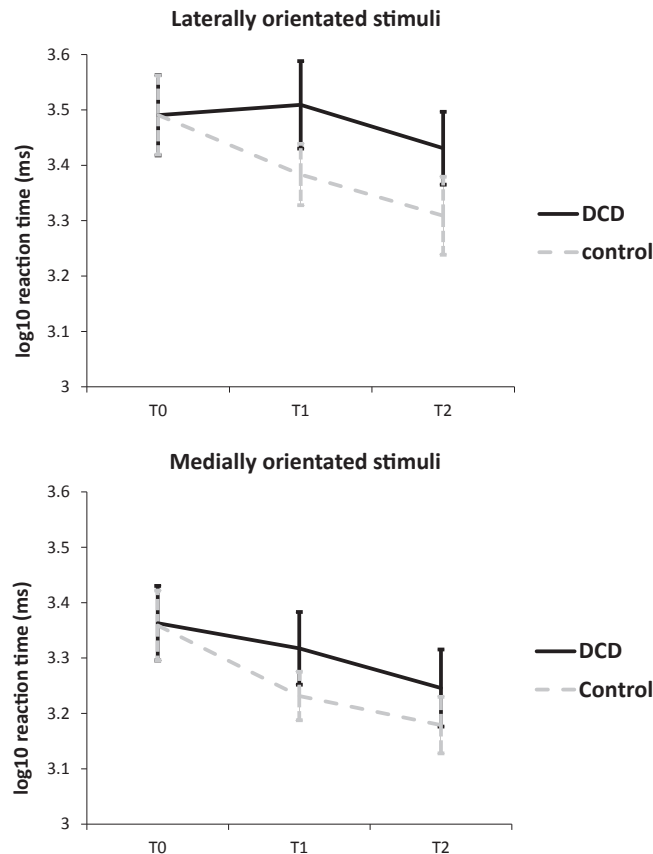


Fig. 3. Mean response time (log10 RT) for lateral and medial orientated Palm View stimuli. Solid line refers to DCD group.

99.40) = 4.323, $p = 0.016$, $\eta^2 = 0.08$, and reflects the fact that the interaction lateral/medial * group was only significant at T1, $F(1, 50) = 5.634$, $p = 0.021$, $\eta^2 = 0.101$. At T1, the difference in RT between the DCD and control group is much larger for laterally orientated stimuli than for medially orientated stimuli. This is also displayed in Fig. 2 and Table 1. Individual data showed that for laterally orientated stimuli most children showed a decreased reaction time at T2 compared to T0 (DCD: 22/25 children, control: 24/27 children). For medial orientated stimuli also most children improved their reaction time at T2 compared to T0 (DCD: 22/25 children, control: 25/27 children).

For palm view stimuli, the 2 (lateral/medial) \times 3 (measurement occasion) \times 2 (group) repeated measures ANOVA showed that there was a trend that the DCD group had longer RTs than the control group, $F(1, 49) = 3.406$, $p = 0.071$, $\eta^2 = 0.071$. RTs to laterally orientated stimuli were longer than RTs to medially orientated stimuli, $F(1, 49) = 180.01$, $p < 0.001$, $\eta^2 = 0.786$. In addition, the RTs for lateral and medial orientated stimuli decreased over time in both groups, $F(1.36, 66.71) = 21.302$, $p < 0.001$, $\eta^2 = 0.303$. There were no significant interactions. The log10 RTs are displayed in Fig. 3, for the DCD and control group separately. For palm view stimuli, the mean RT (without log transformation) for lateral and medial orientated stimuli are displayed in Table 2. Individual data showed that for laterally orientated stimuli most children showed a decreased reaction time at T2 compared to T0 (DCD: 16/24 children, control: 25/27 children). For medial orientated stimuli also most children improved their reaction time at T2 compared to T0 (DCD: 18/24 children, control: 22/27 children).

In line with the developmental delay hypothesis, we hypothesized that the DCD group would show a higher number of errors at

Table 3
Number of errors for back view stimuli at the three measurement occasions (T0, T1, T2).

		Median	Q1	Q3	U	p	r (Z/ \sqrt{n})
T0	DCD	4.0	2.0	7.5	214.50	0.023	-0.31
	Control	2.0	0.0	4.0			
T1	DCD	2.0	1.0	3.0	178.50	0.003	-0.42
	Control	1.0	0.0	1.0			
T2	DCD	1.0	0.0	4.0	161.50	0.001	-0.48
	control	0.0	0.0	1.0			

Table 4
Number of errors for palm view stimuli at the three measurement occasions (T0, T1, T2).

		Median	Q1	Q3	U	p	r (Z/√n)
T0	DCD	5.0	2.25	13.5	201.0	0.019	−0.33
	Control	2.0	1.0	7.0			
T1	DCD	2.0	1.0	4.75	201.5	0.018	−0.33
	Control	1.0	0.0	2.0			
T2	DCD	2.0	0.25	4.75	217.0	0.036	−0.29
	control	0.0	0.0	2.0			

T0, but that both groups would decrease their number of errors over time. For back view stimuli, the Mann Whitney U-tests showed that at all three measurement occasions the DCD group made significantly more errors than the control group, see also Table 3. Number of errors gain scores (T2 – T0) were analyzed with a Mann Whitney U test with group as the between subjects variable. There was no difference between the DCD (median = −4.0) and control group (median = −1.0) in the decrease of number of errors over time, U = 291.50, p = 0.396, r = −0.12. Individual data showed that for lateral orientated stimuli, most children showed a decreased number of errors at T2 compared to T0 (DCD: 13/25 children, control: 13/27 children) or the same number of errors at T2 and T0 (DCD: 9/25 children, control: 13/27 children). Also for medial orientated stimuli, most children had a lower number of errors at T2 compared to T0 (DCD: 8/25 children, control: 7/27 children) or the same number of errors at T2 and T0 (DCD: 13/25 children, control: 17/27 children).

For palm view stimuli, the Mann Whitney U tests showed that at all three measurement occasions, there was a significant difference between the DCD and control group, see also Table 4. There was no difference between the DCD (median = −3.0) and control group (median = −1.0) in the decrease of number of errors over time, U = 254.50, p = 0.187, r = −0.18. Individual data showed that for lateral orientated stimuli, most children showed a decreased number of errors at T2 compared to T0 (DCD: 15/24 children, control: 14/27 children) or the same number of errors (DCD: 4/24 children, control: 12/27 children). Also for medial orientated stimuli most children showed a decreased number of errors at T2 compared to T0 (DCD: 9/24 children, control: 11/27 children) or the same number of errors (DCD: 8/24 children, control: 10/27 children).

3.3. Anticipatory action planning

We hypothesized, based on the developmental delay hypothesis, that the DCD group would show a lower percentage of ESC on critical trials at T0, but that both groups would improve their ESC over time. First, we determined whether there was a significant difference between the DCD and control group on % ESC in critical trials at T0, T1 and T2. At T0, Mann Whitney U test showed that the DCD group had a significant lower % ESC than the control group (median DCD = 16.67%, median control = 50%), U = 242.0, p = 0.030, r = −0.42. However, at T1 and T2 the group difference was not significant (T1: p = 0.102, T2: p = 0.486).

As expected, on control trials, there was no significant difference between children with DCD and controls at either measurement occasion (T0: p = 0.251, T1: p = 0.150, T2: p = 0.241). See also Fig. 4 and the Supplementary material online.

Gain scores (T2 – T0) of the percentage of comfortable end positions in critical trials were analyzed with a Mann-Whitney U test with group as the between subjects variable. There was no significant difference in the change of % ESC over time between the DCD (M = 9.26, SD = 31.12, median = 0.00) and control group (M = −4.32, SD = 38.28, median = 0.00), U = 396.50, p = 0.231, r = −0.16. Individual data showed that in critical trials most children showed an increased % ESC at T2 compared to T0 (DCD: 12/27 children, control: 10/27 children) or the same % ESC (DCD: 8/27 children, control: 8/27 children).

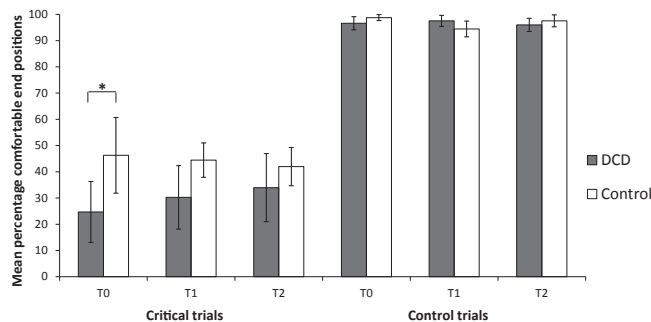


Fig. 4. Sword Task – Mean percentage comfortable end positions. Errors bars represent 95% CI.

4. Discussion

The present study used a longitudinal design to describe and examine the development of predictive control in children with DCD over time. The present study used a test of motor imagery (the hand rotation task) and a test of action planning (the sword task) to examine the predictive control of both children with DCD and age- and gender matched controls. Based on the assumption of a developmental delay, it was hypothesized that the DCD group was impaired in motor imagery and action planning at T0, compared to controls, but would develop motor imagery and action planning skills over time at the same rate as their typically developing peers. The present study confirms and extends these earlier cross-sectional data by showing the development of motor imagery within subjects using a longitudinal design.

Results on the hand rotation task, measuring motor imagery, showed that children with DCD were able to use motor imagery (indicated by a longer RT for lateral than for medial orientated stimuli), and during the two year follow-up became faster and made less errors. Still, there was a trend that children with DCD were slower than their age-matched peers, and made significantly more errors in all subsequent years. In addition, from T0 to T1 the DCD group showed less improvement compared to the control group. Taken together, this suggests that children with pDCD are able to improve their motor imagery abilities over time but did not catch-up with their typically developing peers during the two-year period of the present study.

Results on the sword task, measuring action planning, showed that during the first measurement (T0) children with DCD planned less for end state comfort than the controls. However, in subsequent years, no difference in planning for ESC was found between the DCD and control group, indicating a developmental delay with a catch-up. The difference in end-state comfort planning at T0 between the DCD and control group, is in accordance with our earlier study (Adams, Ferguson, Lust, Steenbergen, & Smits-Engelsman, 2016). Interestingly, the control group showed no improvement of planning for end-state comfort over time. Although this may appear surprising, the results can be explained by motor reorganization at around 8 or 9 years of age. A large part of our typically developing children were aged 6–8 years during the first measurement (17 children; 62.97% of TD sample). In the study of Jongbloed-Pereboom et al. (2013) a decrease, or ‘drop’, in action planning was observed at 9 years of age when using the sword task to examine action planning. Thibaut and Toussaint (2010) used a bar-grasping task and reported a similar ‘drop’ in action planning in their study, with 8-year-olds performing less well than 6-year-olds. At around 8 or 9 years of age, children hold more environmental cues (mostly visual cues) into account in performing the action planning task than younger children. It is assumed that 8-year-olds do not yet sufficiently integrate these cues into their actions compared with 10-year-olds (Thibaut & Toussaint, 2010), which leads to errors. This explains the decrease in ESC planning in children aged 8–9 years. If children with DCD are delayed in the development of action planning, this decrease in ESC planning will probably emerge at a later age. Due to the limited number of participants per age group, we were not able to determine these age-specific developmental trajectories. A limitation of the sword task is its limited number of critical trials and the fact that also with an uncomfortable end-state it is possible to complete the task successfully. This decreases the sensitivity of the task. In accordance with an earlier study of Jongbloed-Pereboom et al. (2013) typically developing children (aged 6–11 years) plan for end-state comfort only in 40–60% of critical trials. Tasks that cannot be successfully completed without planning for end-state comfort (like the hexagonal knob task, used in studies in CP of Mutsaerts et al. (2005, 2006)) and tasks including a greater variety of trials (like the wooden octagon used in the study of Fuelscher et al. (2016)) are recommended for future studies. Such tasks are probably more sensitive to group differences in motor planning ability and provide more insight into the nature of the motor planning deficit.

The issue whether the impaired predictive control seen in DCD reflects a developmental delay of the motor system or a disorder, is a critical issue both theoretically and clinically (Hyde & Wilson, 2013). The present study advances this discussion. The results are in support of a developmental delay as children with DCD do improve their motor imagery skills over time suggesting they have the potential to catch up with their typically developing peers. Ruddock et al. (2016) used longitudinal modeling to examine the online control of movements, and also showed evidence for a developmental delay. However, in the present study performance in the DCD group still lags behind that of their peers after two years of follow-up. This finding is in accordance with earlier cross-sectional studies on motor imagery ability in DCD. Hyde et al. (2014) found that even young adults (aged 19–35 years) with pDCD show a decreased efficiency on the hand rotation task, compared to controls. However, when comparing the performance of the group in that study (efficiency score of 1959.62 ms for back view stimuli) to the performance of the younger pDCD group (aged 8–12 years) in the study of Fuelscher et al. (2015) (efficiency score of 2864.37 ms for back view stimuli), it is clear that motor imagery efficiency is increased in the older group. This suggests that the improvement of performance over time in DCD shown in the present study continues into adolescence, but also that performance is consistently impaired compared to controls. It is warranted that future studies examine the development of predictive control using longitudinal designs that include a larger time-span than the two years included in the present thesis. Only then can it be studied whether children with DCD eventually catch up with their typically developing peers.

Notwithstanding this, the ability to improve but not catch-up strengthens the use of new training techniques that focus on training MI to improve motor skills in children with DCD (Wilson et al., 2002, 2016). Training the motor skills of children with DCD seems necessary in order to help these children and MI training can help refine their internal motor plans (i.e. internal models) (Adams et al., 2016). More awareness of the coupling between motor imagery and actual movement, will likely enhance transfer to other tasks than the task trained.

Theoretically, the diagnostic criteria for DCD (from both the DSM-V (American Psychiatric Association, 2013) and ICD-10 (World Health Organization, 2007)) identify neurological deficit as an exclusion criterion for DCD. This is consistent with a developmental delay model of the disorder. In contrast, a disorder hypothesis suggests that the deficits in predictive control seen in DCD may reflect a disruption to underlying neurocognitive processes (Hyde & Wilson, 2013). This would question current diagnostic scheduling which defined neurological impairments as an exclusion criteria. Intriguingly, indeed several neuro-anatomical regions have been proposed

as possible foci for the etiology of DCD (for a review see (Zwicker, Missiuna, & Boyd, 2009) and researcher and clinicians have suggested in recent years that DCD and cerebral palsy have similar causal pathways and may fall on a continuum of movement disorder rather than being discrete categories (Hadders-Algra & Gramsbergen, 2003; Pearsall-Jones, Piek, & Levy, 2010; Williams, Hyde, & Spittle, 2014). From a clinical perspective, a developmental delay in DCD would suggest that children have the potential to improve their predictive control skills but that development is delayed. Targeted interventions can then help to accelerate this process and improve the motor skills of children with DCD more rapidly, thereby enhancing an early catch-up with typically developing peers. On the other hand, if the impaired predictive control seen in DCD reflects a disorder, possibly with an identifiable neurological basis, children might not be expected to acquire age-appropriate motor skills at all (Hyde & Wilson, 2013). The approach of the intervention will then differ from an intervention that addresses a developmental delay. If the motor problems are the result of a developmental delay, training will speed up the already maturing motor system. In contrast, training for children with a (neurological) deficit might mean that compensative strategies should be taught.

A limitation of the present study is the restricted number of measurement occasions and participants. The use of growth curve modeling statistics was not possible with the presented data set, due to a limited number of measurement occasions and a sample size that is considered small to moderate for these kind of analyses. We have chosen to include a clinical group of children with DCD (all included children were treated or have been treated for a motor coordination problem by a pediatric physical therapist), instead of a group of children with probable DCD recruited on regular primary schools as has been done in previous studies (e.g. (Noten, Wilson, Ruddock, & Steenbergen, 2014; Williams, Thomas, Maruff, Butson, & Wilson, 2006; Wilson et al., 2004). This implied home-based measurements, limiting the number of children and the number of measurement occasions that could be completed within the time span of the project. For future studies, that aim at modelling both individual and group growth trajectories, it is recommended that at least five measurement occasions are included as well as a larger sample size (Bolger & Laurencau, 2013). In addition, some of the included children received treatment between T0 and T1 and T1 and T2, which probably might have enhanced their performance on the motor imagery and action planning task. We could have decided to only include children with DCD who did not receive treatment, but this would likely have resulted in a selection bias of children with DCD who are less impaired. We considered the current sampling of children with DCD to be more in line with the clinical population seen by pediatric physical therapists which favors the generalization of results.

We did not explicitly assess children's IQ, attention and working memory. Children were recruited from mainstream schools and therefore assumed to have IQ levels within the normal range (Geuze, Jongmans, Schoemaker, & Smits-Engelsman, 2001). When children attended special education, parents were asked for their latest IQ score. Given the lack of evidence suggesting a reliable relationship between motor ability and IQ (van der Fels et al., 2015), we argue that it is unlikely that IQ would have influenced the results of this study. In addition, children with an ADHD diagnosis were excluded from this study, preventing the confounding effect that severe attentional problems might have on performing the MI and action planning task. Still, working memory problems could have influenced performance (Alloway & Archibald, 2008). In the current study, we decided to not include a working memory test for two reasons. First of all, the working memory load of the experimental tasks was considered low. Children could respond immediately after the presentation of the hand stimulus or the sword. Secondly, the current test battery (including the mABC-2, hand rotation task and sword task) already took 40 minutes to complete. To prevent fatigue, we decided that adding a working memory task was not desirable. Taken together, it is not likely that differences in working memory skills can explain the described differences between the DCD and control group.

In sum, the present study showed that children with DCD are able to improve motor imagery and action planning ability over time. Using an implicit MI task, it was shown that children with DCD were slower and less accurate than their typically developing peers in all subsequent measurements but were able to improve their motor imagery ability over time. Furthermore, children with DCD showed less planning for ESC at the start of the present study, but were able to catch up with their peers during the two-year follow up. Together, these results provide an important avenue for training and rehabilitation of motor skills in children with DCD. Improvement of implicit MI and action planning ability is possible in DCD, and training might help to enhance an early catch-up with their typically developing peers. This is supported by studies showing that motor imagery training is as effective as perceptual motor training in improving motor skills in children with DCD (Wilson et al., 2002, 2016). Currently, studies that performed motor imagery training in children with DCD, used a mixture of explicit and implicit motor imagery (using action observation) (Adams et al., 2016; Wilson et al., 2002, 2016). The current study focused on the development of implicit motor imagery ability (using a mental rotation task) not explicit motor imagery ability. In a task using explicit motor imagery, direct instructions to use motor imagery are given to participants. Future studies could examine the development of explicit motor imagery (using for example a mental chronometry task) in children with DCD. Experiencing the actual outcome of a planned movement (as for example in the sword task), providing feedback on the result of a movement, and comparing predicted and actual outcomes of movement might be an important aspect to enhance learning in children with DCD. Future studies are recommended to focus on developmental patterns of explicit motor imagery, in order to further test the delay hypothesis and to develop age-appropriate instructions in motor imagery training. Together, this will help to improve current motor imagery trainings and make such interventions both more cost-efficient and more adjusted to a child's individual needs.

Declaration of interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.humov.2017.08.021>.

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