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Second-order motor planning difficulties in children with developmental coordination disorder

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A R T I C L E I N F O

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A B S T R A C T

The second-order motor planning ability of children with developmental coordination disorder (DCD) has often been studied using tasks that require judgements of end-state comfort (ESC). In these studies, children may have chosen to prioritize other aspects of performance (e.g., a comfortable start-posture) over ESC while still being able to complete the goal of the task. This is a limitation that is inherent to previously used ESC paradigms. To avoid this in the present study, 52 children with and without DCD (aged 5–12 years) completed a task that requires second-order motor planning for its successful completion. In the hexagonal knob task, children were instructed to grasp and rotate a hexagonal knob. The rotation angle varied in size: 60°, 120°, 180°, and 240° rotations. Both the 180° and 240° rotation conditions required an uncomfortable starting posture for successful task completion. Results showed that children with DCD were less likely to adjust their initial grip in anticipation of the required rotation angle, resulting in more task failures compared with typically developing (TD) children. Based on this finding we conclude that children with DCD experience genuine second-order motor planning difficulties. Analysis of temporal outcomes, showed that initial reaction time increased with rotation angle, but this was less pronounced for children with DCD than for TD children. There were no between group differences in timing of subsequent events. These results suggest that the difficulties of children with DCD are related to the initial planning process, that is, before the start of the movement.

1. Introduction

Children with developmental coordination disorder (DCD) experience motor coordination difficulties that significantly interfere with their daily life activities. These motor difficulties are evident from an early age and cannot be explained by other known medical conditions (American Psychiatric Association, 2013). A growing number of studies has associated DCD with poor motor planning (for a review, see Adams, Lust, Wilson, & Steenbergen, 2014). In the context of manual action, first-order motor planning involves adjusting grasps towards immediate task goals such as the shape of an object. Second-order motor planning involves the ability to adapt grasps in order to serve subsequent manipulation of an object, a function that is critically important in everyday life; e.g., the ability to grasp a key in such a way that it can be easily inserted into a keyhole and rotated. Second-order motor planning is commonly measured using grip-selection paradigms that focus on the *end-state comfort* (ESC) effect (Rosenbaum et al., 1990). For example, when asked to grasp

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and turn a dial to a target position, mature performance is defined by selection of an uncomfortable grip posture at movement onset so as to finish the rotation movement in a comfortable position, the ESC effect. However, performers may adopt an alternate strategy to achieve the required task goal, like optimizing start state comfort, a comfortable start posture, and uncomfortable end posture which is then unduly coded as a “motor planning error”. In the present study we enlist a grip-selection task that can only be completed successfully via use of second-order motor planning.

To explain the motor coordination difficulties of children with DCD, the *internal modeling deficit* (IMD) hypothesis has been proposed (Katschmarsky, Cairney, Maruff, Wilson, & Currie, 2001; Wilson et al., 2017). The basic tenet of internal modeling is that movement is controlled by its intended consequences (Shadmehr, Smith, & Krakauer, 2010). Internal models provide stability to the motor system by predicting its future states, providing a means of rapid online adjustments before afferent signals are processed (Kawato, 1999; Wolpert, 1997; Wolpert & Ghahramani, 2000). According to the IMD hypothesis, children with DCD have difficulties with using predictive models/estimates of body position to correct actions in real time. Instead, their movement system is more dependent on slower feedback-based control. At the same time, error-based learning via predictive control is compromised, which may explain the much slower rate at which new skills are learned with repeated practice (Wilson, Ruddock, Smits-Engelsman, Polatajko, & Blank, 2013). Predictive motor control underpins the ability to imagine or successfully anticipate the end state of an action (Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016). Accordingly, the IMD account predicts that children with DCD will have second-order motor planning problems when interacting with objects.

The ESC effect enhances over the course of child development but is reduced in developmental disorders that are characterized by motor impairments (for a review, see Wunsch, Henning, Aschersleben, & Weigelt, 2013). In children with DCD, a number of studies have used grip-selection tasks to measure the ESC effect, but results have been mixed. Some studies (Adams, Smits-Engelsman, Lust, Wilson, & Steenbergen, 2017; Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016; van Swieten et al., 2010; Wilmut & Byrne, 2014) have shown a bias in children with DCD towards selecting the simplest initial posture, resulting in a lower level of ESC planning compared with typically developing (TD) children. Other studies (Noten, Wilson, Ruddock, & Steenbergen, 2014; Smyth & Mason, 1997) have found no such effect in DCD. In a recent meta-analysis, it was argued that these discrepancies in findings are likely to reflect differences in task demands (Bhoyroo, Hands, Steenbergen, & Wigley, 2019). For simple movement tasks, children with DCD are able to plan their movements to reach ESC, much like TD children. However, for tasks with more initial grip choices, a higher level of precision, and/or a higher number of action steps, children with DCD perform consistently worse than TD peers (Bhoyroo, Hands, Steenbergen, & Wigley, 2019). Importantly, however, there is a limitation that is inherent to the tasks used to measure the ESC effect. That is, children may use different types of planning strategies, like optimizing start state comfort, and are still able to comply with the task instructions and complete the task successfully (i.e., achieve the required task goal). In those cases, interpreting an uncomfortable end-posture as “motor planning error” is incorrect. To overcome this potential confound, we used a task that can only be completed by first planning for end-state.

While difficulties in second-order planning have been reported in children with DCD (Adams et al., 2014; Wilson et al., 2017), we still understand little of the processes underlying these difficulties. To this point, researchers have relied mainly on raw accuracy measures of performance—i.e., grip selections that either achieve ESC or not. Temporal measures of performance can provide additional insights into the motor planning process. Specifically, the time course of the movement prior to object contact and manipulation has been shown to vary considerably as a function of task demands (Fleming, Klatzky, & Behrmann, 2002; Seegelke, Hughes, Knoblauch, & Schack, 2013; Wilmut, Byrne, & Barnett, 2013). We argue here that a time-based analysis of grip selection and subsequent manual action may provide a more detailed account of the second-order motor planning process. In this regard, it is instructive to divide the total time until movement manipulation into three components: *initial reaction time* (the interval between the stimulus onset and the start of the movement), *movement time* (the interval between the start of the movement and the hand making contact with the object), and *secondary response latency* (the interval between the hand making contact with the object and the start of the object manipulation). Task conditions that dictate how an object is to be manipulated will influence the planning process with more demanding movements resulting in longer preparation time than less demanding movements (Klapp, 1995). In case these task conditions affect initial reaction time only, this indicates that the planning process is completed before movement onset. An effect of task conditions on subsequent movement time and secondary response latency would indicate that online correction of the plan is necessary during the reaching movement or even after first contact with the object (Fleming et al., 2002).

Earlier studies have examined the influence of task demands on the time course of grasping movements in children with a congenital motor disorder—cerebral palsy (CP). Mutsaarts, Steenbergen, and Bekkering (2005) used a hexagonal knob task (HKT) in which adolescents with and without CP (Bax et al., 2005), were instructed to grasp and rotate a knob either 60° or 120° using a pre-instructed grasping pattern. For healthy adolescents, rotation angle had an effect on initial reaction time only, suggesting that the planning process was complete before movement onset; however, this pattern was not observed in adolescents with CP. In adolescents with CP, the rotation angle affected both movement time and the secondary response latency (“second reaction time” in their study), indicating a sequential or step-by-step planning strategy where each phase of the movement sequence is planned anew.

In a more recent study, we used an adapted version of the HKT in a large group of TD children (Krajenbrink, Lust, Wilson, & Steenbergen, 2020). Here, children had to grasp and rotate the knob over 60°, 120°, 180°, or 240° using a self-selected grip. Using this more demanding version of the HKT, rotation angle affected both initial reaction time and subsequent movement time. Initial reaction time and movement time both increased with increasing rotation angle in a similar way for all 5 to 12-year old children. With age, initial reaction time decreased for all rotation angles, while the subsequent movement time remained relatively stable. To date, no studies have been reported on the effects of task demands on the time course of a grasping movement in children with DCD. Based on the IMD hypothesis (Wilson & Butson, 2007) we expected to find a similar step-by-step planning strategy in children with DCD as in adolescents with CP.

The aim of the present study was to examine the second-order motor planning process in children with DCD using the HKT task which requires second-order motor planning for its successful completion. From the perspective of the IMD account, we hypothesized that children with DCD would adapt their grasps less successfully according to the rotational requirements of the task than their TD peers. Poor predictive motor control and hence greater reliance on online adjustments during the movement phase due to inadequate movement plans in children with DCD would be reflected in a weaker effect of rotation angle on the initial reaction time, but an elevated effect of angle on subsequent movement time and secondary response latency compared with their TD peers. We also compared performance on the HKT with other grip selection tasks—the sword task (Crajé, Aarts, Nijhuis-van der Sanden, & Steenbergen, 2010) and the cup task (Adalbjornsson, Fischman, & Rudisill, 2008). Here, the aim was to examine whether children with DCD and TD children would be more consistent in planning for end-state on a task with a high necessity to plan for end-state (i.e., the HKT) compared with previously used tasks with a low necessity to plan for end-state (i.e., the sword and cup task).

2. Method

2.1. Participants

Twenty-nine children with DCD participated in the present study. Children with DCD were recruited through pediatric physical therapists and via advertisements on websites for parents of children with DCD. Twenty-three of these children had received a medical diagnosis of DCD. It was determined if both these and the undiagnosed children met the Diagnostics and Statistical Manual of Mental Disorders, Fifth Edition (DSM-5; American Psychiatric Association, 2013) criteria for DCD. Twenty-six children met the following DSM-V criteria for DCD and were included in the study: Movement Assessment Battery for Children 2 (MABC-2; Henderson, Sugden, & Barnett, 2007) total score ≤16th percentile or any of the three component scores ≤5th percentile (criterion A); treated or have been 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 Developmental Coordination Disorder Questionnaire (DCD-Q, Dutch translation; Schoemaker, Reinders-Messelink, & de Kloet, 2008) and the DCDDaily-Q (van der Linde, van Netten, & Schoemaker, 2015) (criterion B); early onset of symptoms (criterion C); and finally, none of the parents of the children with DCD indicated any cognitive impairment, visual impairment, or neurological deficit which would explain their child's motor difficulties (criterion D). Based on parent reports, co-morbid disorders were Attention Deficit Hyperactivity Disorder (ADHD) ($n = 3$), Developmental Language Disorder ($n = 2$), Attention Deficit Disorder ($n = 1$), Autism Spectrum Disorder ($n = 1$), and Dyslexia ($n = 1$).

In addition, 54 TD children were recruited from mainstream primary schools and via the network of the researcher. Twenty-six TD children matched for gender and age (within 6 months, except for 2 children that were matched within 8 months) were (randomly, in case of multiple options) selected from this group. All TD children had a MABC-2 total score >16th percentile.

Finally, parents of all children completed the ADHD-questionnaire (AVL; Scholte & van der Ploeg, 2004) as a descriptive measure of ADHD symptoms. Participant characteristics are presented in Table 1. Written informed consent was obtained from the parents/guardians. Participants themselves gave assent for participation if they were 12 years old. The study was approved by the ethics committee of the Faculty of Social Sciences at Radboud University (ECSW-2018-101).

2.2. Materials and outcome measures

2.2.1. Hexagonal knob task

The HKT (Krajenbrink et al., 2020; Mutsaarts et al., 2005) was used to assess second-order motor planning ability. The HKT was programmed in Delphi and is depicted in Fig. 1. The apparatus consisted of a circular platform with a circle of 265 light-emitting diodes (LEDs) situated 1.0 cm from the edge of the platform. At the center of the platform, a hexagonal knob was placed with an arrow attached to one side. Starting every trial, children placed their dominant hand on the start box. The arrow then automatically moved

Table 1
Participant characteristics for the DCD group and TD group.

	DCD group ($n = 26$)	TD group ($n = 26$)
Age in years *M* (*SD*)	8y,7 m (*1y,10 m*)	8y,7 m (*1y,11 m*)
Sex (males/females) (*n*)	19/7	19/7
Dominant hand (left/right) (*n*)	1/25	4/22
MABC-2 total score in percentiles *M* (*SD*)	5.12 (*7.96*)	48.12 (*20.79*)
AVL total sum score *M* (*SD*)	25.26 (*11.97*)	12.04 (*11.90*)
DCD-Q total sum score *M* (*SD*)	30.52 (*7.98*)	66.92 (*7.72*)
DCDDaily-Q participation total sum score *M* (*SD*)	46.02 (*7.43*)	34.54 (*4.99*)
DCDDaily-Q activities total sum score *M* (*SD*)	50.32 (*6.96*)	29.58 (*5.99*)
DCDDaily-Q learning total sum score *M* (*SD*)	16.68 (*4.30*)	1.04 (*2.62*)

Note. MABC-2, Movement Assessment Battery for Children 2; AVL, attention-deficit/hyperactivity disorder questionnaire, score can theoretically vary between 0 and 72 with higher scores indicating more symptoms; DCD-Q, developmental coordination disorder questionnaire, score can theoretically vary between 15 and 75 with lower scores indicating more symptoms. DCDDaily-Q, questionnaire focusing on difficulties in activities of daily living. Scores on subscales participation, activities, and learning can theoretically vary between 23 and 92, 23 and 69, and 0 and 23, respectively, with higher scores indicating more difficulties.

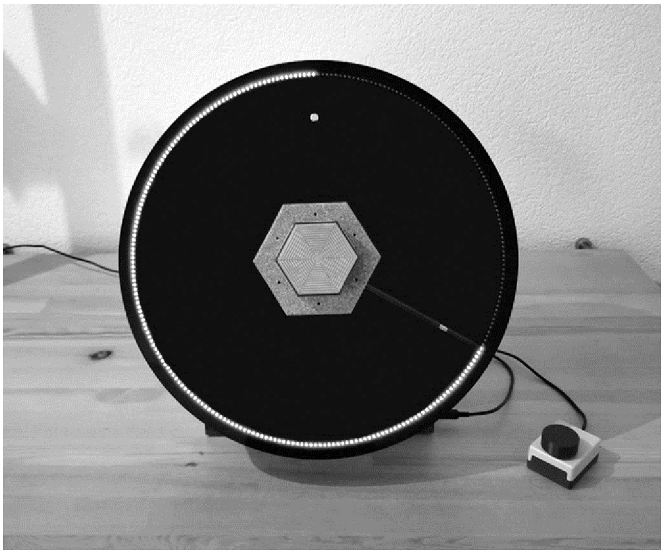

Fig. 1. The hexagonal knob task displaying an experimental trial with a clockwise rotation of 240°, starting with the arrow pointing at 120° (set-up with startbox at the right of the platform for a right-handed participant).

towards one of six possible start positions (i.e., 0°, 60°, 120°, 180°, 240°, or 300° from the top). When the arrow was at the right position, all LEDs lit up for 1000 ms (priming cue) to alert children for the upcoming trial. Next, there was a random delay between 600 and 1500 ms, after which a path of LEDs lit up all at once, indicating the length of the rotation (starting cue). There were four different rotation angles ascending in size: 60°, 120°, 180°, and 240°. Children were instructed to use their dominant hand to grasp the hexagonal knob and rotate it in the direction of the lights, so that the arrow pointed towards the final LED in the path. They were instructed to complete the rotation as fast as possible. Furthermore, they were not allowed to adjust the initial grip and they had to remain seated throughout the experiment. The 180° and 240° rotation angles served as critical rotations. For these, children needed to sacrifice comfort of the start position in order to be able to complete the rotation movement successfully. The 60° and 120° rotation angles served as control rotations in which children could complete the rotation movement with a comfortable start posture. All four rotation angles appeared 10 times, equally distributed across clockwise and counterclockwise trials, yielding a total of 40 trials. The trials appeared in a pseudo-random order with all four rotation angles appearing every four trials.

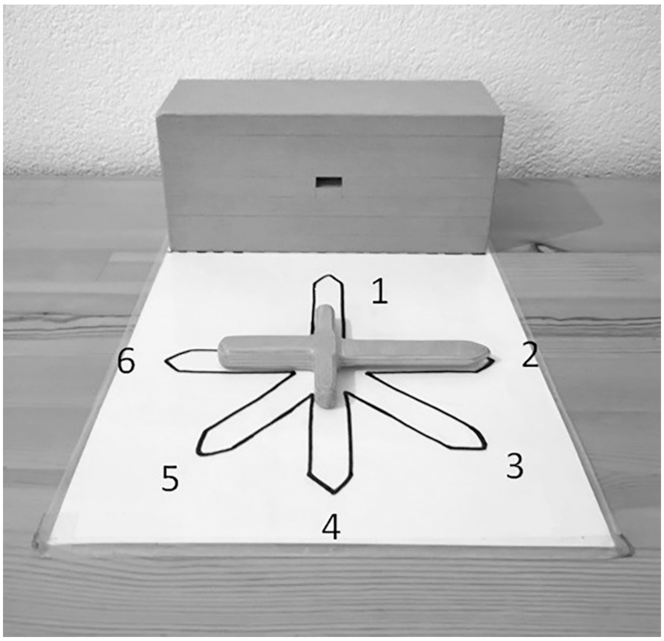

Fig. 2. The sword task with the sword placed at orientation 2.

For each trial, it was determined whether the trial was successfully completed or not which served as a measure of *planning accuracy*. A score of 1 (i.e., successful task completion) or 0 (i.e., unsuccessful task completion) was assigned for each trial for each child. Successful task completion was determined based on the position of the thumb of the children when grasping the hexagonal knob. Based on the thumb position, it was established whether it would be biomechanically possible to reach the end of the rotation movement (i.e., the arrow pointing towards the final LED in the path). This was possible because the slope of the platform and the distance from the platform to the front edge of the table were adjusted based on children's range of motion before the start of the task. More information about the coding and recording of this measure can be found in the supplementary material part 1. In addition to planning accuracy, three time events were recorded: *initial reaction time* (i.e., the interval between the starting cue and the moment the hand released the start box), *movement time* (i.e., the interval between the moment the hand released the start box and the moment the hand touched the hexagon), and *secondary response latency* (i.e., the interval between the moment the hand touched the hexagon and the commencement of the rotation movement). These measures were recorded with a time resolution of ±20–25 ms.

2.2.2. Sword task

The second task to measure motor planning was the sword task (Crajé et al., 2010). In this task, a sword was presented on a sheet with a template board with six possible sword orientations that was placed before a wooden block with a hole in it. Children were instructed to grasp the sword with the dominant hand, using a whole hand grip, and stick it into the hole in the wooden block. As can be seen in Fig. 2, two orientations served as critical orientations, orientations 2 and 3 for right-handed participants and orientations 5 and 6 for left-handed participants. In these, children had to sacrifice comfort of the start position in order to end the task in a comfortable position. The other four orientations served as control orientations in which comfort at the start position resulted in comfort at the end position. Each orientation was repeated three times, yielding a total of 18 trials. The trials appeared in a pseudo-random order with all six orientations appearing every six trials. A score of 1 (i.e., action ended with the thumb towards the blade) or 0 (i.e., action ended with the thumb away from the blade) was assigned for each trial for each child.

2.2.3. Cup task

The third task to measure motor planning was the cup task (Adalbjornsson et al., 2008). In this task, a cup was placed upside down in front of the children. The children were instructed to grasp the cup with the dominant hand and to turn it over. Three trials were assessed. A score of 1 (i.e., action ended with the thumb up) or 0 (i.e., action ended with the thumb down) was assigned for each trial for each child.

2.3. Procedure

Participants were seated so that they could comfortably reach the experimental materials on the table. The session started with a general explanation of the study. Then, participants were asked to write down their name on the session form, which served to determine hand preference (Jongbloed-Pereboom, Nijhuis-van der Sanden, Saraber-Schiphorst, Crajé, & Steenbergen, 2013). Next, the three motor planning tasks were administered. The order of the three tasks was counterbalanced across participants. Performance on the motor planning tasks was recorded on video to allow for offline scoring. Finally, the MABC-2 was assessed. (If the MABC-2 had already been assessed during the past year, that score was used instead). For all children with DCD, the data collection took place in one session, often at the home of the child. A break was provided prior to the MABC-2 assessment to prevent fatigue. For most TD children, data collection took place at school. For these children, there were two test sessions, with the MABC-2 being assessed at the second session.

2.4. Data processing and analyses

2.4.1. HKT planning accuracy

In order to examine the difference in planning accuracy between children with DCD and TD children, a generalized linear mixed-effect model was performed with a binomial link function using the glmer function of the lme4 package (Bates, Maechler, Bolker, & Walker, 2015) in R (R Core Team, 2013). In the model, planning accuracy (proportion of successful task completion, included as the number of successfully completed trials and the number of unsuccessfully completed trials) was predicted as a function of the fixed effect of group (DCD vs. TD), the fixed effect of rotation angle (120°, 180°, or 240°), as well as the interaction thereof. The 60° rotations were not included because the model was not able to fit this data due to a lack of variation in scores. A random intercept for participant was included in order to control for individual variances across measurements. Contrasts were manually adjusted such that 120° and 180°, and 180° and 240° rotations were compared to each other. Values of p are based on confidence intervals and the beta coefficients that resulted from the model were converted into odds ratios (ORs).

2.4.2. HKT time events

Due to registration errors, data was missing for 2 (0.10%), 3 (0.14%), and 46 (2.21%) of the total trials for the initial reaction time, movement time, and secondary response latency data, respectively. In addition, 114 of the remaining trials (5.62%) were classified as invalid because of extremely long initial reaction times, movement times, and or secondary response latencies (a deviation from the mean of more than three times the standard deviation was used as an outlier-procedure for each participant separately) or short initial reaction times (less than 200 ms). These invalid trials were excluded from data analyses. For each child, the average *initial reaction time* data, *movement time* data, and *secondary response latency* data for all four rotations angles (i.e., 60°, 120°, 180°, and 240° rotations)

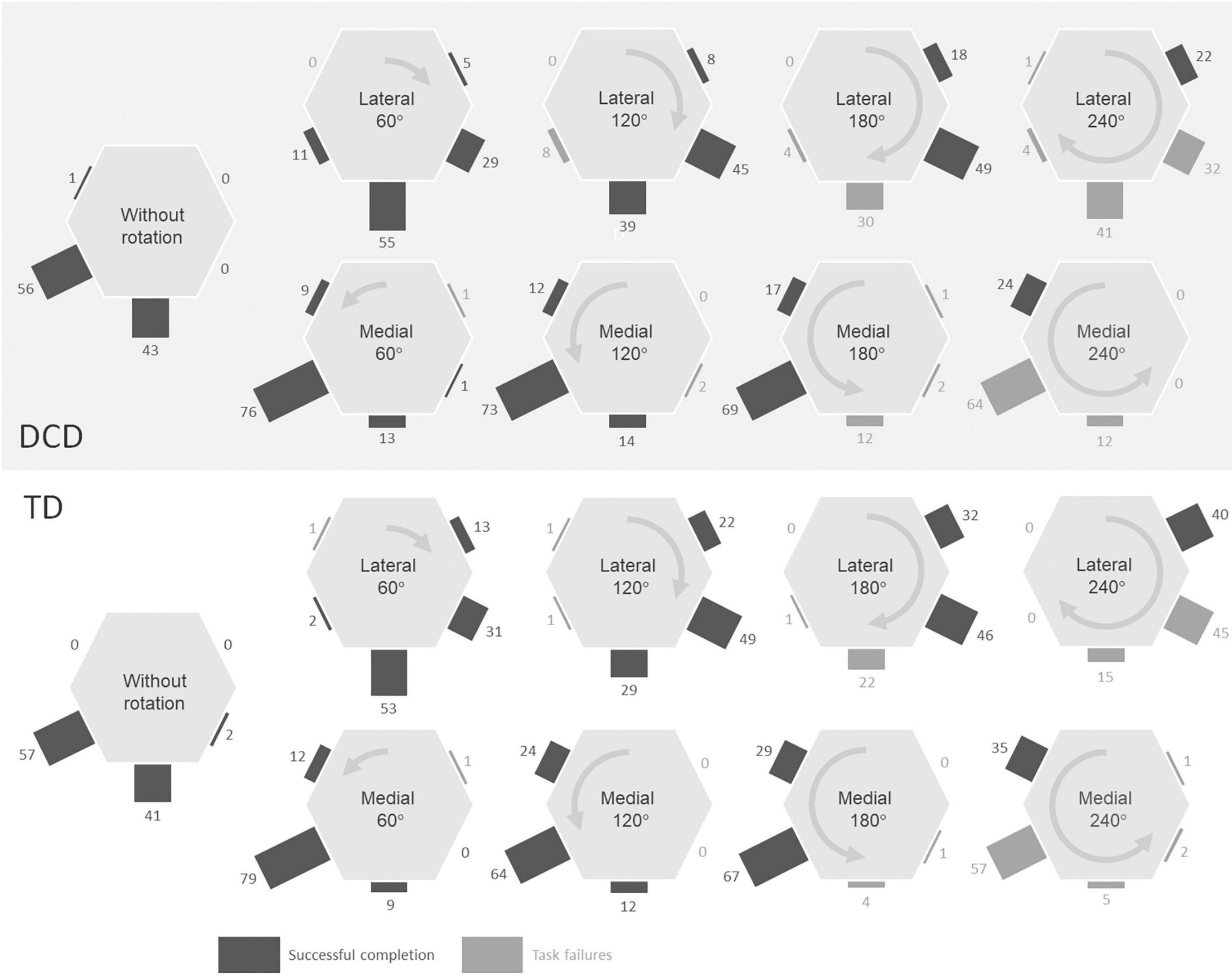

Fig. 3. The grasping pattern distribution for children with DCD and TD children separately. For each angle and direction of rotation, the percentage of grasps with the thumb on that particular side of the hexagon are displayed by the length of the bars and related numbers. Results are visualized for right-handed children (data of left-handed children are mirrored in the figure).

were calculated and these scores were used in the analysis. As the initial reaction time data, movement time data, and secondary response latency data were all positively skewed, log transformations were performed on all three variables to obtain more normally distributed data. In order to examine the difference in time events between children with DCD and TD children, a repeated measures MANOVA was conducted in SPSS version 22 (IBMCorp., Released 2013). In the analysis, group (DCD vs. TD) was included as between-subject variable, rotation angle (60°, 120°, 180°, or 240°) as within-subject variable, and (log-transformed) initial reaction time, movement time, and secondary response latency as dependent variables. Repeated contrasts were used to analyze the effect of rotation angle on the dependent variables.

2.4.3. Comparison between HKT and sword and cup task

Finally, in order to compare the pattern of performance on the HKT to the performance on the sword and cup task between children with DCD and TD children, again a generalized mixed effects model approach was used. In this model, performance (proportion of planning accuracy on the HKT and proportion of ESC on the sword and cup task, included as the number of successfully completed trials/trials that ended in ESC and the number of unsuccessfully completed trials/trials that did not end in ESC) was predicted as a function of the fixed effects of group (DCD vs. TD), task (HKT task 180° condition, HKT task 240° condition, sword task, or cup task), as well as the interaction thereof. A random intercept for participant was included in order to control for individual variances across measurements. Contrasts were manually adjusted such that the performance on the 180° and 240° conditions of the HKT task together was compared to the performance on the sword and cup task together. Values of p are based on confidence intervals and the beta coefficients that resulted from the model were converted into odds ratios (ORs). Follow-up analyses were conducted using Welch's *t*-test on the estimated marginal means of the model.

3. Results

3.1. HKT planning accuracy

Fig. 3 shows the grasping pattern distribution on the HKT for children with DCD and TD children, separately. As can be seen, for both groups, grasping patterns changed according to the direction and size of the required rotation angle.

Fig. 4 shows the average *planning accuracy* for the four rotation angles. Results of the generalized linear mixed-effect model showed a significant main effect of rotation angle, both for the comparison between 120° and 180° rotations, $OR = 0.12$, $b = -2.08$, $SE = 0.35$, $z = -5.97$, $p < .05$, 95% CI [−2.96, −1.39]; as well as for the comparison between 180° and 240° rotations, $OR = 0.06$, $b = -2.85$, $SE = 0.24$, $z = -11.66$, $p < .05$, 95% CI [−3.37, −2.36]. This indicates that planning accuracy was higher for 120° compared with 180° rotations, and for 180° compared with 240° rotations. In addition, in line with the expectation, the main effect of group was statistically significant, $OR = 3.21$, $b = -1.17$, $SE = 0.42$, $z = 2.75$, $p < .05$, 95% CI [0.24, 5.71]; which indicated that overall, the DCD group had a lower planning accuracy than the TD group. However, the interaction between rotation angle and group was not significant, both for the comparison between 120° and 180° rotations, $OR = 0.34$, $b = -1.09$, $SE = 0.82$, $z = -1.33$, $p < .05$, 95% CI [−15.07, 0.34]; and for the comparison between 180° and 240° rotations, $OR = 0.71$, $b = -0.34$, $SE = 0.36$, $z = -0.94$, $p < .05$, 95% CI [−1.02, 0.45]. This indicated that the difference in planning accuracy between the DCD and TD group did not vary per angle of rotation.

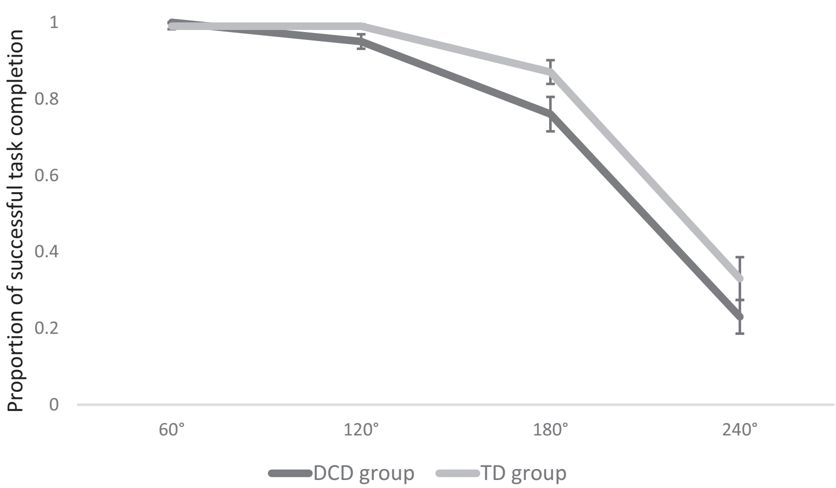

Fig. 4. Planning accuracy (proportion successful task completion) by rotation angle for the DCD group and the TD group. Error bars represent standard errors.

3.2. HKT time events

Table 2 gives an overview of the log-transformed time course data that was analyzed using a repeated-measures MANOVA (the raw time course data can be found in the supplementary material part 2 and 3, on individual and group level, respectively). Results of the multivariate test indicated a significant main effect of angle, $F(9, 42) = 9.52$, $p < .001$, $\eta_p^2 = 0.67$. The main effect of group, $F(3, 48) = 0.28$, $p = .838$, $\eta_p^2 = 0.02$; as well as the interaction between angle and group, $F(9, 42) = 1.44$, $p = .201$, $\eta_p^2 = 0.24$; were not statistically significant. Yet, given the size of the effect ($\eta_p^2 = 0.24$) related to the interaction between rotation angle and group, we decided to report the univariate tests and interpret them with caution.

Fig. 5 shows the average log-transformed *initial reaction times* for the four rotation angles, separately for the DCD and the TD group. The repeated measures MANOVA showed a main effect of rotation angle, $F(2.62, 131.01) = 15.46$, $p < .001$, $\eta_p^2 = 0.24$. In addition, the interaction between rotation angle and group was statistically significant, $F(2.62, 131.01) = 2.89$, $p = .045$, $\eta_p^2 = 0.06$. This indicated that the effect of rotation angle on initial reaction times was different for the DCD and the TD group. The main effect of group was not statistically significant, $F(1, 50) = 0.13$, $p = .721$, $\eta_p^2 < 0.01$. In line with our hypothesis, follow-up analysis revealed that for the TD group, the main effect of rotation angle was statistically significant, $F(2.72, 68.08) = 15.27$, $p < .001$, $\eta_p^2 = 0.38$; initial reaction times were significantly higher for 240° compared with 180° rotations, $F(1, 25) = 20.33$, $p < .001$, $\eta_p^2 = 0.45$; and for 180° compared with 120° rotations, $F(1, 25) = 7.07$, $p = .013$, $\eta_p^2 = 0.22$; the difference between 120° and 60° rotations was not significant, $F(1, 25) = 0.28$, $p = .601$, $\eta_p^2 = 0.01$. Also for the DCD group, the main effect of rotation angle was statistically significant, $F(2.30, 57.57) = 4.17$, $p = .016$, $\eta_p^2 = 0.14$. Here, initial reaction times were significantly higher for 240° compared with 180° rotations, $F(1, 25) = 5.20$, $p = .031$, $\eta_p^2 = 0.17$; but there was no significant difference between 180° and 120° rotations, $F(1, 25) < 0.01$, $p = .926$, $\eta_p^2 < 0.01$; and between 120° and 60° rotations, $F(1, 25) = 2.42$, $p = .132$, $\eta_p^2 = 0.09$.

For *movement time*, the repeated measures MANOVA showed a significant main effect of rotation angle, $F(2.61, 130.34) = 19.96$, $p < .001$, $\eta_p^2 = 0.29$. Repeated contrasts revealed that movement times were longer for 240° compared with 180° rotations, $F(1, 48) = 5.55$, $p = .022$, $\eta_p^2 = 0.10$; and for 180° compared with 120° rotations, $F(1, 48) = 10.40$, $p = .002$, $\eta_p^2 = 0.17$; the difference between 120° and 60° rotations was not significant, $F(1, 48) = 3.01$, $p = .089$, $\eta_p^2 = 0.06$. Contrary to our hypothesis, the main effect of group, $F(1, 48) = 0.59$, $p = .445$, $\eta_p^2 = 0.01$; and the interaction between rotation angle and group, $F(2.61, 130.34) = 0.22$, $p = .857$, $\eta_p^2 < 0.01$; were not statistically significant. This indicated that movement times in general and the effect of rotation angle on movement times did not differ significantly between the DCD and the TD group.

Finally, for *secondary response latency,* the repeated measures MANOVA showed a significant main effect of rotation angle, $F(2.88, 143.91) = 2.75$, $p = .047$, $\eta_p^2 = 0.05$. However, repeated contrasts revealed no significant differences in secondary response latency between the 240° and 180°, $F(1, 48) = 3.07$, $p = .086$, $\eta_p^2 = 0.06$; between the 180° and 120° rotations, $F(1, 48) = 1.62$, $p = .210$, $\eta_p^2 = 0.03$; or between 120° and 60° rotations, $F(1, 48) = 2.22$, $p = .143$, $\eta_p^2 = 0.04$. Contrary to our hypotheses, neither the main effect of group, $F(1, 48) < 0.01$, $p = .954$, $\eta_p^2 < 0.01$; nor the interaction between rotation angle and group, $F(2.88, 143.91) = 0.69$, $p = .552$, $\eta_p^2 = 0.01$; were statistically significant. This indicated that secondary response latencies in general and the effect of rotation angle on secondary response latencies did not differ significantly between the DCD and the TD group.

3.3. Comparison between HKT and sword and cup task

Finally, a generalized mixed effects model with a binomial link function was used to examine the difference in performance between the DCD and TD group on the HKT and the sword task (proportions of ESC: DCD group *Mdn* = 0.00, *M* = 0.26, *SD* = 0.37; TD group *Mdn* = 0.42, *M* = 0.45, *SD* = 0.38) and cup task (proportions of ESC: DCD group *Mdn* = 0.67, *M* = 0.58, *SD* = 0.45; TD group *Mdn* = 1.00, *M* = 0.94, *SD* = 0.21). The interaction of interest between group and task (comparison between the performance on both the 180° and 240° conditions of the HKT to the performance on both the sword and cup task), was statistically significant, $OR = 0.09$, $b = -2.40$, $SE = 0.69$, $p < .05$, 95% CI [−3.83, −1.09]. Follow-up analyses showed that the DCD group performed lower than the TD group both on the 180° and 240° conditions of the HKT, $t(101.91) = -2.03$, $p = .045$; as well as on the sword and cup task, $t(90.59) =$

Table 2
Log-transformed initial reaction times, movement times, and secondary response latencies by rotation angle for the DCD group and the TD group.

		DCD group		TD group	
		M	*SD*	*M*	*SD*
Initial reaction time	60°	6.74	0.38	6.79	0.33
	120°	6.82	0.36	6.77	0.32
	180°	6.82	0.41	6.86	0.40
	240°	6.88	0.37	6.99	0.45
Movement time	60°	6.42	0.22	6.51	0.40
	120°	6.47	0.24	6.52	0.39
	180°	6.52	0.31	6.60	0.47
	240°	6.58	0.31	6.65	0.44
Secondary response latency	60°	5.54	0.50	5.53	0.54
	120°	5.48	0.45	5.49	0.51
	180°	5.50	0.41	5.56	0.56
	240°	5.61	0.40	5.57	0.49

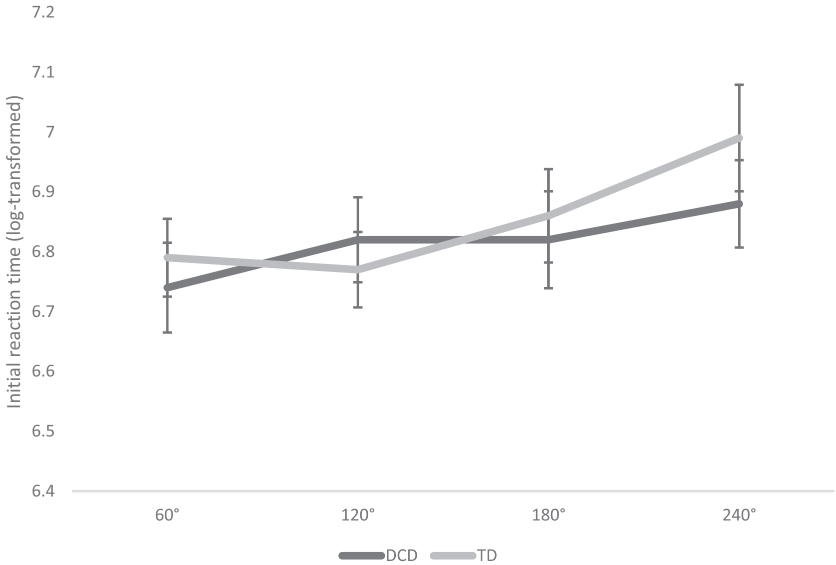

Fig. 5. Initial reaction times (log-transformed) by rotation angle for the DCD and TD group separately. Error bars represent standard errors.

$-5.77, p < .001$. Results are visualized in Fig. 6 (logits transformed to proportions) and indicate that performance differences between the DCD group and TD group are higher on the sword and cup task than on the 180° and 240° conditions of the HKT.

4. Discussion

The present study focused on the second-order motor planning process in children with DCD and TD children which was measured using the HKT. Contrary to other paradigms like the sword and cup task, the HKT is a grip-selection task that can only be completed successfully by planning for end-state. That is, in certain conditions, children had to adjust their initial grasp in order to successfully complete the rotation movement. The results showed that children with DCD were less likely to adapt their grasps to the upcoming rotation angle compared to TD children, which resulted in more task failures. These results suggest that children with DCD have genuine second-order motor planning difficulties. In other words, it obviates the possibility that children with DCD prefer to use different types of planning strategies as this was maladaptive resulting in unsuccessful task completion. Next to planning accuracy, we collected temporal measures to increase our insights into the second-order motor planning process. On temporal outcomes, the effect of rotation angle on the initial reaction time was shown to be less pronounced for children with DCD than for TD children. There was no

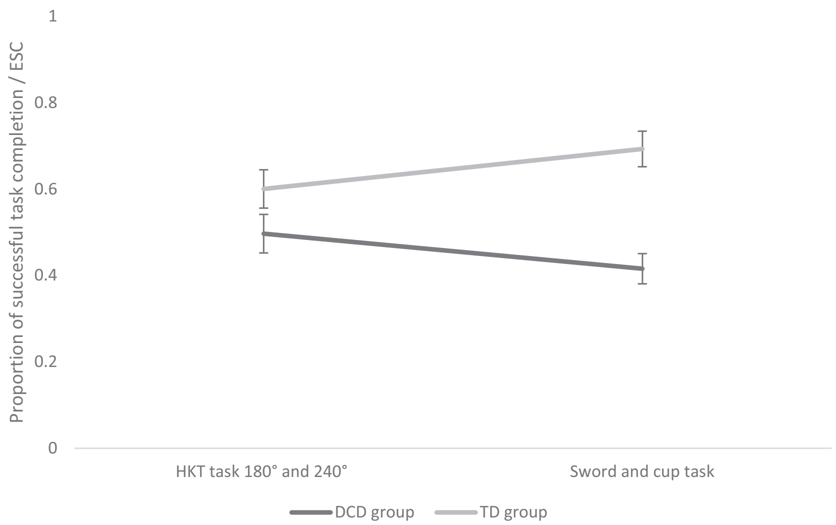

Fig. 6. Estimated proportion of successful task completion of both the 180° and 240° conditions together and the estimated proportion of ESC of the sword and cup task together, for the DCD group and TD group separately. Error bars represent standard errors.

difference between children with DCD and TD children for the subsequent movement time and secondary response latency. Below we first discuss the results for grip-selection and compare these results with the sword and cup task. We then discuss results for the time course of the movement.

The HKT is a second-order motor planning task that can only be completed successfully by planning for end-state. That is, in some conditions, the HKT demands adjustment of the initial grip in order to be able to complete the task. There were two control conditions, the 60° and 120° rotation conditions, in which the rotation movement could be completed with a comfortable start-grip. Additionally, there were two critical conditions, the 180° and 240° rotation conditions, that could only be completed if children adapted their initial grip. Although our results show that both children with DCD and TD children change their grip according to the direction and size of the upcoming rotation angle, we found that overall, children with DCD were less likely to do this accurately, resulting in more task failures, compared with TD children. This finding is consistent with earlier work that suggest a reduced tendency for ESC planning in children with DCD (Adams, Smits-Engelsman, Lust, Wilson, & Steenbergen, 2017; Fuelscher, Williams, Wilmut, Enticott, & Hyde, 2016; van Swieten et al., 2010; Wilmut & Byrne, 2014). Unlike these earlier studies, however, our results show that these issues in ESC planning are real and not attributable to the use of a different type of planning strategy, such as maximizing start-state comfort or a strategy in which children minimize initial rotation (Bhoyroo, Hands, Wilmut, Hyde, & Wigley, 2019; van Swieten et al., 2010; Wilmut & Byrne, 2014). Thus, the results suggest that children with DCD have genuine second-order motor planning difficulties.

While children with DCD performed worse than TD children on a task with a high necessity to plan for end-state (i.e., the HKT), these differences are smaller than on previously used tasks with a low necessity to plan for end-state (i.e., the sword and cup task). In the 240° rotation condition of the HKT, both groups show low success rates, which is in line with previous results and may reflect the high task demands for both groups (Krajenbrink et al., 2020). Also in the 180° rotation condition results are in line with our previous study, with both groups performing rather well (mean proportions successful task completion of 0.76 and 0.87 for the DCD and TD group respectively), with particularly the DCD group performing better than in the sword and cup task as the mean proportions of ESC are much lower on these tasks (mean proportions ESC of 0.26 and 0.56 for the sword and cup task, respectively). This seems to reflect an effect of the induced necessity for second-order motor planning. An effect that was also shown when performance on the sword task of a subgroup of children with DCD and TD children was compared to a newly developed hammer task (Krajenbrink, Lust, & Steenbergen, 2021). Alternatively, it may reflect an effect of increased task experience as the HKT includes more trials than both the cup and the sword task. We therefore also calculated the percentages of successful task completion and comfortable end-states based on the first three critical trials only and replicated the success rates found with the initial analysis using all 10 trials (see supplementary material part 4). This suggests that although children with DCD had a statistically significant higher number of task failures than TD children on the HKT, children with DCD are more likely to use the same strategy as TD children and to plan for end-state when this is a prerequisite for successful task completion.

With respect to the time course of the second-order motor planning process, our results supported the hypothesis that differences in initial reaction time with rotation angle would be less pronounced in children with DCD compared with TD children. More precisely, the time from stimulus (i.e., the path of LEDs lights up) until the start of the movement varied as a function of the size of the rotation angle, more so for TD children than for DCD children. Although it should be noted here that the differences are only small, this indicates that in comparison to TD children, children with DCD are less likely to take the size of the rotation angle into consideration, before starting their movement. Linking these results to motor control theories, the results suggest that for children with DCD, the size of the rotation angle is less well incorporated in their movement plan before the start of the movement compared to TD children. The less pronounced differences in initial reaction time for the different sized rotation angles indicate that the plan is less accurate and precise than that of TD children. These results are in line with the internal model deficit hypothesis, which states that children with DCD have a reduced ability to utilize predictive motor control (Wilson & Butson, 2007).

Interestingly, contrary to our hypothesis, we found no group differences on subsequent movement time and secondary response latency. For movement time, we found an increase for larger rotation angles. This is in line with previous studies that found an effect of experimental manipulations on movement time (Rosenbaum, Vaughan, Barnes, & Jorgensen, 1992; Seegelke et al., 2013) and the results of our previous study among a large group of TD children (Krajenbrink et al., 2020). In that study, we showed that movement execution (i.e., extra physical rotation of the arm and wrist for larger rotation angles) cannot solely explain the differences in movement time for different angles of rotation. This indicates that both children with DCD and TD children continue the second-order motor planning process after movement onset. The movement plan is being updated and corrected online while the hand is in motion (Scott, 2012). Finally, for the secondary response latency, there was an overall effect of rotation angle, but repeated contrasts showed that there were no differences between consecutive angles of rotation. This indicates that movement planning was complete when grasping the hexagon after which the size of the rotation angle no longer required a higher amount of online correction and monitoring (Wilson & Butson, 2007). Taken together, children with DCD differ from TD children in their initial reaction time, which is likely related to difficulties in the second-order motor planning process before the start of the movement. Subsequent to this, there are no temporal differences between children with DCD and TD children in the process after movement onset.

The cognitive load of the HKT can be considered low relative to previously used rotation tasks. Although the cognitive demands vary for the different rotation extent (i.e., higher demands for the 240° rotations compared with the 180°), the required rotation movement was displayed visually during task completion. By comparison, required rotations for the octagon task (i.e., one, two, or three color sequences) are called out by the researcher; thus, children have to listen carefully and remember the correct sequences placing additional demands on attention and working memory (Bhoyroo, Hands, Wilmut, Hyde, & Wigley, 2018). This is important since, next to biomechanical factors, performance on second-order motor planning tasks likely relies on the child's cognitive functions as well (Seegelke et al., 2013; Stöckel & Hughes, 2016). Previous studies demonstrated that children with DCD have impaired cognitive functions such as working memory, inhibition, and executive planning (e.g., Bernardi, Leonard, Hill, Botting, & Henry, 2018; Leonard, Bernardi, Hill, & Henry, 2015; Wilson et al., 2020). We recommend that future studies include measures of cognitive function to examine the impact of individual differences on task performance. In addition, we suggest assessment of the cognitive effort that it takes to perform a second-order motor planning task using a questionnaire or by dual-task paradigm. This will enable comparison of cognitive load as a function of the specific task and whether this differs between children with DCD and TD children.

In summary, children with DCD are less able than TD peers to take into account the end-state of a prospective action and to sacrifice comfort of the start-grip if this is needed to complete the task successfully. This suggests that children with DCD have genuine second-order motor planning difficulties. While prospective control was indicated by a prolongation of initial reaction time for more demanding rotation movements, this was less pronounced in children with DCD than for TD children. Finally, there were no differences in subsequent movement time and secondary response latency between groups. These findings suggest that the difficulties are particularly prominent in the initial part of the second-order motor planning process and that, in comparison to TD children, children with DCD are less likely to take the size of the rotation angle into consideration, before starting their movement.

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Data availability statement

The data supporting the findings of this study will be made available by the authors to any qualified researcher upon reasonable request.

Author statement

All authors have contributed to the work in a meaningful way. HK, JL, and BS were involved in the conceptualization and design of the methodology. HK conducted the research, analyzed the data, and wrote the initial draft. JL, DB, and BS critically reviewed the manuscript. All authors agree with publication of the final version of the manuscript.

Declaration of Competing Interest

All authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2021.102836.

References

Adalbjornsson, C. F., Fischman, M. G., & Rudisill, M. E. (2008). The end-state comfort effect in young children. *Research Quarterly for Exercise and Sport, 79*(1), 36–41. https://doi.org/10.1080/02701367.2008.10599458.

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

Adams, I. L. J., Smits-Engelsman, B., Lust, J. M., Wilson, P. H., & Steenbergen, B. (2017). Feasibility of motor imagery training for children with developmental coordination disorder – A pilot study. *Frontiers in Psychology, 8*(1271). https://doi.org/10.3389/fpsyg.2017.01271.

American Psychiatric Association. (2013). *Diagnostics and statitical manual of mental disorders: DSM-5*. American Psychiatric Association.

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*(1), 1–48. https://doi.org/10.18637/jss.v067.i01.

Bax, M., Goldstein, M., Rosenbaum, P., Leviton, A., Paneth, N., Dan, B., … Damiano, D. (2005). Proposed definition and classification of cerebral palsy, April 2005. *Developmental Medicine & Child Neurology, 47*(8), 571–576. https://doi.org/10.1017/S001216220500112X.

Bernardi, M., Leonard, H. C., Hill, E. L., Botting, N., & Henry, L. A. (2018). Executive functions in children with developmental coordination disorder: A 2-year follow-up study. *Developmental Medicine & Child Neurology, 60*(3), 306–313. https://doi.org/10.1111/dmcn.13640.

Bhoyroo, R., Hands, B., Steenbergen, B., & Wigley, C. A. (2019). Examining complexity in grip selection tasks and consequent effects on planning for end-state-comfort in children with developmental coordination disorder: A systematic review and meta-analysis. *Child Neuropsychology, 26*(4), 534–559. https://doi.org/10.1080/09297049.2019.1695768.

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

Bhoyroo, R., Hands, B., Wilmut, K., Hyde, C., & Wigley, A. (2019). Motor planning with and without motor imagery in children with developmental coordination disorder. *Acta Psychologica, 199*, 102902. https://doi.org/10.1016/j.actpsy.2019.102902.

Crajé, C., Aarts, P., Nijhuis-van der Sanden, M., & Steenbergen, B. (2010). Action planning in typically and atypically developing children (unilateral cerebral palsy). *Research in Developmental Disabilities, 31*(5), 1039–1046. https://doi.org/10.1016/j.ridd.2010.04.007.

Fleming, J., Klatzky, R. L., & Behrmann, M. (2002). Time course of planning for object and action parameters in visually guided manipulation. *Visual Cognition, 9*(4–5), 502–527. https://doi.org/10.1080/13506280143000557.

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). https://doi.org/10.3389/fpsyg.2016.00108.

Henderson, S. E., Sugden, D. A., & Barnett, A. (2007). *Movement Assessment Battery for Children - second edition (Movemetn ABC-2)*. Pearson Assessment.

IBMCorp. (2013). Released. *IBM SPSS Statistics for Windows, Version 22.0. In IBMCorp*.

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 10 years of age in typically developing children. *Journal of Experimental Child Psychology, 114*(2), 295–305. https://doi.org/10.1016/j.jecp.2012.08.008.

Katschmarsky, S., Cairney, S., Maruff, P., Wilson, P. H., & Currie, J. (2001). The ability to execute saccades on the basis of efference copy: Impairments in double-step saccade performance in children with developmental co-ordination disorder. *Experimental Brain Research, 136*, 73–78. https://doi.org/10.1007/s002210000535.

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

Klapp, S. T. (1995). Motor response programming during simple choice reaction time: The role of practice. *Journal of Experimental Psychology: Human Perception and Performance, 21*(5), 1015–1027. https://doi.org/10.1037/0096-1523.21.5.1015.

Krajenbrink, H., Lust, J. M., & Steenbergen, B. (2021). Eliciting end-state comfort planning in children with and without developmental coordination disorder using a hammer task: A pilot study. *Frontiers in Psychology, 12*(56). https://doi.org/10.3389/fpsyg.2021.625577.

Krajenbrink, H., Lust, J., Wilson, P., & Steenbergen, B. (2020). Development of motor planning in children: Disentangling elements of the planning process. *Journal of Experimental Child Psychology, 199*, 104945. https://doi.org/10.1016/j.jecp.2020.104945.

Leonard, H. C., Bernardi, M., Hill, E. L., & Henry, L. A. (2015). Executive functioning, motor difficulties, and developmental coordination disorder. *Developmental Neuropsychology, 40*(4), 201–215. https://doi.org/10.1080/87565641.2014.997933.

van der Linde, B. W., van Netten, J. J., & Schoemaker, M. M. (2015). *DCDDaily Questionnaire Manual*.

Mutsaarts, M., Steenbergen, B., & Bekkering, H. (2005). Anticipatory planning of movement sequences in hemiparetic cerebral palsy. *Motor Control, 9*(4), 439–458. https://doi.org/10.1123/mcj.9.4.439.

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

R Core Team. (2013). R: A language and enviroment for statistical computing In. http://www.R-project.org/.

Rosenbaum, D. A., Marchak, F., Barnes, H. J., Vaughan, J., Slotta, J., & Jorgensen, M. (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.

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. https://doi.org/10.1037/0278-7393.18.5.1058.

Schoemaker, M. M., Reinders-Messelink, A. J., & de Kloet, A. J. (2008). *Coordinatievragenlijst voor Ouders (CVO) [Coordination Questionnaire for Parents] - translation of DCD-Questionnaire by Wilson (2007)*.

Scholte, E. M., & van der Ploeg, J. D. (2004). *ADHD vragenlijst (AVL) [ADHD questionnaire]*. Nippo - Nederlands Instituut voor Pedagogisch en Psychologisch Onderzoek.

Scott, S. H. (2012). The computational and neural basis of voluntary motor control and planning. *Trends in Cognitive Sciences, 16*(11), 541–549. https://doi.org/10.1016/j.tics.2012.09.008.

Seegelke, C., Hughes, C. M. L., Knoblauch, A., & Schack, T. (2013). Grasp posture planning during multi-segment object manipulation tasks — Interaction between cognitive and biomechanical factors. *Acta Psychologica, 144*(3), 513–521. https://doi.org/10.1016/j.actpsy.2013.09.002.

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. https://doi.org/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. *The Journal of Child Psychology and Psychiatry, 38*(8), 1023–1037. https://doi.org/10.1111/j.1469-7610.1997.tb01619.x.

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. https://doi.org/10.1007/s00426-015-0662-0.

van Swieten, L. M., van Bergen, E., Williams, J. H. G., 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. https://doi.org/10.1037/a0017177.

Wilmut, K., & Byrne, M. (2014). Grip selection for sequential movements in children and adults with and without developmental coordination disorder. *Human Movement Science, 36*, 272–284. https://doi.org/10.1016/j.humov.2013.07.015.

Wilmut, K., Byrne, M., & Barnett, A. L. (2013). Reaching to throw compared to reaching to place: A comparison across individuals with and without developmental coordination disorder. *Research in Developmental Disabilities, 34*(1), 174–182. https://doi.org/10.1016/j.ridd.2012.07.020.

Wilson, P. H., & Butson, M. (2007). Deficits underlying DCD. In R. H. Geuze (Ed.), *Developmental coordination disorder: A review of current approaches*. Solal Éditeurs.

Wilson, P. H., Ruddock, S., Rahimi-Golkhandan, S., Piek, J., Sugden, D., Green, D., & Steenbergen, B. (2020). Cognitive and motor function in developmental coordination disorder. *Developmental Medicine & Child Neurology, 62*(11), 1317–1323. https://doi.org/10.1111/dmcn.14646.

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

Wilson, P. H., Smits-Engelsman, B., Caeyenberghs, K., Steenbergen, B., Sugden, D. A., 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. https://doi.org/10.1111/dmcn.13530.

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

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience, 3*, 1212. https://doi.org/10.1038/81497.

Wunsch, K., Henning, A., Aschersleben, G., & Weigelt, M. (2013). A systematic review of the end-state comfort effect in normally developing children and in children with developmental disorders. *Journal of Motor Learning and Development, 1*(3), 59–76. https://doi.org/10.1123/jmld.1.3.59.